

CRANFIELD UNIVERSITY

MOHAMMADALI (PARSA) BAHRAMI

**A CONCENTRATED SOLAR STILL FOR COMMUNITY SCALE
DESALINATION**

**CRANFIELD UNIVERSITY SCHOOL OF AEROSPACE, TRANSPORT
AND MANUFACTURING
Concentrated Solar Power Engineering**

**DOCTOR OF PHILOSOPHY
Academic Year: 2013-2017**

Supervisors:

Dr Christopher Sansom

Dr Xavier Tonnellier

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Abstract

Water and energy are two main basic elements that human lives are dependent on to improve our life standards. Unreliability and a lack of safe drinking water source constitute a major difficulty in developing countries. Among many water purification technologies, solar desalination/distillation has become one of the best solutions as the most attractive and sustainable method to supply drinkable water in remote areas at reasonable cost for future generations. Seawater desalination technologies needed substantial amount of energy in order to convert brackish water into drinkable water. Thus, an extensive research on many desalination technologies has taken place in the last few decades, and solar desalination technology has become one of the most favourable sustainable methods to provide fresh water of sufficiently high quality for human communities. However, this method is not commercialized yet due to its low productivity, but improving this it has become a great source of interest for many researchers.

A solar still consumes direct solar energy to produce distilled water through evaporation and condensation process of brackish water. Much research has been conducted in order to increase the productivity, but the outcomes mostly require complex components and a notable increase in cost. Consequently, developing a productive, compact, easy to operate and reasonable cost solar distillation unit was the main challenge in this body of work. A comprehensive literature review is presented in order to illustrate different modifications and their properties on the productivity of solar stills. Even though there are considerations, which cannot be controlled by human intervention (such as meteorological parameters), design and operational factors could make a direct influence on the productivity of the solar still.

A novel transportable single basin, double slope shape solar still, enhanced with an internal ventilation fan connected to a copper material heat exchanger, was designed and built without forsaking its basic remit order to increase both evaporation and condensation process. The unit was also designed to use two linear focused Fresnel lenses as a solar radiation concentrator to direct radiation onto the top of solar still basin area. A detailed comparison of theoretical and laboratory experimental results were obtained for the present solar still to find the influence of different modification factors to the present solar still productivity. The temperatures of different parts of the solar still unit such as basin water, top cover glasses, heat exchanger condenser etc. were measured to evaluate different modifications including different fan airflow ratios, with and without a fan shroud, and lava stone effects to the distillate water output. The results presented an increase in productivity of 25.73% in comparison with a conventional solar still, by using a ventilation exhaust fan at its maximum airflow. Also an increase of 16.3% was also achieved by using lava stone as a heat storage material in the basin area.

Keywords: Solar Distillation; Productivity enhancement; Ventilation fan; Heat storing material; Heat transfer; Design and operational parameters

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List of Abbreviation

Symbols	Description
<i>CPC</i>	Compound Parabolic Collector
<i>ED</i>	Electrolysis
<i>EDR</i>	Electro dialysis reversal
<i>ETC</i>	Evacuated tube collector
<i>EX</i>	Experiment
<i>FPC</i>	Flat plate collector
<i>FRP</i>	Fibber reinforced plastic
<i>GI</i>	Fibre galvanized iron sheet
<i>H/D</i>	Humidification – Dehumidification
<i>ISES</i>	International Solar Energy Society
<i>MHD</i>	Multiple Humidification – Dehumidification
<i>MD</i>	Membrane Distillation
<i>MED</i>	Multiple effect distillation
<i>MSF</i>	Multistage flash distillation
<i>OSW</i>	Office of Saline Water
<i>PCM</i>	Phase change material
<i>PPM</i>	Parts per million
<i>PTC</i>	Parabolic trough collector
<i>RO</i>	Reverse osmosis
<i>SD</i>	Solar distillation
<i>TVC</i>	Thermal vapour compression

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Glossary

Azimuth is the direction of a celestial object from the observer, expressed as the angular distance from the north or south point of the horizon to the point at which a vertical circle passing through the object intersects the horizon.

Blackbody is a hypothetical perfect absorber and radiator of energy, with no reflecting power.

Beam Radiations is the part of total radiation that reaches earth's surface directly without being scattered by the atmosphere

Convective heat transfer is often referred to simply as convection; it is the transfer of heat from one place to another by the movement of fluids.

Desalination is a process that extracts mineral components from saline water. More generally, desalination refers to the removal of salts and minerals from a target substance, as in soil desalination, which is an issue for agriculture.

Distillation is the action of purifying a liquid by a process of heating and cooling.

Diffuse radiation is the part of total radiation that reaches earth's surface after a change of its directions due to scattering by the atmosphere.

Fan Shroud is a Critical Cooling System Component. They focus airflow through the entire radiator as compared to just the area that is covered by the traditional fan, creating a vacuum that pulls air across the entire surface area of the radiator, thus increasing cooling.

Fins are a thin component or appendage attached to a larger body or structure. Fins typically function as foils that produce lift or thrust, or provide the ability to steer or stabilize motion while traveling in

water, air, or other fluid media. Fins are also used to increase surface areas for heat transfer purposes, or simply as ornamentation.

Fresnel lenses are a type of compact lens originally developed by French physicist Augustin-Jean Fresnel for lighthouses. The design allows the construction of lenses of large aperture and short focal length without the mass and volume of material that would be required by a lens of conventional design.

Grashof number is a dimensionless number in fluid dynamics and heat transfer which approximates the ratio of the buoyancy to viscous force acting on a fluid. It frequently arises in the study of situations involving natural convection and is analogous to the Reynolds number.

Heat exchanger is a device used to transfer heat between a solid object and a fluid, or between two or more fluids.

Heat flux is a flow of energy per unit of area per unit of time.

Humic acid is a principal component of humic substances, which are the major organic constituents of soil (humus), peat and coal. It is also a major organic constituent of many upland streams, dystrophic lakes, and ocean water.

Infrared radiation is a type of electromagnetic radiation, as are radio waves, ultraviolet radiation, X-rays and microwaves. Infrared (IR) light is the part of the EM spectrum that people encounter most in everyday life, although much of it goes unnoticed. It is invisible to human eyes, but people can feel it as heat.

Intensity of solar radiation is the transfer rate of the beams energy across the unit area of a body.

Irradiance is called the rate by which the radiant solar energy hits the unit area of a surface.

Lauric acid is a saturated fatty acid with a 12-carbon atom chain, thus having many properties of medium chain fatty acids, is a white, powdery solid with a faint odor of bay oil or soap. The salts and esters of lauric acid are known as laurates.

Latitude is a geographic coordinate that specifies the north–south position of a point on the Earth's surface. Latitude is an angle (defined below) which ranges from 0° at the Equator to 90° (North or South) at the poles.

Longitude is a geographic coordinate that specifies the east-west position of a point on the Earth's surface. It is an angular measurement, usually expressed in degrees and denoted by the Greek letter lambda (λ).

Nano fluid is a fluid containing nanometre-sized particles, called nanoparticles. These fluids are engineered colloidal suspensions of nanoparticles in a base fluid. The nanoparticles used in Nano fluids are typically made of metals, oxides, carbides, or carbon nanotubes.

Nusselt number is the ratio of convective to conductive heat transfer across (normal to) the boundary. In this context, convection includes both advection and diffusion.

Parabolic trough is a type of solar thermal collector that is straight in one dimension and curved as a parabola in the other two, lined with a polished metal mirror.

Phase change material is physical chemistry, engineering, mineralogy, and materials science is a type of chart used to show conditions (pressure, temperature, volume, etc.) at which thermodynamically distinct phases occur and coexist at equilibrium.

Photovoltaics are best known as a method for generating electric power by using solar cells to convert energy from the sun into a flow of electrons by the photovoltaic effect. Solar cells produce direct current electricity from sunlight which can be used to power equipment or to recharge a battery.

Prandtl number is a dimensionless parameter used in calculations of heat transfer between a moving fluid and a solid body, equal to $c_p \rho / k$, where c_p is the heat capacity per unit volume of the fluid, ρ its kinematic viscosity, and k its thermal conductivity.

Polyvinyl Chloride is the world's third-most widely produced synthetic plastic polymer, after polyethylene and polypropylene.

Rayleigh number is a dimensionless parameter that is a measure of the instability of a layer of fluid due to differences of temperature and density at the top and bottom.

Sky radiation refers to the heat exchange between a surface area and the sky.

Stearic acid is a saturated fatty acid with an 18-carbon chain and has the IUPAC name octadecanoic acid.

Solar irradiance is the power per unit area received from the Sun in the form of electromagnetic radiation in the wavelength range of the measuring instrument. The solar irradiance integrated over time is called solar irradiation, insolation, or solar exposure.

Thermal radiation is electromagnetic radiation generated by the thermal motion of charged particles in matter. All matter with a temperature greater than absolute zero emits thermal radiation. Particle motion results in charge-acceleration or dipole oscillations which produce electromagnetic radiation.

Thermal conduction is the transfer of heat (internal energy) by microscopic collisions of particles and movement of electrons within a body.

Total dissolved solids refer to any minerals, salts, metals, cations or anions dissolved in water. Total dissolved solids (TDS) comprise inorganic salts (principally calcium, magnesium, potassium, sodium, bicarbonates, chlorides, and sulphates) and some small amounts of organic matter that are dissolved in water.

Ultraviolet is an electromagnetic radiation with a wavelength from 100 nm to 400 nm, shorter than that of visible light but longer than X-rays.

Visible light is a form of electromagnetic radiation, as are radio waves, infrared radiation, ultraviolet radiation, X-rays and microwaves. Generally, visible light is defined as the wavelengths that are visible to most human eyes. This broad range of wavelengths is known as the electromagnetic spectrum.

Vinyl chloride is an organochloride with the formula $\text{H}_2\text{C}=\text{CHCl}$ that is also called vinyl chloride monomer (VCM) or chloromethane.

Wick is a strip of porous material up which liquid fuel is drawn by capillary action to the flame in a candle, lamp, or lighter.

Zenith angles is the angle between the sun and the vertical. The zenith angle is similar to the elevation angle but it is measured from the vertical rather than from the horizontal, thus making the zenith angle = 90° - elevation.

List of Symbols

Symbols	Unit	Description
Nomenclature		
A	m^2	Area
A_s	m^2	Basin area
A_{ss}	m^2	Solar still sides area
b	m	Width of still
b_{wf}	m	Thickness of water film
C, C_p	$J/kg\ K$	Specific heat capacity
C_{gs}	J	Heat capacity of transparent cover and supports per unit of basin area
C_{wb}	J	Heat capacity of water basin and contents per unit of basin area
d	m^2/s	Thermal diffusivity
d_f	m	Average spacing between water and glass cover
d_w	m	Depth of water mass
e	-	Evaporation
F_s	-	Shape factor
Gr	-	Grashof number
$g.c$	-	Glass cover
g_h	Kg/h	Amount of evaporated water per hour
H	W/m^2	Solar radiation flux on a horizontal surface
h	$W/(m^2K)$	Heat transfer coefficient
h_c	$W/(m^2K)$	Heat transfer coefficient by convection, water to transparent cover
h_b	$W/(m^2K)$	Heat transfer coefficient, basin to grounds and surrounds
h_w	$W/(m^2K)$	Heat transfer coefficient by convective between basin inner and water mass
h_{cq}	$W/(m^2K)$	Heat transfer coefficient by convection from glass to ambient
h_{cw}	$W/(m^2K)$	Heat transfer coefficient by convection from glass to ambient
h_{ew}	$W/(m^2K)$	Heat transfer coefficient by convection from water to condenser
h_{lw}	$W/(m^2K)$	The total internal heat loss coefficient
h_3	$W/(m^2K)$	Heat transfer coefficient by convection from basin liner and water
$I(t)$	W/ m^2	Intensity of solar radiation
K	$W/(mK)$	Thermal conductivity
L	W	Latent heat of vaporisation
L_{hx}	m	Length of heat exchanger
Le	-	Lewis number
m	kg/ m^2	Mass per unit basin area
$\dot{m}$	Kg/s	Mass flow rate

M	kg	Mass
M_a	Kg/ m ²	Mass of water vapour transfer per unit of area
m_w	kg	Mass of dry air
n	-	Constant in Nusselt number expression
P_a	Pa	Saturated pressure at room temperature
P_a	N/m ²	Atmospheric pressure of moist air
P_{ci}	N/m ²	Partial saturated vapour pressure at condensing cover temperature
P_w	N/m ²	Vapour pressure at temperature of water surface
P_i	N/m ²	Partial pressure of water at air-water
P_∞	N/m ²	Partial pressure of vapour far from front still
P_{wg}	N/m ²	Vapour pressure of water at temperature of transparent cover
P_{ws}	N/m ²	Saturation pressure of water vapour
p	N/m ²	Partial pressure of water vapour
Pr	-	Prandtl number
Q	W	Heat transfer energy
q_{conv}	W/s	Conviction heat transfer ratio
q_{cond}	W/s	Conduction heat transfer ratio
q_{rw}	W/s	Radiative heat transfer ratio
q_b	W/ m ²	Heat transfer, still basin to grounds and surrounds
q_c	W/ m ²	Convection heat, water surface to transparent cover
q_e	W/ m ²	Evaporation/condensation heat transfer water surface to transparent cover
q_{eg}	W/ m ²	Evaporative heat transfer from water to glass cover
q_{ga}	W/ m ²	Heat transfer, transparent cover to air
q_r	W/ m ²	Heat transfer by radiation, water to cover
q_{rg}	W/ m ²	Radiative heat transfer from water to glass cover
q_{cg}	W/ m ²	Convective heat transfer rate from water to glass cover
q_w	W/ m ²	Heat transfer rate between basin liner and water mass
R	-	Reflectivity
R_h	-	Relative humidity
Ra	-	Rayleigh number
r	W/(m. K)	Thermal conductivity
t	s	Time
T	°C	Temperature
T_a	°C	Ambient temperature
T_g	°C	Temperature of glass
T_w	°C	Water temperature
U	W/ m ² K	Overall heat loss coefficient
U_b	W/ m ² K	Overall bottom loss coefficient between water mass and atmosphere

U_{bs}	W/ m ² K	Total bottom and side loss coefficient between water mass and ambient
U_L	W/ m ² K	Overall heat loss coefficient from top bottom sides
v	m/s	Wind velocity
V	m ³	Volume
x_s	(kg/kg)	Humidity ratio in saturated air
x	(kg/kg)	Humidity ratio in the air
Greek		
α	-	Absorptivity
α_g	-	Absorptivity of glass
α_w	-	Absorptivity of water radiation
β	-	Coefficient of volumetric expansion coefficient (1/k)
ε	-	Emissivity
τ	-	Transmissivity
σ	5.670373×10 ⁻⁸ (W/ m ² k ⁴)	Stefan-Boltzman number
θ	-	Inclination
γ	-	Azimuth angle of the solar still
ϕ	-	Latitude
ψ	-	Longitude
φ	-	Azimuth angle of sun
ρ	Kg/ m ³	Density
μ	N s/ m ²	Viscosity
η	-	Efficiency
η_i	-	Instantaneous Efficiency
λ	-	Wavelength
ζ	-	Vapour extraction ratio
ω	-	Hour angle
Δt	°C	Time interval

1. Introduction

1.1. Research Background

Potable water is a human right as much as clear air. However, much of the world's population does not have access to safe drinking water. More than one billion (one in six) lack accesses to safe drinking water, out of 6 billion people on earth. Moreover, about 2.5 billion (more than one in three) do not have access to even suitable sanitation services. Collectively, these short comings generate waterborne diseases that kill on an average more than 6 million children each year [1].

About 70% of the total earth's surface is covered by water, but most of it in the sea as saltwater. Fresh water covers only 3% of the earth's surface and much of it lies frozen in the Antarctic and Greenland polar ice. Humans consume fresh water available from rivers, lakes, underground sources and aquifers [2]. In total, these sources account only for 1% of all the water available on earth. A significant portion of the world's population now faces water shortage. As an example, 31 countries representing 2.8 billion people, including China, India, Kenya, Nigeria and Peru, are confronted by chronic water problems [3]. Within a generation from today, the world's population will go up to an estimate 8 billion people [4] and the amount of water will remain the same or may be less. The challenge is as clear and compelling as pristine water cascading down a mountain system.

Hence, we must find new ways of saving, using and recycling the water that we have on planet earth.

Using renewable energy, as a power supplier for desalination purposes, offers a promising solution to both water scarcity and environmental contamination issues. Different technologies have been proposed and studied to address these issues. Solar distillation is one of such continuous process that has been employed for hundreds of years, especially in remote areas. In their most basic design, a solar still consists of a top roof of transparent material with a black painted basin to absorb maximum solar radiation. The basin is filled with brackish or seawater that evaporates slowly due to heating by the sun radiation. Then, the vapour starts to condense as it loses its temperature against a cooler roof cover. The water drops drip down and collected in distinct channels as distillate water. Solar stills can have different shapes, structure, and cover materials while their setup need little maintenance, the basin is flushed occasionally to remove accumulated salts as required.

Solar stills have numbers of major limitations compared to fuel-based desalination methods. These limitations are low productivity per unit installation area, high primary costs per production unit, large installation area and energy source variability. Therefore, increasing the productivity of solar stills has been the focus of intensive research. Some studies have used different radiation absorber on the basin area such as sponges, gravel, rubber, charcoal, dyes and inks. Other researchers experimented different solar still such as flat-plate-collector materials to increase the water temperature inside the

basin, with reflectors to concentrate and direct sun light into the basin area. Others systems used digital sun tracking device to rotate the solar still unit with the sun movement, humid-dehumidification process, multiple-effect solar still, vacuum or to use separate the condenser, and wick technologies. In some cases, new designs or shapes of the solar still were investigated such as tubular solar still, transportable hemi-spherical still, and horizontal transparent tubes instead of basins.

A comprehensive literature review of numerous developments in solar stills, presented in the chapter 2 was carried out in order to interpret the effect of different modifications of solar still to the unit productivity. It was noted that many of these modifications and developments increased the productivity to a limited extend while commonly proposing complex or high cost component. These solutions do not match the low level of framework and abilities, which categorized places with water scarcity. Applying solar photovoltaic panels, external condenser, ponds, sun-tracking devices and other devices to increase the productivity also require extensive land area and significant increase in capital cost. In many cases, the gain of productivity reached does not justify the added disadvantages. Therefore, the main challenge emerging is for novel solar still to remain compact and have simplicity in operation with low cost.

A novel simple conventional solar still unit was developed in this research to be used in remote areas with difficulty to access fresh water. The present modifications were found to increase the productivity of solar still considerably while conserving its basic features and advantages such as sustainability, compactness and use of market available components. The performance of this new system was compared via conventional solar still using theoretical and laboratory experimental results achievements.

The proposed concept was introduced by Green Water Desalination by Mohammed Sanduk [5], and the evaluation and calculation of the type of ventilation fan and its principles was started at the master project thesis by M Bahrami [6] as figure 1 presents.

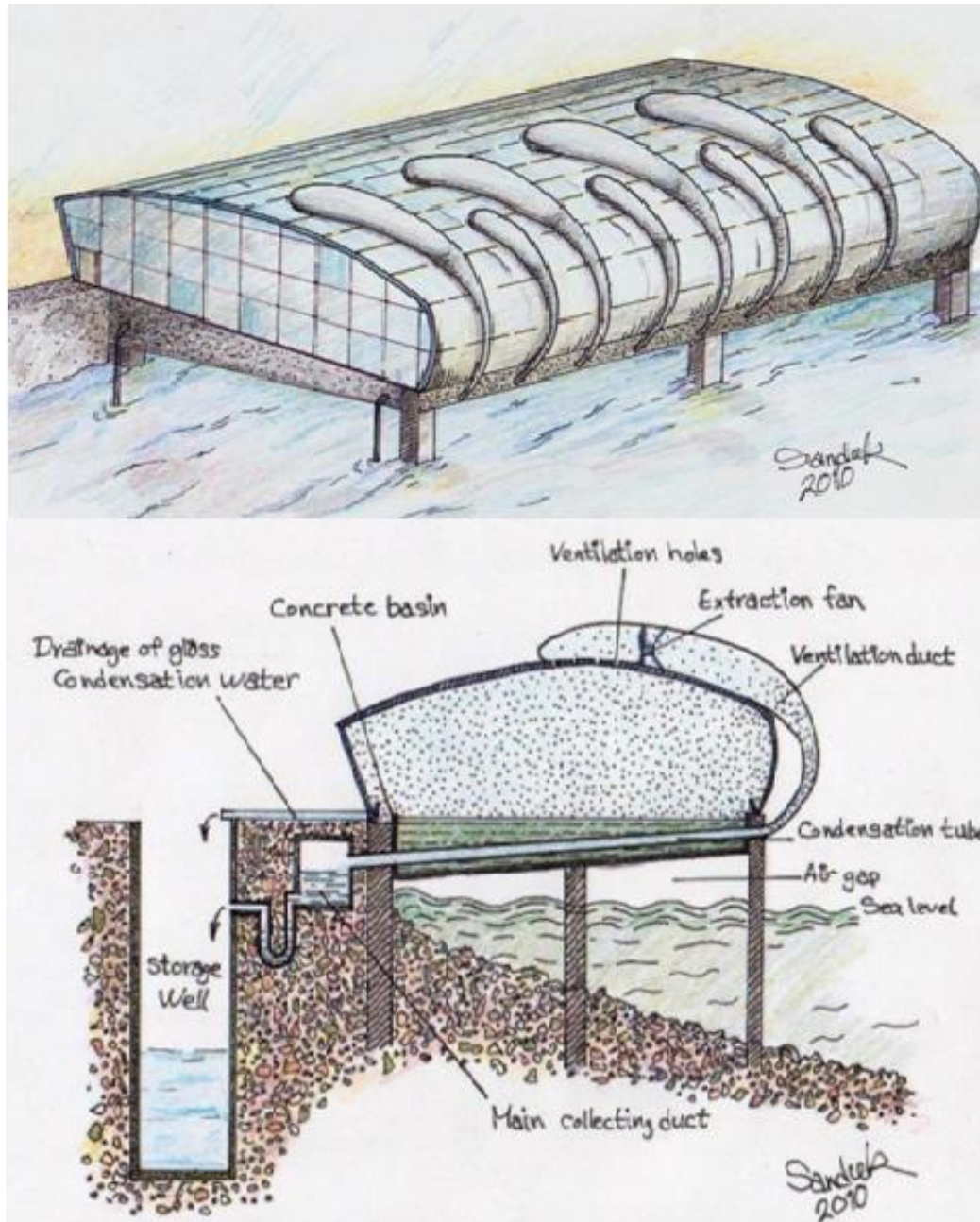


Figure 1: Dr. Sanduk Green Water Desalination concept [5]

The introduced model was designed to be used in remote areas with access to brackish water for desalination purposes. The suggested strategy is based on solar water desalination with improvement of low efficiency problem. One of the suggested techniques is to use a ventilation fan to pump out the evaporated water and pass it through heat exchanger pipes that sit on top of the basin area to cool vapour down into condense pure water. Extracting vapour out also assists to avoid vapour saturation which would have positive affect on both evaporation and condensation rate. The solar still unit was also designed in order to use two linear focused Fresnel lenses on top of the transparent material (figure 2) in order to direct solar radiation on top of the basin area so as to increase evaporation ratio.

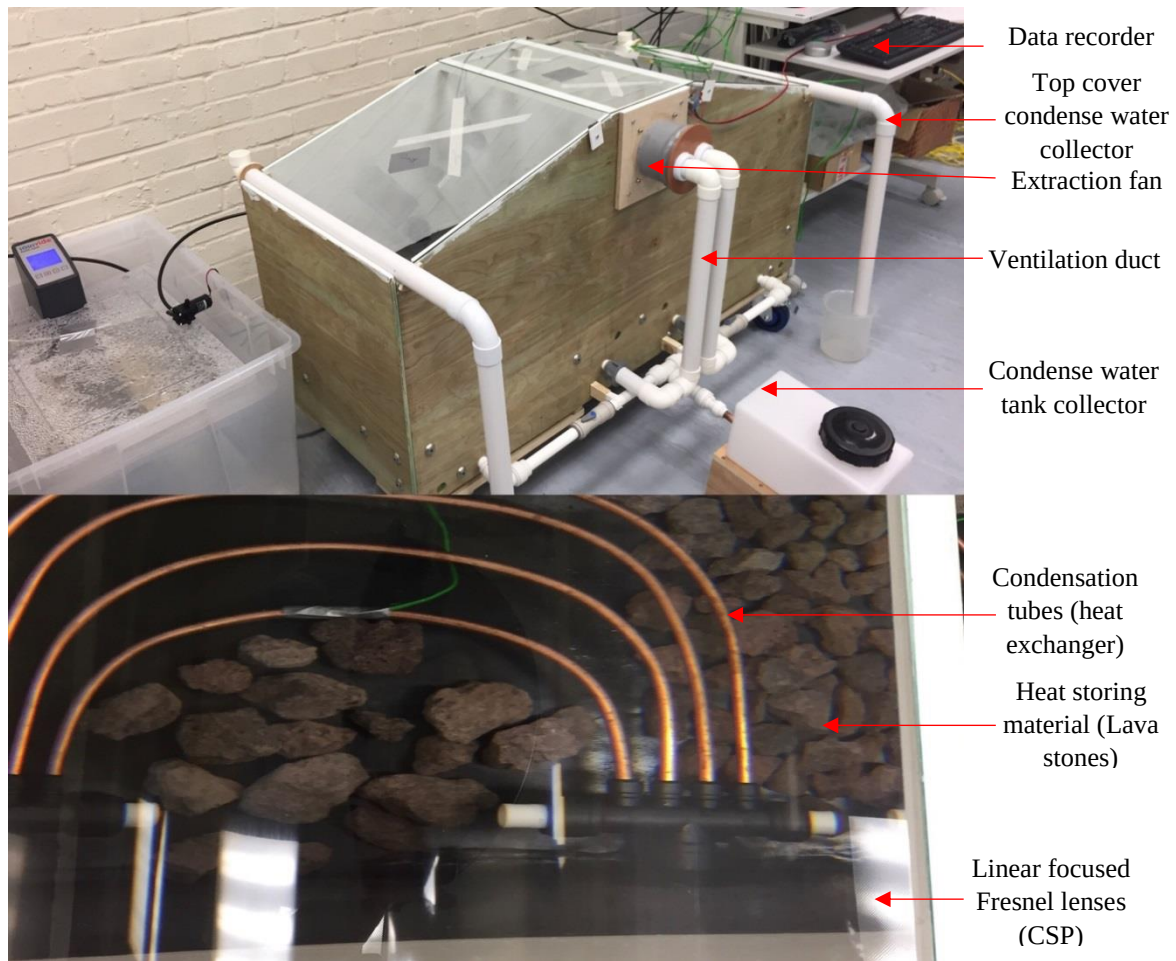


Figure 2: Laboratory scale the solar still unit

1.2. Thesis Outline

This thesis is delivered in eight chapters undertaking the new design of enhance solar still unit. A short summary of each chapter is defined:

Chapter 1

This chapter presents the purpose of using solar still distillation technique and its advantages for both environment and water scarcity.

Chapter 2

This chapter reviews existing comprehensive literature review in desalination method and its technologies, solar still types and parameters affecting the solar still productivity.

Chapter 3

Chapter 3 presents the aim and objectives of this research, the methodology followed and its scope. The research structure of the study is also described.

Chapter 4

Thermal and heat principles mechanism of solar still explained in details, by using different heat refers models to analyse theoretical productivity of the unit.

Chapter 5

In this chapter, the design and construction of a double slope solar still unit with a ventilation fan and on heat exchanger is presented. Theoretical and experimental results for different case scenarios are described.

Chapter 6

This chapter describes the various equipment and their operations employed in the experimental work. Furthermore, the procedure of experimental work and measuring instrument used are delivered.

Chapter 7

Theoretical and experimental outcomes of the solar still are presented and evaluated in this chapter such as the effect of using ventilation fan, heat exchanger and heat storage material.

Chapter 8

This chapter discussed the benefit of the new solution implemented on the productivity in comparison with literature review. Additionally, a case study and an economic analysis are presented analysed for both Almeria (Spain) and Qeshm (Iran).

Chapter 9

This chapter summarises the important findings of this thesis and identifies some potential areas for further research.

Chapter 10

This chapter presents the points to consider for future research including the environmental field to experiment the solar still unit productivity.

2. Literature Review

2.1. Water the Raw Material for Desalination

Approximately 70% of earth surface area is cover with water, which it is about $1.4 \times 10^9 \text{ km}^3$ out of 96.5% of all water on the planet. The remaining 2.5% is fresh water with 68.6% of this amount frozen in the icecaps or combined as soil moisture. Both forms are not easily accessible for human use [7]. The remaining quantity, about 0.3%, is believed to be adequate to support all life on earth (figure 3).

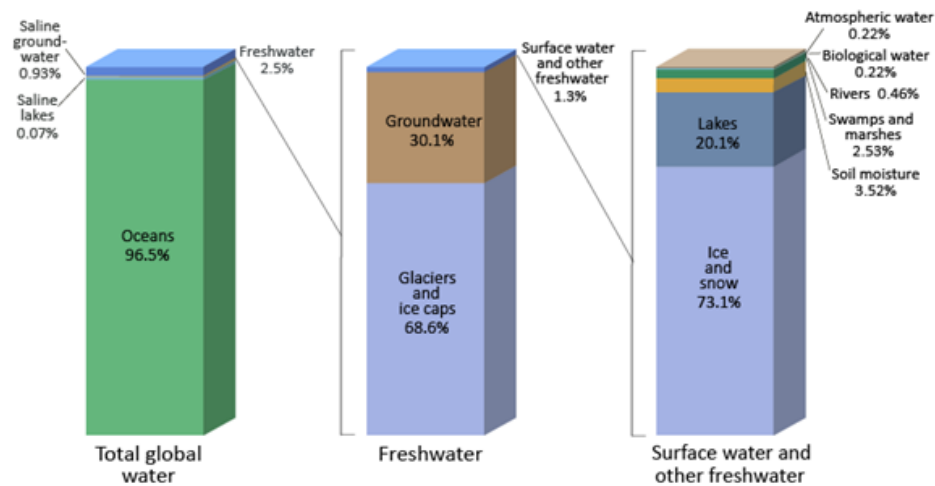


Figure 3: Distribution of world water resources [8]

This water is not distributed ultimately all over the plant, thus it is not accessible in appropriate quantity both when and where it is needed. Table 1 presents a summary for distribution of various water resources across the globe. The global daily average of rainfall is $2 \times 10^{11} \text{ m}^3$ [9]. The amount is poorly distributed across the world.

Table 1: Distribution of water resources across the globe [7]

Resources	Volume km^3	Percent of total water	Percent of fresh water
Atmospheric water	12,900	0.001	0.01
Glaciers	24,064,000	1.72	68.7
Ground ice	300,000	0.021	0.86
Rivers	2,120	0.0002	0.006
Lakes	176,400	0.013	0.26
Marches	11,470	0.0008	0.03

Soil moisture	16,500	0.0012	0.05
Aquifers	10,530,000	0.75	30.1
Lithosphere	23,400,000	1.68	-
Oceans	1,338,000,000	95.81	-
Total	1,396,513,390	-	-

People can survive for days or weeks without food, but cannot live for more than a week without water. The body uses water for digestion, absorption, circulation, transporting nutrients, building tissues, carrying away waste and maintaining body temperature.

There are three main sectors in which the fresh water is used, domestic (10%), industrial (20%) and agriculture (70%)[10]. The domestic use includes household, municipal and water used for commercial establishments are public services. Industrial use includes water drawn by various industries, with an increasing part being used to cool power plants. The agriculture sector includes water for irrigation and livestock.

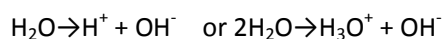
Pure (fresh) water production generally made from atmospheric condensation of vapour (as rain). The vapours are made by the seas, oceans and lakes by solar radiations by plant transpiration activities, the atmospheric humidity and clouds. Fresh water is existent only in the vapour state. As condensation of water vapour starts impurities are accumulated from the surrounding atmosphere, such as oxygen (O_2), and carbon dioxide (CO_2), that exist naturally in the air but also various other gases, created by human activities, such as sulphur dioxide (SO_2), nitrogen dioxide (NO_2), etc. The gases dissolve into condensate droplets and then form acids increasing hydrogen content. This is the reason for acid rain. During the rainy season condensed water returns to the earth's surface, penetrates into the soil forming aquifer and surface creeks or torrents. In both cases the final place is the ocean or a lake. Flowing through the soil the water enriches in various soluble salts forming hard or brackish waters. The salts accumulate into the seas and oceans forming their salinity. This procedure is called the "water cycle or hydrological cycle" which may be considered as a natural desalination operation, a huge, open solar distillation procedure going on continuously through the millennia [11].

Water is made of two hydrogen molecules and one oxygen molecule (H_2O). As all dipolar molecules, it is a good solvent for ions. Compared to other solvents, water and its aqueous solutions show unique properties that are very sensitive to temperature and pressure. Water vapour is really the only pure state of water and has no substance. Liquid pure water is something of an enigma as it possesses

unusual properties and is characterized in general as anomalous. It is categorized by the following properties [12]:

1. It is stable by phase changing from solid to liquid and vapour and vice versa;
2. Water has moderately high boiling temperature as strong as it has a intermolecular forces to escape to vapour phase;
3. Its melting enthalpy is the highest;
4. It has a high melting point due to a kind of quasicrystal line structure;
5. Its evaporation enthalpy is the highest of all substances. This property is extremely important in heat transfer procedures;
6. Its heat capacity is one of the highest of all liquids and solids;
7. Its specific heat is almost the highest in compare with other liquids;
8. It has the highest heat conductivity;
9. It has the highest surface tension of all liquids;
10. Its maximum density is at a temperature about 4 °C above freezing point. With increasing salinity temperature freezing point decreases;

As water has got strong molecular bond, it is rare to find pure condition in nature. The pure water only exists at time of condensation and it can be only by physical or chemical procedures, even though it is still has minor electrical conductance (approximately $0.75 \times 10^{26} \Omega^{-1} \text{ cm}^{-1}$ at 18°C). It is for the reason of dissolved carbon dioxide in equilibrium with atmospheric carbon dioxide with a slight dissociation of the water molecules [13]:



Various type of water quality can be categorized based on the reason for which the water needed. The first category is set for domestic, drinking and some of the industrial purposes. The salinity for this group should be in range of 5-1000 ppm. This sort of water can be found in lakes and rivers, which it can be produced by industrial desalination. The salinity below 150 ppm is best to be used for drinking purposes, while the salinity above 1000 ppm is best for several domestic applications. This demonstrated that drinking capita consumption is approximately 2 litres/day, while domestic use would be 200-400 litres/day. The domestic use of water is mostly for washing, cooking, gardening and etc. On an industrial scale, the most stringent water quality is set by makeup water for boilers and application related to the electronic industry and pharmaceuticals.

The water quality for these applications is limited to a maximum salinity of 5 ppm. This high degree of purity is achieved through the use of ion exchangers, which operates on low salinity river water or industrial desalinated water. Other industrial applications call for less stringent water quality. Including chemical reactions, dairy and food, washing and cleaning, and cooling [14].

The second water category has a salinity range of 1000-3000 ppm. This type of water is suitable for irrigation purposes and industrial cooling. This applies for higher salinity water, which includes

brackish and seawater. The salinity range for brackish water is 3000-10,000 ppm. As for the seawater its average salinity is 34,000 ppm. Water with salinity above 10,000 ppm is termed as high salinity water. The salinity of seawater varies subject to local conditions, where it is affected by ambient and topographical conditions. For example, enclosed seas have higher salinity than open seas and oceans. Also, seas, which are found in areas of high temperature or that receive high drainage rates of saline water; would certainly have higher degree of salinity. For example, the salinity of the Persian Gulf water near the shores lines of Iran, Kuwait, Saudi Arabia and the United Arab Emirates may reach maximum values close to 50,000 ppm. On the other hand, the salinity of the Gulf water near the Western Shores of Florida, USA, may reach low values of 30,000 ppm. This is because of the large amount of fresh water received from rivers and springs in that area [14].

The amount of fresh water exist on the earth is almost constant, while, the world population has grown considerably in last 200 years. Figure 4 presents the rate of population growth in last 200 years and estimate the next 50 years.

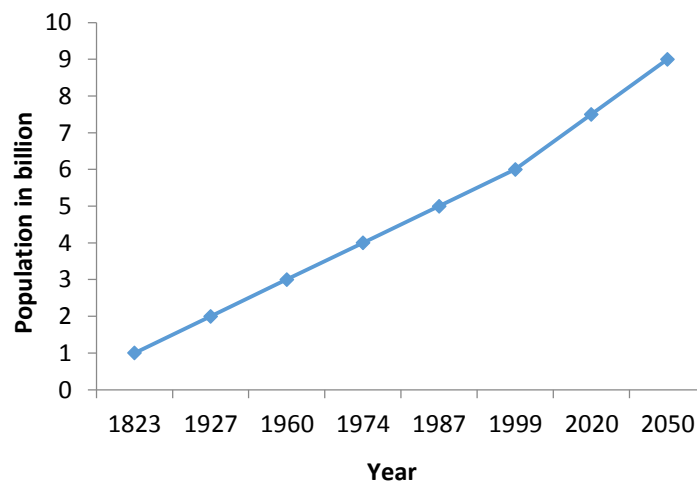


Figure 4: World population since 1823 and until 2050 [15]

Based on figure 4, the world population in year 1804 was about one billion and it only took 123 (1927) years to be double. At that time, it took only 33 years (1960) when the population reached 3 billion and then the population reached to 6 billion in year 1999. Thus, it is predicted that the population will reach 7.5 billion by 2020 and about 9 billion in year 2050 [16].

As the water reaches earth's surface or penetrates underground, many components are dissolved from various rock or soil (either organic or inorganic) that give the water its chemical or physical features. The most resources that are dissolved are chemical compounds such as magnesium (Mg^{++}), potassium (K^+), calcium (Ca^{++}) and sodium (Na^+), whereas the least compounds are copper (Cu) and etc. [17]. Further inorganic materials contained within are suspended solid matter and organic material. Organic combinations exist mostly in very small quantities and contain Humic acid that initiates from the decay of animal and plant matter, detergents and other harmful organic or inorganic material causing by human activities and from untreated hazardous waste discharges. Carbon compounds of hydrogen,

oxygen, nitrogen, phosphorus, and sulphur are the most organic material in nature that condense water that is inappropriate for drinking purposes or domestic operation [18].

The logarithm of concentration (logC) of total dissolved solids (TDS) can be used in order to measure the quality of many types of water. The same manifestation could be used for the fractional substances such as calcium or sodium or other molecules or ions. The values “logC” concentration is presented in table 2 as follow with unit of parts per million (ppm):

Table 2: Quality different of natural water [19]

Natural water	Log(C)	Units*	PHI/F
Pure salt	0	%	12
Dead Sea water	-1	%	11
Sea water	-2	%	10
Well water	-3	g kg ⁻¹	9
Lake water	-4	ppm	8
Spring water	-5	ppm	7
River water	-6	ppm	6
Dew (Humidity concentrate)	-7	ppb	5
Rain water	-8	ppb	4
Snow water	-9	ppb	3
Hail water	-10	ppt	2
Ice water	-11	ppt	1
Pure water	< -12	ppt	<0

It can be noted from table 2 that the Dead Sea water and pure salt are the most extreme circumstances due to their salt concentration. The last column shows the parameter PHI (Power Hydro-Impurities or F), which is identical to pH where the impurities are given in negative logarithms [20].

$$PHI = F = 12 + \log(C)$$

The population is expected be about 8.5 billion by 2025 and that leads to great amount of waste water mostly in countries with rich water resources [21]. There are countries that use more fresh water than their sources can afford, therefore, the excess in water pollutants makes some of the water resources unsuitable for any purposes. Then, the concern of drinking water comes to be more treasurable. As result, water regulation becomes harder.

The amounts of water requested for domestic usage are extensively different depending on economic, social, geography and culture of life. The World Health Organization (WHO) present guidelines with its regulations including desalination water that are divided into five segment as follow [22]–[24]:

1. Desalination technology and technical issues associated with desalination;
2. Chemical aspects of desalination water;

3. Sanitary microbiology of production and distribution of desalination water;
4. Monitoring surveillance and regulations;
5. Environmental impact assessment of desalination projects.

Water requirement can be grouped as domestic, community, industrial and agriculture with its own usage and definition as follow:

- *Domestic* use includes drinking, cleaning, cooking, small household industries and garden irrigation.
- *Community* use includes public gardens irrigation; local water distribution networks, fire-fighting water, and all water used for transportation such as canals, rivers, etc.
- *Industrial* water are all water used in chemical industries, in power plants for vapour production or other industries, water for hydroelectric power stations, cooling water for industries, etc.
- *Agriculture*, in general, consumes the larger water amounts for farming, raising cattle, and fisheries.

The main source of all these (Domestic, community, industrial and agriculture) purposes are mostly from ground waters, surface water (include river and lakes) and spring. The water quality for each category is different according to the WHO specifications that may be more or less flexible base on local national regulations [22].

2.2. Desalination Method and Technologies – Water and Energy

A physical process to remove the dissolved salts from waters, seawater and brackish water to collect low-salt content water is called desalination. The desalinated water from such a process could be used for industrial, household or drinking purposes. Desalination producers are an intensive technology that require large amount of energy, as a result rendering energy cost as the major economic problem. Distillation technology require large amount of energy in comparison with any other in chemical industry. Therefore, distillate water is still expensive despite the dramatic decline in cost during the recent years.

The cost of natural water pumping is due mainly to the capital cost of the installation. At the beginning of the operation, consumption may be lower than real capacity installed and the cost is relatively high. Consumption usually increases rapidly and cost decreases until the water source is almost exhausted. Then another source must be found further away from the site to start again. A desalination plant is more flexible to demand fluctuations and capacity may be increased according to demand by installing new units. Furthermore it is the only solution for places blessed with an

abundance of brackish water wells or area that are surrounded by seawater but have no fresh water resources.

Desalination technologies and their methods resulted from the activities of Office of Saline Water (OSW) of the US Department from 1952 till 1972. During these years, the intensive OSW activities in research and development (R&D) and the construction of five demonstration plants, of 1 millions of gallons per day each, developed and promoted desalination to its large industrial application. Since 1972, industry undertook R&D and technical applications [25].

2.2.1. Desalination processes

Desalination technologies mainly divide into two categories as thermal and non-thermal processes. These categories mainly include, based on the applied energy type as follow [26]:

1. Thermally driven desalination methods (or distillation processes)

- Thermal vapour compression (TVC);
- Multistage flash distillation (MSF);
- Multiple effect distillation (MED);
- Membrane Distillation (MD);
- Multiple Humidification – Dehumidification (MHD);
- Humidification – Dehumidification (H/D);
- Solar Distillation (SD).

SD, MD, and H/D do not belong yet to the conventional desalination methods, as they are still under investigation not completely commercialized. Conventional desalination thermal methods are driven by steam produced by conventional fuels.

2. Electrically (non-thermal) driven desalination methods

- Electrolysis (ED), Electro dialysis reversal (EDR);
- Reverse Osmosis (RO).

Figure 5 shows the existing conventional desalination processes, which are either still totally commercialized or under investigation.

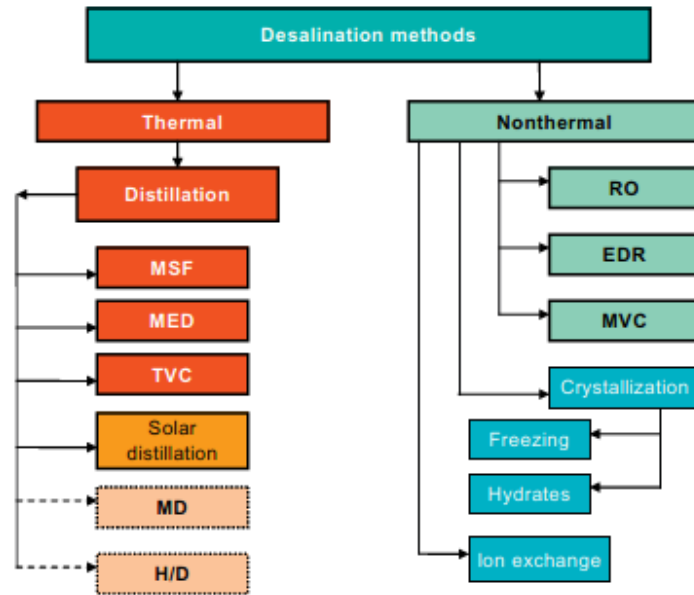


Figure 5: Flow diagram of the existing desalination methods according to type of energy used.

Most thermal processes are determined by energy sources such as fuel in the form of vapour pressure or non-thermal by grid electrical energy. Based on the methods from figure 5, ED/EDR, RO, MED, MSF and TVC are industrially settled. The main focus in these technologies is to minimise energy consumption to increase productivity, simultaneously reducing the weight and installation cost to reduce the final cost of produced fresh water. The rest of techniques are still in the stage of industrial development due to their financial matters.

There are more than 15,000 desalination plants that producing approximately 70 million m³ of fresh water per day in the world. More than half of these plants exist in Middle-East regions (60% RO, 27% MSF, 8% MED and 15% thermal desalination method) [27].

The summary of each method of desalination can be described as follow:

Solar distillation (SD): This is a method that uses solar radiation directly, with solar radiation being taken into devices called “solar stills”. Radiations are absorbed by the basin water and are transformed into thermal energy, which evaporates the water. The vapour then condenses on the inner surface of transparent lid material by losing its latent heat and is then collected by side channels. It is sort of Humidification/Dehumidification technique taking place in same device (Figure 6).

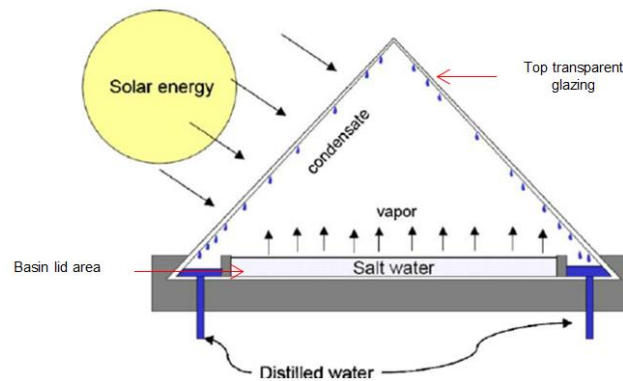


Figure 6: Schematic diagram of Solar Distillation unit [28].

Humidification-Dehumidification (H/D): This is a different version of solar distillation, a technique that uses separate partitions, called towers or chambers, for the evaporation (humidification) and condensation (dehumidification) procedures. Solar energy is collected independently mostly by solar flat plate collectors (Figure 7).

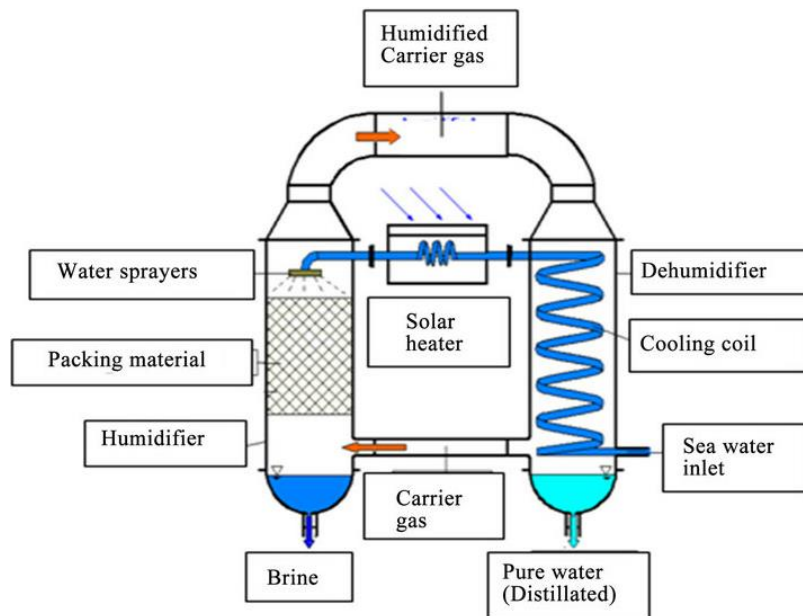


Figure 7: Schematic diagram of simple Humidification/ Dehumidification unit [29].

Membrane distillation (MD): The hot brackish water feed flows across a membrane surface which is permeable only to water vapour. Vapour permeates through the membrane pores and condenses on the other side of the membrane. This method uses microporous hydrophobic membranes permeable only to water vapour (Figure 8).

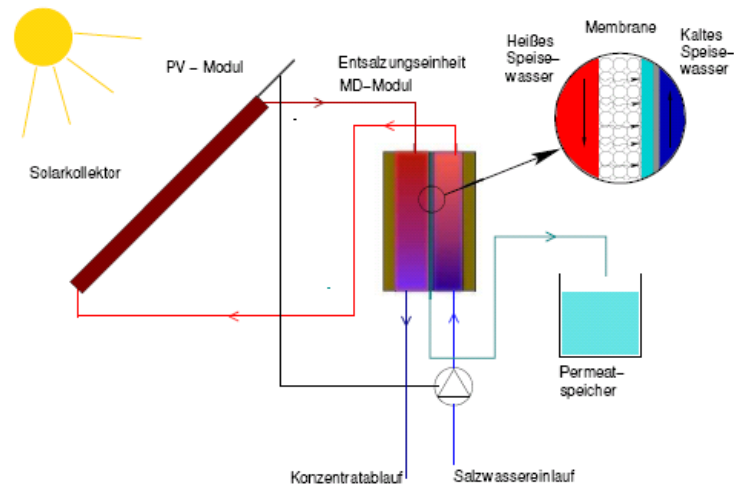


Figure 8: Schematic diagram of Membrane Distillation unit [30].

Multiple effect distillation (MED): The feed seawater is heated by pressurized steam in the first stage and then forwarded in a battery of consecutive chambers each having a lower pressure than the previous one. Created vapours are condensed giving the condensation enthalpy to incoming feed seawater (Figure 9).

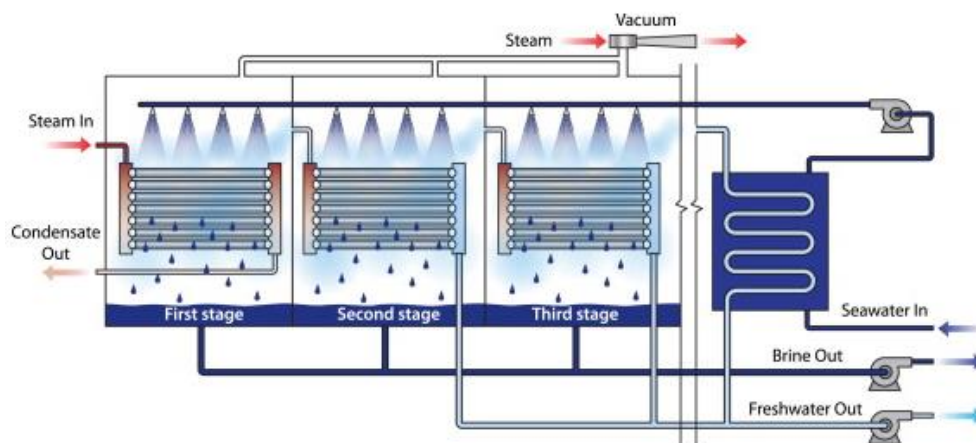


Figure 9: Schematic diagram of MED unit [31].

Multistage flash distillation (MSF): The hot feed water heated by steam in the first stage enters a battery of compartments, each at lower pressure than the previous one. The hot water expands into each chamber releasing vapour which condenses giving fresh water and simultaneously its condensation enthalpy to the incoming seawater feed (Figure 10).

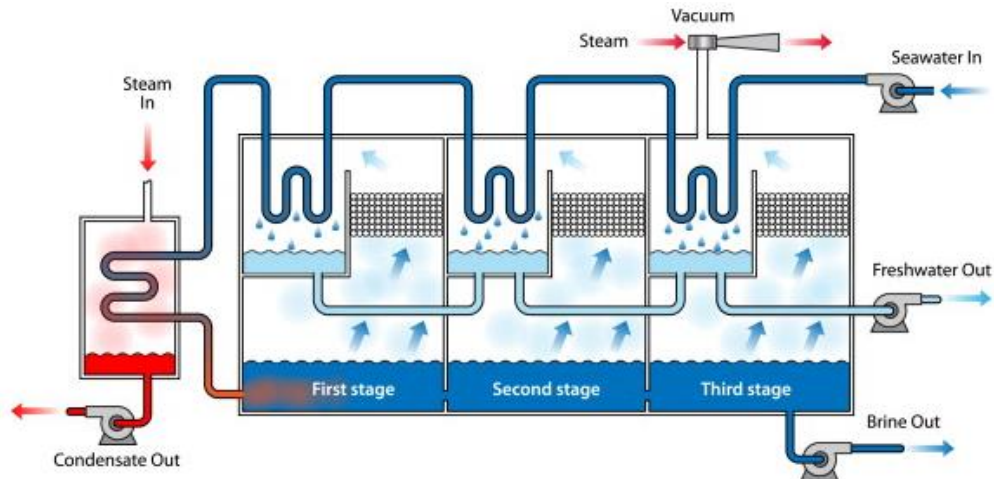


Figure 10: Schematic diagram of MSF unit [31].

Thermal vapour compression (TVC): By this distillation technique, part of the released vapour which remains in vapour phase during operation is compressed to high pressure by means of a steam thermos compressor. The compressed vapour is used to heat the feed seawater entering the distillation compartment (Figure 11).

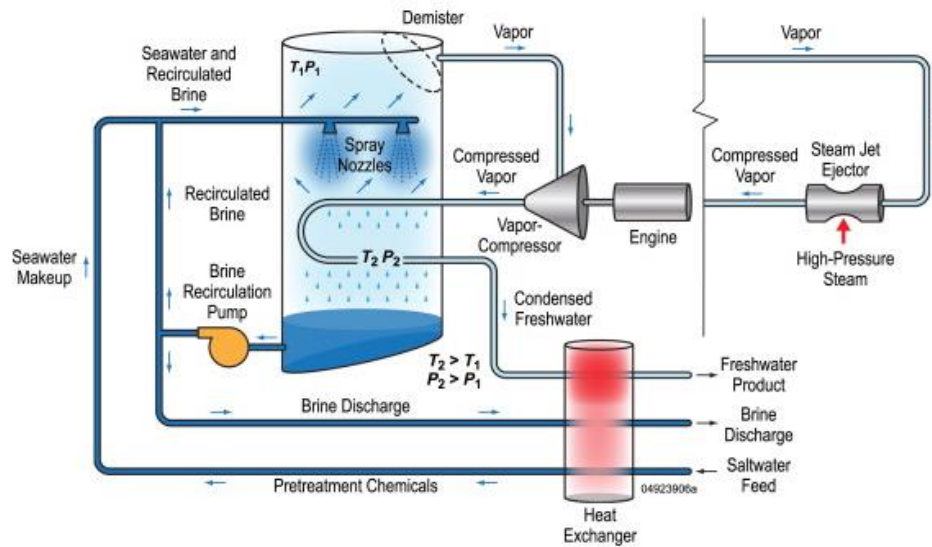


Figure 11: Schematic diagram of TVC unit [31].

Reverse Osmosis (RO). It is a form of pressurized filtration in which the filter is a semi-permeable membrane that allows water, but not salt, to pass through. This yields permeated fresh water and leaves a concentrated solution on the high-pressure side of the membrane. It has four subsystems: (1) pre-treatment, (2) high-pressure pump, (3) membrane, and (4) post-treatment. Feed-water pre-treatment involves filtration, sterilization, and addition of chemicals to prevent scaling and biofouling. The high-pressure pump generates the pressure needed to force the water to pass through the membrane; therefore, the energy needed is electricity to drive the pumps. The membranes are designed to yield a permeate water of about 500 ppm and made in a variety of configurations [32][33]. Figure 12 is a schematic diagram of an RO system.

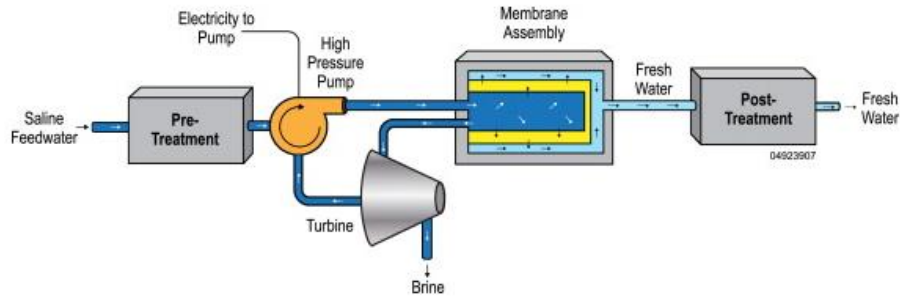


Figure 12: Schematic diagram of RO system [31].

Electrolysis (ED), Electro dialysis reversal (EDR): It is an electrochemical separation process that operates at atmospheric pressure and uses direct electrical current to move salt ions selectively through a membrane, leaving fresh water behind (Figure 13).

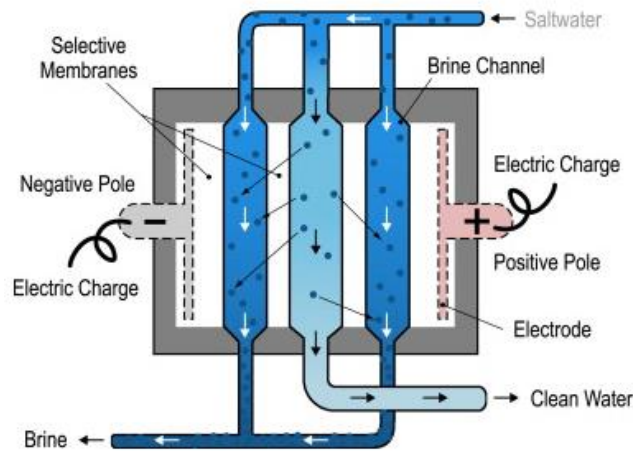


Figure 13: Schematic diagram of ED unit [31].

The ED unit consists of the following components: pre-treatment system, membrane stack, low-pressure circulation pump, direct-current power supply (rectifier or photovoltaic system), and post-treatment system. The operational principle of ED is as follows: electrodes (generally constructed from niobium or titanium with a platinum coating) are connected to an outside source of direct current in a container of salt water containing an ion-selective membrane connected in parallel to form channels. When brackish water flows between these channels and electricity is charging the electrodes, positive salt ions travel through the cation-permeable membrane toward negative electrodes, and negative salt ions travel through the anion-permeable membrane to the positive electrode, which results in the removal of salinity from the water [34].

As part of the main process, the MSF and RO play a key role, comprising 44% and 42% of worldwide capability, correspondingly [35]. Whereas the MSF process accounts for more than 93% of the thermal process generation, while RO method are accountable for more than 88% of membrane processes production [36].

2.2.2. Energy requirement for desalination processes

Almost every kind of energy sources is appropriate for desalination purposes by generating either electricity or thermal energy to separate saline solution in brackish or seawater into fresh water. The industrial scale distillation plants (more than 10,000 m³ per day) mostly are operating by fuel and electricity from grid to ensure efficient and continuous operation [37]. Renewable energies as a thermal or non-thermal (such as wind, biomass, solar, wave and geothermal) are alternative energy sources to be applied as power generator for desalination plants. Almost 0.1% of global desalination plant are using renewable energy and it is still under investigation and research [38] [39][40].

Using renewable energy sources for the desalination technologies it is feasible to produce fresh water in different parts of the world. Incidentally, renewable energy has exclusive collaborations in sections where desalination is most needed.

Solar energy has found a wider application base in comparison with other renewable energy technologies. The main advantage of using solar energy is the global availability that delivers approximately 89,000 Trillion Watt per day while earth's consumption is about 15 Trillion watt [41], plus it can be transformed to either electrical or thermal energy (or both).

There are restrictions on the collections of solar energy that has direct effect in solar desalination operation. Firstly, the sun is only available during daylight hours and secondly it is fluctuating energy source with low density periods which spread out unequally. The maxim rate that solar radiation incidents can be collected is about 50.68% [42]. Thus, the low-density collection can be beneficial to use solar radiation concentrator or Photovoltaic (PV) to generate higher temperature to be use in MSF or MES units. Converting the solar radiation into electrical (PV) or thermal (PV, CSP) energy to be used for different applications has lower efficiency in comparison with not using solar energy as power source of desalination and it also requires large land area. Table 3 presents the main desalination technologies with the consistent appropriate solar energy collection system.

Table 3: Water production and energy consumption desalination plants coupled with renewable energy

Solar power desalination process	Typical capacity (m³/day)	Energy demand (kWh/m³)	Water production cost (US\$/m³)
Solar still [43]	< 100	Solar passive	1.3-6.5
Solar MEH [44]	1-100	Thermal: 29.6 Electrical: 1.5	2.6-6.5
Solar MD [45]	0.15-10	45-49	10.5-19.5
Solar pond/ MED [46]	20,000-200,000	Thermal: 12.4-24.1 Electrical: 2-3	0.71-0.89
Solar pond/RO [47]	20,000-200,000	Seawater: 4-6 Brackish water: 1.5-4	0.66-0.77

Solar CSP/ MED [48]	> 5,000	Thermal: 12.4-24.1 Electrical: 2-3	2.4-2.8
Solar PV/RO [49]	< 100	Seawater: 4-6 Brackish water: 1.5-4	11.7-15.6 6.5-9.1
Solar PV/EDR [43]	< 100	1.5-4	10.4-11.7

The most important characteristic of desalination plant running by solar energy in inaccessible area must be simple, easy handling, must fit to the site of installation and easy to extend the size for optimisation of efficiency [50].

2.2.3. Thermal Solar Desalination

Using sun as power generation to remove dissolve salts from brackish water to extract pure water is referred to “solar desalination”. Correspondingly, separating salts and other dissolved or suspended matter such as organic compounds from waste water, is also defined as desalination . Depending on the way that solar energy is utilised for desalination purposes, it can be categorised into two methods.

Solar distillation: In this technique, the solar radiation is used directly to distil the water into solar stills. Solar stills are mostly simple and easy to operate devices that transform solar radiation into heat and at the same time evaporate the brackish water. They may also be combined, as supplementary tools, with solar ponds and/or flat plate collectors to increase the productivity.

Solar desalination: There are also different names for this method such as solar power, solar assisted and solar driven desalination. In this method, the solar energy is used indirectly to generate power by taking solar energy from a solar collector field.

Solar driven desalination plants are dual plant techniques consisting of two completely different independent systems: the solar radiation conversion system and the conventional desalination units. Thus, solar radiation capture and conversion can be grouped as follow:

Solar collectors, these are mostly parabolic trough collector (PTC), evacuated tubes (ETC), flat plate collector (FPC) and compound parabolic collectors (CPC) based on the capacity required and desalination method. Central receivers provide either high temperature steam and electricity or low temperature waste heat to be used either as heat to power conventional distillation units such as MSF, MED, and combined TVC.MED or is converted to electricity (for high temperature concentrators) mostly of medium capacity to fire ED, RO, and MVC units. Therefore, solar collectors could be used either by steam generation or seawater heating to determine conventional distillation plants.

Photovoltaic cells, these convert solar radiation directly into electricity, or wind energy as an indirect solar driven energy that may also be used to harvest electricity for desalination purposes.

Desalination plants that are driven by solar power are mostly small to medium scale (5,000 m³ per day). The largest solar distillation plant ever fabricated was normally of about 20 m³ per day [51]. Figure 14 shows the use of solar energy in various desalination fields.

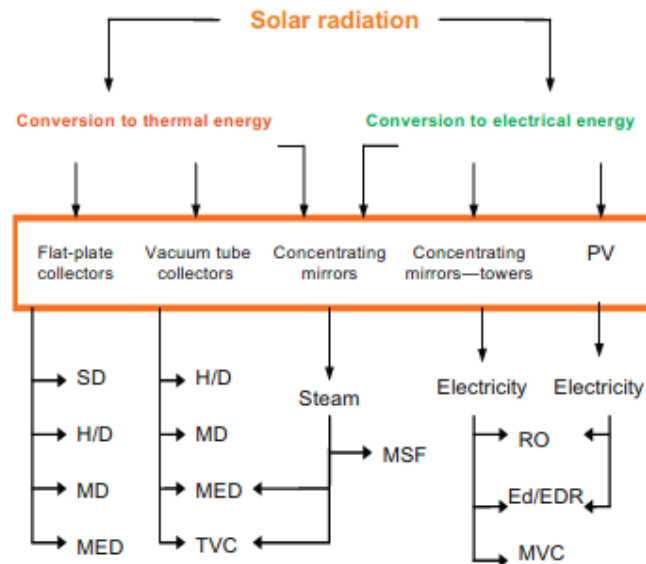


Figure 14: The coupling of desalination methods to a solar energy converting system [52].

2.3. History and Definitions of Solar Still

Many reviews have been performed on solar distillation to produce fresh water from seawater starting from antiquity. Most are great ideas but the concept designs are not efficient. The main concept comes from beginning of the fourth century when Aristotlet introduced the process of evaporation of sea water to produce fresh water [53]. Probably one of the first seawater desalination applications is as shown in figure 15.



Figure 15: Sailors producing fresh water by distillation of seawater [54].

The idea of desalination for producing fresh water was developed on board ship for long distance journeys. Aphrodisias (200 A.D.) said sailors boiled seawater and used large mops at the mouth of a bowl to absorb the evaporated water (figure 14) [54].

There was no significant desalination application generated by solar power until medieval times. Solar energy was mostly used to make fire for herbal extraction or dilute alcoholic solutions for medical purposes.

Mouchot the French scientist references in one of his various books that Arab alchemists used polished concave mirrors shape to concentrate solar radiation onto glass vessels enclosing seawater in order to produce fresh water (in the 15th century). He also used solar energy to distil alcohol. He developed a linear focus metal mirror to use as a boiler [55].

Later on during the Renaissance, Giovanni Batista Della Porta (1535–1615) wrote many books which were translated into French, Italian and German. In one of the books published in 1558, he mentions seven methods of desalination systems [53] to use solar power to convert brackish water into fresh water in wide earthen pots subjected to the intense heat of the solar rays to evaporate water and collect the condensate into bottles located beneath [56].

In 1870, the first patent on solar distillation was granted in America to Wheeler and Evans experimental work [57]. The solar distillation basic design and operation were explained fully in the mentioned patent. A full description on the cover condensation analysis and evaporation were discussed by inventors. Solar incident radiation tracking by rotating the still and high operating temperature ($900^{\circ}\text{F} \approx 482.22^{\circ}\text{C}$) were also claimed in the aforementioned patent.

C. Wilson, a Swedish engineer in 1872 [58], constructed the first solar distillation plant, in Las Salinas, Chile as a first large-scale distilled water production unit. This unit was built to provide the freshwater required for the workers and their families. The unit was filled with saltpetre mine wastes (salinity of 140,000 ppm), as feed water to stills. The materials that were used to construct stills were timber and wood with a glass sheet lid or cover. The system was made with 64 bays with total surface area of $4,450 \text{ m}^2$ and a total land surface area of $7,896 \text{ m}^2$. The productivity of 22.70 m^3 of fresh water per day (about 3.9 l/m^2) was gained with an operating life of 40 years.

There are definitions, taken from books of solar energy [59] and Elango review articles [60], to understand the functionality of solar ratios to be used in solar distillation process. These are briefly explained as follows (symbols/units are given base on International Solar Energy Society (ISES) [61] and SI [62]).

2.3.1. Absorptivity – Transmittance – Reflectance of Cover Material

Cover Absorptivity (a_c) refers to absorption of solar radiation by transparent material. The term definition is the ratio of absorbed solar radiation to the incident radiation:

$$a_c = \frac{G_{abs}}{G_{inc}}$$

Cover Emittance or Coefficient of Emissivity (ε_c) refers to the ratio of intensity emitted by the cover “ ε_c ” at constant temperature, to the intensity of a black body emittance “ ε_{bl} ” of exactly the same temperature and dimension/shape and temperature as given:

$$\varepsilon = \frac{\varepsilon_c}{\varepsilon_{bl}}$$

Cover Reflectivity (ρ_{enc}) refers to the ratio of reflected solar radiation to the incident:

$$\rho_c = \frac{G_{ref}}{G_{inc}}$$

Cover Transmissivity (τ_c) refers to the property of a transparent material to let the solar radiation to be transmitted through its path length with instantaneous refraction. It is obtainable by the ratio of solar radiation passing the cover to the incident solar radiation:

$$\tau_c = \frac{G_{ra}}{G_{inc}}$$

2.3.2. Solar Radiations

Black body refers to a body having ultimate solar radiation absorptivity. Incident solar radiations (G_g) is the radiant solar energy that reaches the earth's with unit of W/m^2 . Solar radiations consist of:

- *Beam (or direct) radiations (G_b)* is the part of total radiation that reaches earth's surface directly without being scattered by the atmosphere (W/m^2);
- *Diffuse radiations (G_d)* is the part of total radiation that reaches earth's surface after a change of its directions due to scattering by the atmosphere (W/m^2).

Incident solar radiation to normal refers to solar radiation falling perpendicular on a surface.

Global irradiance (G) is the total solar flux density (W/m^2).

Intensity of solar radiation is the transfer rate of the beams energy across the unit area of a body (W/m^2).

Irradiance (E, H) is called the rate by which the radiant solar energy hits the unit area of a surface. Irradiance can be divided into diffuse (G_d), beam (G_b), or spectral (G_s). The radiation above atmospheric is " G_o ". By means of incorporating irradiance over a constant period of time (an hour or a day) originate the incident solar energy per unit surface area of surface (specifically insolation or irradiation).

Insolation (I) is expressed as instantaneous (G , W/m^2), hourly (I , $\text{J/m}^2 \text{ h}$), or daily (H , $\text{MJ/m}^2 \text{ d}$) that is referred as beam or diffuse insolation.

Radiant energy (Q) is the energy transmitted by electromagnetic waves from a hot body to a colder one (J).

Sky radiation ($^{\circ}\text{C}$) refers to the heat exchange between a surface area and the sky. The sky is considered as a black body of temperature (T_{sky}). The net thermal loss from the surface, at temperature “ T ” and of emittance “ ϵ ”, to the sky is given as:

$$Q = \epsilon A \sigma (T^4 - T_{sky}^4)$$

where “ σ ” is the Stefan. Boltzmann constant. It is applied to solar stills and flat plate collectors especially during night operation.

2.4. Solar Stills

Solar stills are devices that contain brackish or saline water in a basin, which collect solar radiation to evaporate the water. As a result, the vapour changes its phase to liquid and condenses as fresh water. The most common solar stills can be described as follows:

- **Conventional solar still:** It is simple design which is also known as “greenhouse” as it acts like it. This type are also known as “tent type,” “roof type,” etc. as figure 16 presents. It can be symmetrical (double slope, figure 16A) or asymmetrical (single slope) as shown in figure 16B and C.

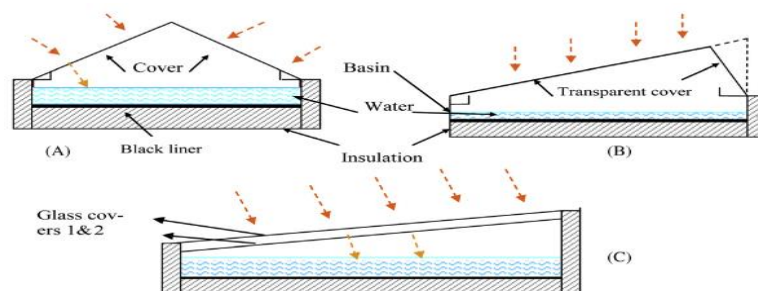


Figure 16: sketches of the conventional simple symmetric and asymmetric stills ("A" and "B" with single glass cover and "C" with double glasses cover) [50].

Conventional, multiple effect solar stills: It consists of multiple stages or "effects". In each stage the feed water is heated by steam in tubes, usually by spraying saline water onto them. Some of the water evaporates, and this steam flows into the tubes of the next stage (effect), heating and evaporating more water. Each stage essentially reuses the energy from the previous

stage, with successively lower temperatures and pressures after each one. Additionally, between stages this steam uses some heat to preheat incoming saline water.

Solar stills with basin wicks: In this type the basin surface area is covered with jute and charcoal as a wick in addition with a black liner that present large surface area to water flow. The system consists of a simple basin enclosed in a thermally insulated box and covered by a glass. Jute wick material is floated on the basin water and charcoal wick material is introduced in the basin.

Solar stills of various geometric forms: There are many types of solar still base on its geometries and shapes with internal or external parts such as reflectors, focusing collector, etc.

Solar stills are mostly oriented towards the North in the Southern hemisphere and towards the south in the Northern. They are mostly easy to fabricate with inexpensive materials with a lifetime that mostly depends on the material and operational conditions. Thus, it is best solution to provide fresh water for inaccessible areas with poor economies such as Africa, the Caribbean islands, and other remote regions on earth. A conventional solar still consists of:

- *A basin area* with variety of geometries;
- *A black liner* in order to absorb most solar radiation to transform it into thermal energy. Black surface can be a black plastic material, black paint, or any material that increases radiation absorption;
- *A top case* to receive the transparent upper shield;
- *A transparent cover material* (glass or a durable plastic material);
- *Insulation material* which covers the basin bottom and sides of the still;
- *Feeding and blow down pipes* comprising joints fittings to collect output fresh water;
- *Pumps for feed water* circulation and brine blow down;

Insulation of spaces between solar still structure and top cover is one of the most important parameters in operation of solar still, because brackish water evaporation and its condensation are placed all together and the vapour is condensing at the inside transparent cover surface. The black body cover of the basin area absorbs solar radiation through the tilted angle top cover, which causes basin water to be heated to a temperature (40-80 °C) higher than the top cover temperature (30-50 °C) to begin evaporation process (less than boiling point). Solar radiation wave-length changes to long-wave heat as it passes through the transparent material and reaches the black liner surface area.

Solar stills are operated either in batch that is known as passive or in continuous mode as active ones.

Batch operation (Passive solar still): In this operation, the basin surface area fills with brackish water every morning to heat up until the right temperature is achieved. As the evaporation starts, the salt water mass in basin area decreases that cause algae formation, as a result the basin water needed to be change every hour or day. Water depth on the basin has a direct effect on the productivity, which means a lower water depth means a higher daily productivity in the still. Conversely, a deep water depth in the basins act as heat storage units ongoing to produce fresh water during night time, while in decreasing rate, till sunrise period[63].

Continues operation (Active solar still), In this operation, the basin surface area is filled with brackish water constantly at low rates to keep the water depth almost stable. Their characteristics are described below[63]:

- They are appropriate for remote areas that face water scarcity with high solar intensity radiation and an access to brackish water;
- Conventional passive solar stills may be coupled to solar collectors in order to increase their productivity by raising feed water (brackish or waste water) temperature;
- Active solar stills have an average operation temperature in the range of 50 - 80°C, while passive stills are operating in lower temperatures, eg, $\sim > 50^{\circ}\text{C}$;
- Average productivity of a conventional solar still is between 30-50%, depending on the solar radiation intensity, construction, geometric and the environmental conditions.
- Based on different references by investigators, the average productivity of a solar still during summer is 4.6 litre/m² and 2-2.4 litre/m² day during winter time, based on solar radiation intensity and day clearness.

Most of the passive solar still configurations are based on single effect or multiple effect conventional solar stills. Cooper [64] pointed out that the prime parameters that influence the productivity and consequently the effective radiation collection as time of the year, site latitude, cover tilt angle, orientation, day clearness (or atmospheric haze), thickness of to cover, solar basin liner reflectance and still geometry.

Much research works have been carried out on designs of solar stills by various researchers throughout the world. Most of the conventional stills developed employ a single basin for meeting water requirements up to 4 litres/day [65]. The various designs of domestic solar still developed so far includes single basin single slope, single basin double-slope, hybrid solar still, hemi-spherical, triangular and pyramid type solar still. The broad classifications of solar still are illustrated in figure 17.

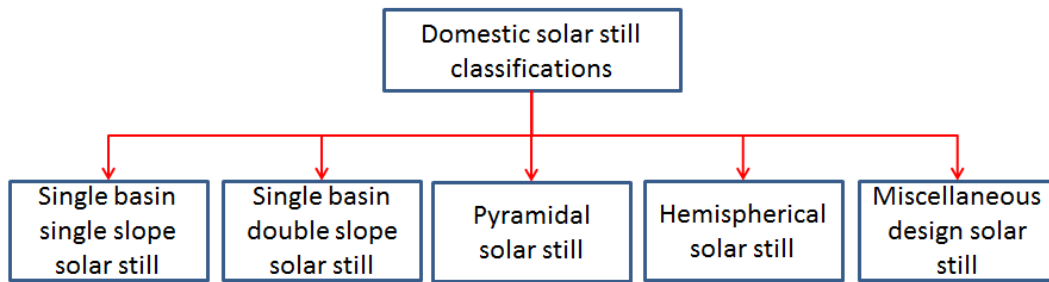


Figure 17: Classification of domestic solar still.

2.4.1. Single Slope Solar Still

Construction and operation of a single basin solar still is very simple. A black-painted basin contains brackish or sea water. This is enclosed in a completely air tight area formed by a transparent cover. Incident solar radiation passes through the transparent cover. The black basin absorbs the radiation. Consequently, water contained in the basin heated is up and evaporates in the saturated conditions inside the still. Water vapours rises until they come in contact with the cooler inner surface of the cover. There they condense as pure water, run down along the cover bottom surface due to gravity and is collected by using drainage. The construction of this type of still can easily be performed in rural areas using the locally available materials. However, this type is not widely used because of its lower productivity compared with other methods of desalination. This makes the system highly uneconomical. Numbers of methods are available to improve the effectiveness of the still.

Sahoo et al. [66] designed and constructed a single slope solar still at Centre of Energy IIT Guwahati, with a basin area of $0.73 \text{ m} \times 0.73 \text{ m}$, was fabricated from 4 mm fibre reinforced plastic. The 8 mm glass cover is placed such that it makes an angle of 10° with the horizontal edge of the container. The condensed water on the lower surface of the glass cover is collected by a measuring glass beaker kept along the lower edge of the glass cover (Figure 18).

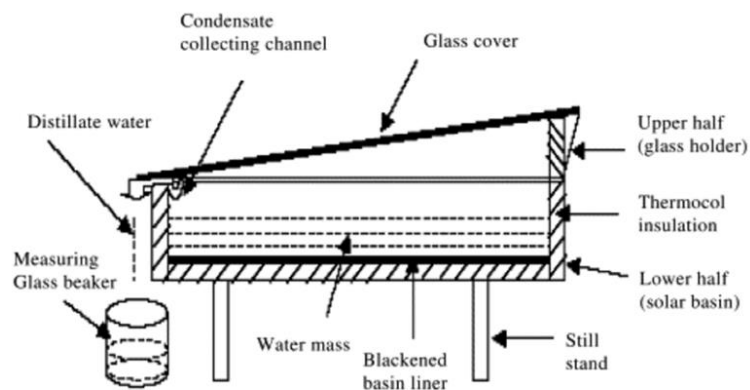


Figure 18: Sahoo's Schematic of experimental setup [66]

Swetha and Venugopal [67] built a single slope solar still with Lauric acid as a phase change material (PCM) placed under the liner of the basin as a heat reservoir by which it changes its phase during addition and removal of heat. The results of numerical and analytical shown increment of 36% is

observed in the collection of distillate when the still is used with PCM (Lauric acid) and also 13% increment when the still is used with sand as a heat reservoir (Figure 19).



Figure 19: Single slope solar still with Lauric acid as heat reservoir [67].

A single basin single slope solar still was fabricated by Phadatare and Verma [68] using Plexiglas material for all sides and the bottom (Figure 20). This system has been tested under different operational and environmental parameters. This design was fully sealed to reduce the vapour leakage to the surrounding area to improve productivity. The output was tested for different water depths (0.01, 0.025, 0.05 and 0.075 m) to find the effect of water depth on productivity. The maximum output of solar still was 3.07 litres/m² day for lowest water depth of 0.01 m.

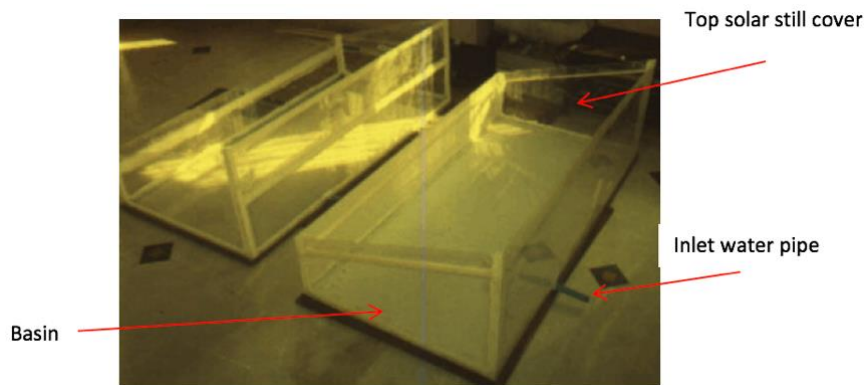


Figure 20: Solar still with Plexiglas material [68]

Dev and Tiwari [69] dealt with different inclination angles of the condensing cover (15°, 30°, 45°) for both summer and winter. Different water depths (0.04, 0.08, 0.12, and 0.16 m) have also been taken for solar still with 30° inclination angle for summer weather condition. In their experimental setups of single slope passive solar stills and also evaluate optimum water depth (0.04 m) inside the basin to maximize the yield. The optimum inclination angle was obtained 45° for the best performance of single slope solar stills. Figure 21 shows the different solar still used in the experiment.



Figure 21: Different solar still used by Dev and Tiwari [69]

El-Sebaai et al. [70] investigated stearic acid as phase change material (PCM) up to 0.033 m height beneath the basin liner to increase thermal performance of the single slope solar still to enhance the overnight productivity. On a summer day, the daily productivity of the still is found to be 9.0 (litres/m² day) with a daily efficiency of 84.3% on using 0.033 m of stearic acid under the still absorber compared to 4.998 (litres/m² day) when the still is used without the PCM.

Badran [71] designed and tested a single slope solar still by using asphalt as heat storing material and solar radiation absorptivity because of its black colour for the top basin (1.4 mm thickness) containing in addition a constant head tank and a feeding tank with 32° tilted glass cover. The results highlighted that iron sheet on the basin was placed to measure solar radiation and wind effect over output productivity. Using asphalt on the basin increased productivity by 29%. While the combination of asphalt and sprinkler could increase it by 51%. It was also concluded that ambient conditions have an influence on productivity of solar still.

Abdallah et al. [72] modified a single slope solar still flat plate basin with step-wise basin with a sun tracking system and installing an interior reflecting mirror (Figure 22). Each of these modifications increased productivity by 380%, 180% and 30% for sun tracking system, step-wise plate and reflecting mirror respectively.

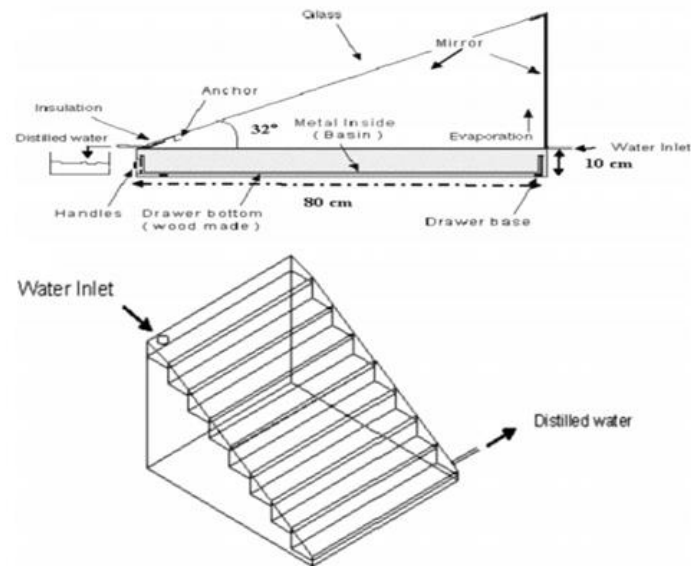


Figure 22: Single slope step-wise solar still [72]

Ali Samee et al. [73] fabricated simple a single solar still. The basin area of the still is 0.54 m^2 , fabricated using galvanized iron sheet. The daily distillate output of 1.7 litre/day with basin area of 0.54 m^2 (3.18 litre/ m^2 day) was obtained with the average efficiency 30.65% (Figure 23).

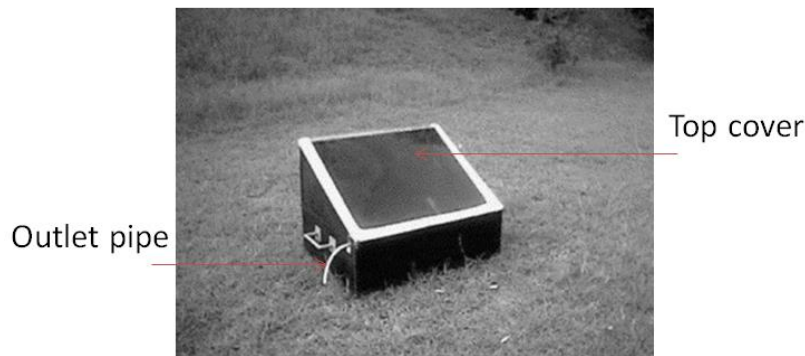


Figure 23: Samee's fabricated solar still being tested in outdoor condition [73].

V. Velmurugan et al. [74] used fins (sponges) and sponges on the basin of solar still to measure the effect of them on the productivity of solar still (Figure 24). It was found that 29.6% productivity increased, when wick type solar still was used, 15.3% productivity increased when sponges were used and 45.5% (productivity increased from 1.88 litre/ m^2 day to 2.8 litre/ m^2 day) increased when fins were used.

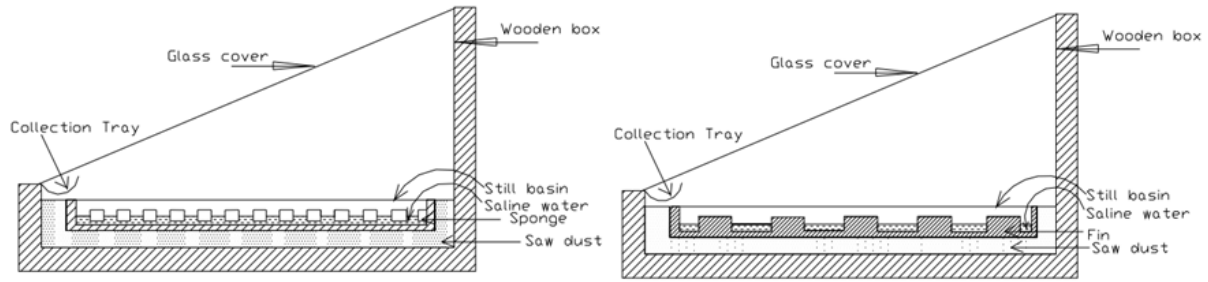


Figure 24: Left side: Cross-sectional view of the basin type still with sponges, Right side: Cross sectional view of basin type solastill integrated with fins [74].

Shanmuga et al. [75] studied the performance of an acrylic mirror boosted solar distillation unit. The productivity of the unit was analysed and a booster mirror (acrylic) attached just above the glass cover of solar still. The mirror reflects larger amount of the solar radiation in excess to basin water and it is possible to adjust the booster mirror for perfect reflection depending upon the sun moving angle as shown in figure 25. The maximum amount of water collected per day was about 4.2 litre/ m² day. The efficiency of the still was 35%, and increased to 45% with the mirror.

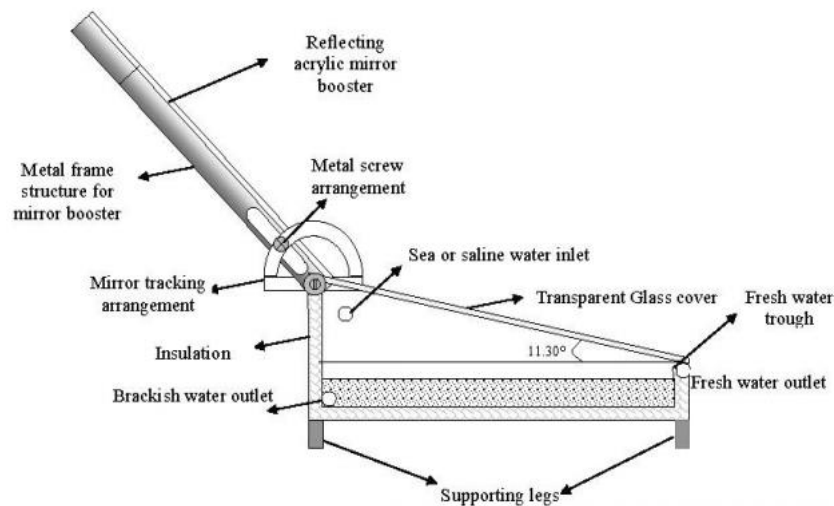


Figure 25: Schematic view of solar distillation unit with mirror booster [75]

Tiwari et al. [76] analysed of an inverted absorber solar still. The schematic diagram of inverted absorber solar still is shown in figure 26. The solar radiation is concentrated and reflected back to the inverted absorber plate of the inverted solar still, after transmission through the glass cover. The absorbed solar radiation is partially converted to water above the inverted absorber and heats it; while the rest of the radiation is lost to the atmosphere through the glass covers. The evaporated water is condensed on the inner surface of the condensing cover, trickles down the condensing surface under gravity and is finally collected through drainage provided at the lower end. The result shows that, the inverted absorber solar still is capable of producing double the output of the conventional solar still.

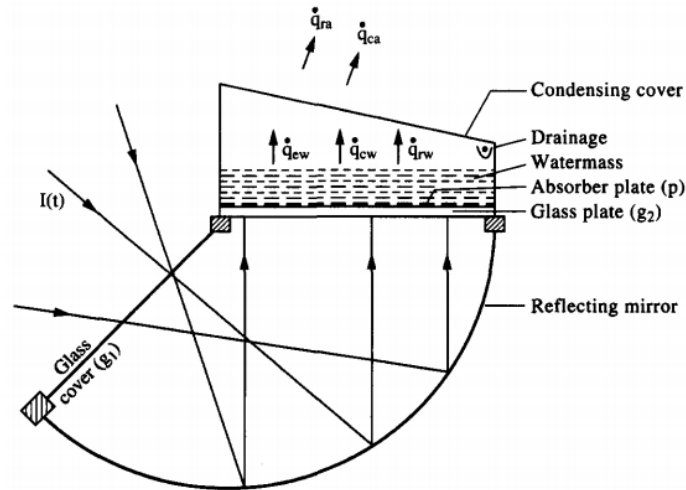


Figure 26: Schematic diagram of inverted absorber solar still [76].

T. Elango [77] compared the efficiency of single slope solar still with and without water Nano-fluid (heat transfer enhancement) of Aluminium Oxide (Al_2O_3), Zinc Oxide (ZnO), Iron Oxide (Fe_2O_3) and Tin Oxide (SnO_2). Two experimental stills of the same basin area have been fabricated and tested with water and different Nano-fluids simultaneously (Figure 27). The still with Aluminium Oxide (Al_2O_3) Nano-fluid has 29.95% higher production and the still with Zinc Oxide (ZnO) and Tin Oxide (SnO_2) Nano-fluids has 12.67% and 18.63% more production respectively than the still with water.



Figure 27: T. Elango experimental view of solar still [77].

A.A. El-Sebaai [78] constructed a single slope solar still with the baffle suspended absorber to decrease the preheating time with locally available materials (Figure 28). A comparison of the performance of the single slope solar still with baffle suspended absorber and single slope single basin solar still carried and it was found that the daily productivity of the solar still with baffle is about 20% higher than the conventional still.

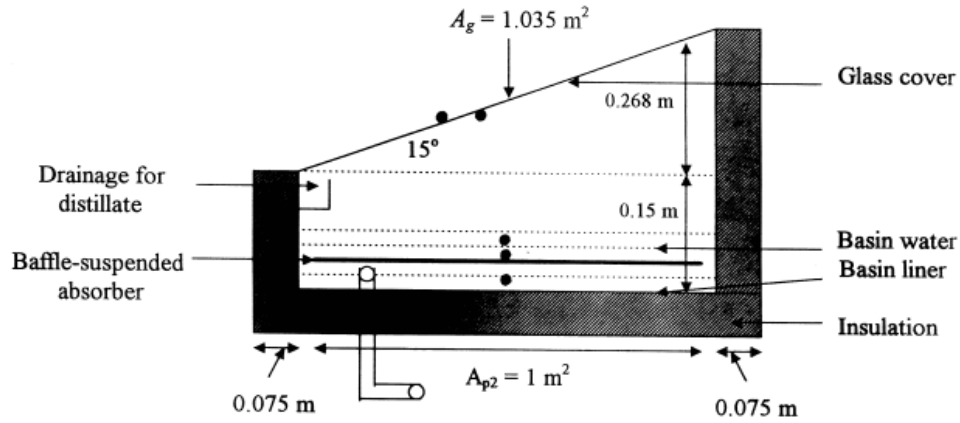


Figure 28: Schematic diagram of constructed with baffle suspended absorber [78].

2.4.2. Double Slope Solar Still

Tabrizi and Sharak [79] fabricated a single basin double slope solar still. The basin was loaded with sand because of its low cost and large availability as a heat reservoir. Average measured specific heat capacity of the sand is $704 \text{ J/kg } ^\circ\text{C}$. The $3.0 \text{ litre/ m}^2 \text{ day}$ distilled output yield was obtained in the experiment of 14 hours and observed 75% increment in productivity using sand as heat reservoir (Figure 29).



Figure 29: Tabrizi's double slope solar still tested with sand [79]

Kalidasa Murugavel et al. [80] made a single basin double slope solar still, tested with a layer of water and different sensible heat storage materials such as quartzite rock, red brick pieces, cement concrete pieces, washed stones and iron scraps. Their research was focused to find the best material as heat storage material in on the basin are to increase the productivity and they found that 0.02 m sized quartzite rock is the effective basin material (Figure 30).

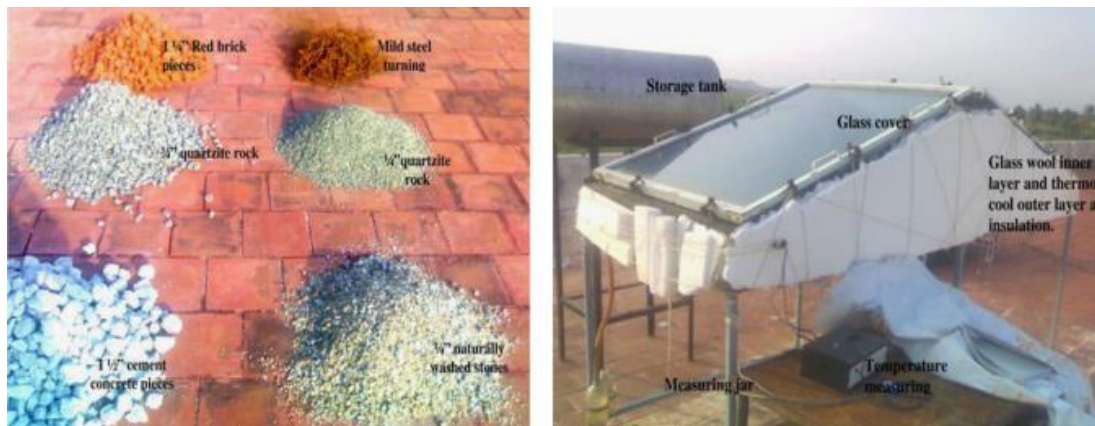


Figure 30: Different storage material on solar still [80]

Kalidasa Murugavel et al. [81] constructed single basin double solar still with lined concrete basin to reduce the heat loss through the bottom of the still. Maximum productivity was obtained, using surface heating effect, i.e. aluminium fins of size $0.065 \text{ m} \times 0.045 \text{ m}$ covered with light black cotton and jute cloths were used figure 31.



Figure 31: Photograph of the still with aluminium fin covered with black cloth in the basin [81]

Zeroual et al. [82] used two identical solar still prototypes (Figure 32). The first series, the condenser was cooled by flowing water on the north glass cover throughout the run. This enhanced the still productivity by 11.82%. The second series consisted of lowering the glass temperature (condenser), and this was realised by an intermittent shading of the north glass cover. This procedure improved the yield by just 2.94%.



Figure 32: Zeroual's solar still [82]

Rajamanickam and Ragupathy [83] fabricated two experimental set up Single Slope and Double Slope of same area and tested with different water depth at same and fixed orientation. The maximum distillate output of 3.07 litre/ m² day was obtained with water depth 0.01 m with double slope solar still with north-south orientation figure 33.

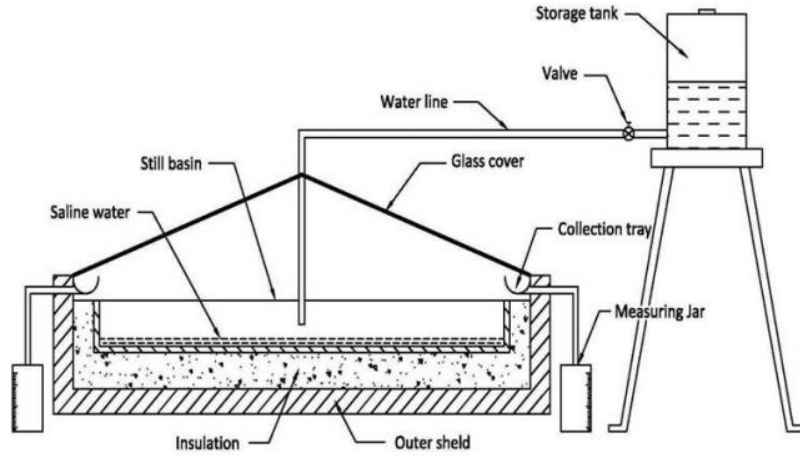


Figure 33: Rajmanickam and Ragupathy's schematic of double slope solar still [83]

Aburideh et al. [84] designed and tested double slope solar still with glass fibres and a resin layer, represents the lower part of the surface 1.39 m² painted in black in order to capture the maximum solar energy. The absorber is covered with basin water of 0.03 m depth and sides and lower walls are insulated by glass woollen with 0.004 m thickness as figure 34. The experiment was tested for different atmospheric temperature and maximum output of solar still was 4.0 litre/m² day in atmospheric temperature of 32 °C.



Figure 34: overview of double slope solar still [84]

K. Khalidasa et al. [85] fabricated double slope solar still with basin area of 1.75 m². The performance of the still is compared by using wick materials like light cotton cloth, light jute cloth and sponge sheets and porous materials like washed natural rock and quartzite rock as spread materials. The actual solar radiation condition is simulated by 2 kW electrical resistance heater placed below the inner basin. The results show that the still with black light cotton cloth as spread material is found to be more productive (Figure 35).

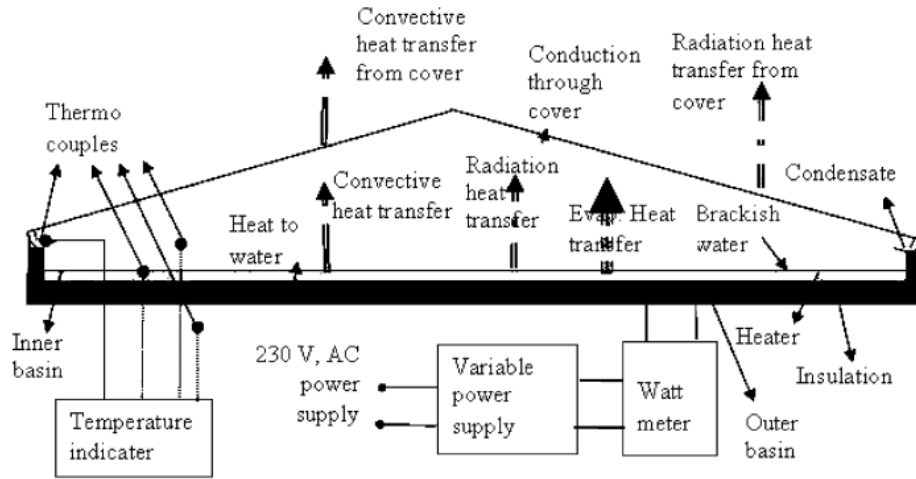


Figure 35: K. Khalidasa schematic double slope solar still [85]

Suneesh et al. [86] fabricated V-shape double slope solar still with basin area of 1.5 m^2 . The productivity of the still was calculated as 28% and the distillate output collected as $4.0 \text{ litre/m}^2 \text{ day}$ (Figure 36).

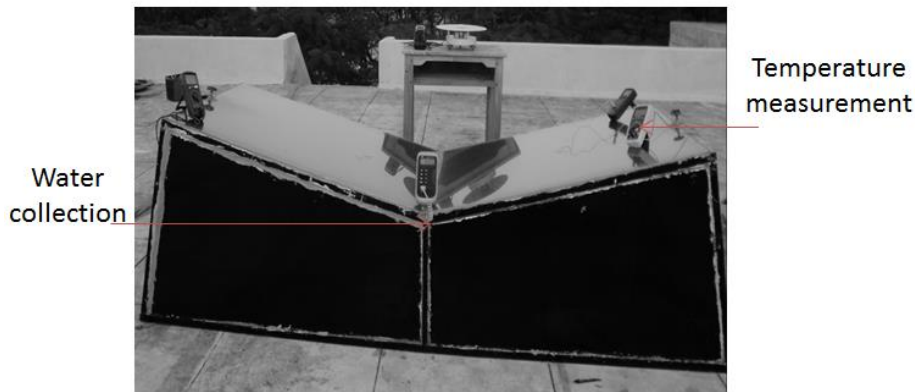


Figure 36: "V" shape double slope solar still [86]

Selva Kumar et al. [87] fabricated V-shape double slope solar still with charcoal absorber. The main advantage of this type of still is that the distilled water collection was directed towards the central water collection channel as shown in figure 37. The production of the outlet distillate water has increased. The overall efficiency is found to be 24.47% and 11.92% for the still without and with the boosting mirror, respectively. He also conducted similar experiment which was carried out for the charcoal absorber in the still without and with the boosting mirror which yielded 30.05% and 14.10% respectively.

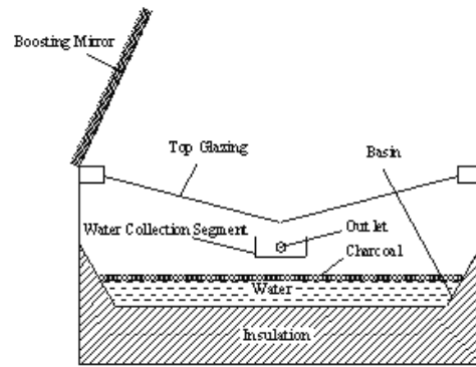


Figure 37: Selve Kumar et al. "V" shape solar still with mirror [87]

Ahsan et al. [88] made simple triangular (double slope) solar still with waste material such as PVC pipe for structure, Polythene cover, Nylon rope, Perspex for though and transparent scotch tape to seal the solar still as figure 38 shows. The productivity of solar still had recorded by 1.6 and 1.55 litre/m² day for water depth of 0.015 and 0.025 m respectively.

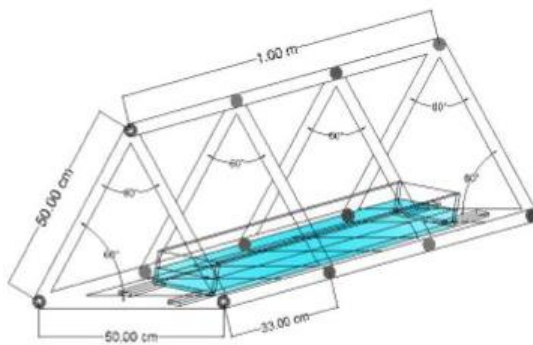


Figure 38: double slope solar still with waste material [88]

T. Rajaseenivasan [89] fabricated double slope solar still to test the performance of still by using black cotton cloth, jute cloth, waste cotton pieces, clay pot and mild steel pieces as figure 39. They all had a positive effect on the productivity of still. The maximum productivity was measured 5.68 litter/m² day with mild steel pieces.



Figure 39: Photographic view of the double slope solar still [89]

M. M. Morad [90] fabricated double slope solar still with different water depth (figure 40). The effect of cooling top glasses was also measured for productivity of solar still. The highest productivity of 6.38 litre/m² day was obtained when the brine depth was 0.01m with glass cover thickness of 3 mm (without applying glass cover cooling); while, the highest productivity was 7.80 litre/m² day (with applying cover cooling flash tactic 5 min on and 5 min off).



Figure 40: The double slope solar still with glass cover cooling [90]

T. Elango [91] fabricated single and double basin double slope glass stills under insulated and un-insulated conditions for their production at various water depths of 0.01, 0.02, 0.03, 0.04 and 0.05 m (Figure 41).



Figure 41: Experimental view of double and single basin double slope glass based solar stills [91]

The results showed that the output was high at the lower water depth of 0.01 m for both single and double basin double slope solar stills. A maximum of 4.31 litre/m² day was obtained at 0.01 m water depth by the insulated double basin double slope glass still. But, the insulated single basin double slope still gave only 3.565 litre/ m² day.

2.4.3. Pyramidal Solar Still

Sathyamurthy et al. [92] constructed a triangular pyramid solar still was as figure 42.



Figure 42: triangular pyramid solar still [92]

The basin of solar still was covered by sawdust by thickness of 0.01 m to insulate from surrounding and sides. The maximum productivity achieved was 4.3 litre/m² day with water depth of 0.02 m on the basin. The results show that the production of fresh water was increased by 40% compared to that of other conventional solar still without sawdust.

Ravishankar et al. [93] fabricated a triangular pyramid solar still to conduct the effect of wind speed variations to cool down the glass cover (Figure 43).

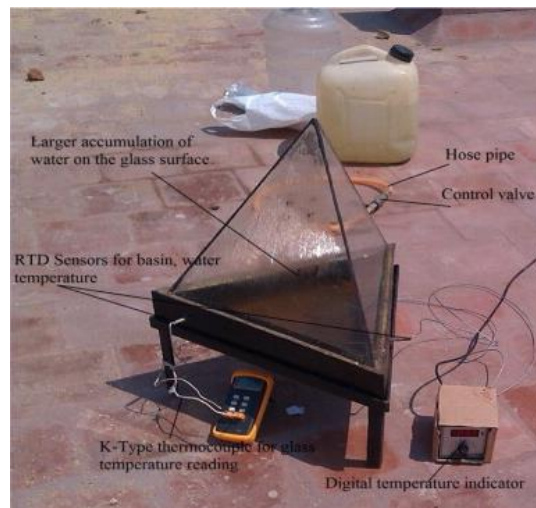


Figure 43: Ravishankar triangular pyramid still [93]

It was found that increasing the wind speed from 1.5 m/s (the average measured wind speed) to 3 m/s and to 4.5 m/s have the effect of increasing the still productivity (wind makes top covers of solar still to cool down its temperature in compare to inner surface, thus it increases solar still productivity) by 8 and 15.5% respectively.

Taamneh et al. [94] made a pyramidal solar still with area basin area of 0.95 m² with top glass cover (figure 44).



Figure 44: triangular solar still with fan to decrease the temperature of inner face of glasses [94]

It has been shown using ventilation fan work with photovoltaic solar panels is cost-effective to cool down the inner side of glasses. By using ventilation fan evaporation and condensation rate increase considerably and hence freshwater production. The distillate production for natural and force convection was found to be 2.61 and 3.14 litre/ m² day respectively.

Kabeel [95] built a pyramidal solar still with a concave wick surface to increase the amount of absorber solar radiation (Figure 45).

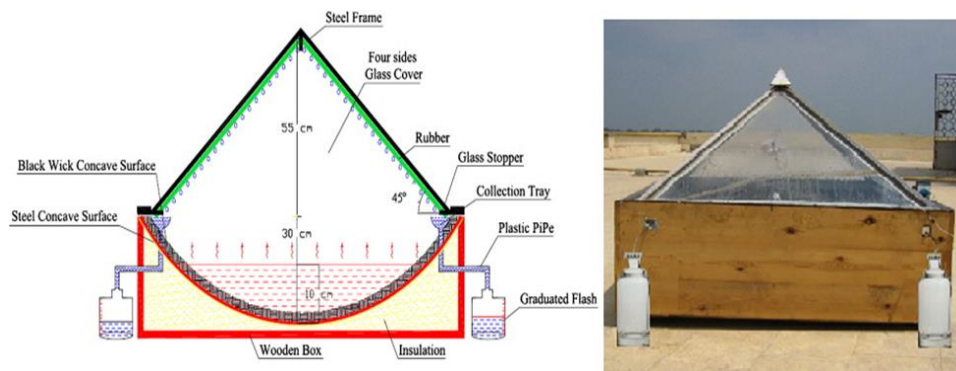


Figure 45: Triangular pyramid solar still with concave wick basin surface [95]

Concave wick surface was used for evaporation, whereas four sides of pyramids shaped cover was used for condensation process. Results show that average productivity was 4.1 litter/m²day and a maximum instantaneous system efficiency of 45% and average daily efficiency of 30% were verified.

Kabeel et al. [96] investigated on the effects of glass cover angle on the performance of a square pyramid solar still. Three types of a square pyramids solar still with the same absorber area of 0.64 m² (system-A, system-B and system-C) with inclined angles of the condensation surface are 30.47°, 40° and 50° was constructed respectively (figure 46).

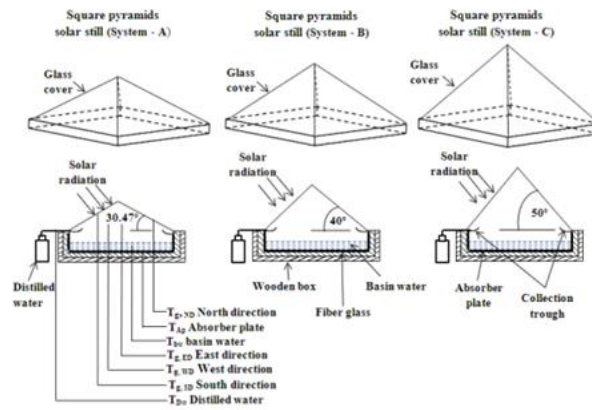


Figure 46: Three square pyramids solar still with three inclined angle [96]

Results showed that the accumulated distillate water productivity up to almost 4.13 litre/m²day in the system-A, 3.5 litre/m²day in the system-B and 2.93 litre/m²day in the system-C. The increase in accumulated distillate water for system-A is 41 % compared to the system-C and 18 % compared to system-B. It was also found that, the accumulated distillate water productivity from the square pyramid solar stills decrease with increase the glass cover angle above the Latitude angle.

Wassouf et al. [97] built two prototypes design (Figure 47). First still were 0.2 m² Poly Vinyl Chloride (PVC) Pyramidal still and second were 0.6 m² triangular-prisms PVC solar still. The stills yielded an average of 2.5 litter/m² day and 1.5 litre/m²day of distilled water respectively.



Figure 47: Pyramidal solar still and triangular prism solar still [97]

Neeraj Kumar et al. [98] investigated on two pyramidal shaped solar still (figure 48). They were built with solar inclination 45 ° and 60 °. The 3 mm glass cover got replaced by thin fibre sheet just to test

the results. Readings were taken placing inclination part of solar stills facing sun with an angle of 45° . It was founded in this empirical study that the fresh water production for 3 litres water was better than the quantity of 2.00 and 4.00 litres.



Figure 48: Kumar's pyramidal shape solar still [98]

Ahmed J. Mohammed et al. [99] fabricated a pyramidal solar still with basin area of 0.025 m^2 (figure 49).



Figure 49: Pyramidal solar still with external reflector [99]

Several additions were examined in order to increase the performance of the solar still and the outcomes as thermal efficiency account to solar still. The maximum efficiency of the experimental still varies from (44%) pyramidal solar still.

2.4.4. Hemispherical Solar Still

Arunkumar et al. [100] fabricated hemispherical shape of solar still with diameter of 0.95 m and height 0.10 m. The top cover transparent acrylic sheet was 3 mm thick with solar transmittance of 88%. The outer box for the still was constructed of wood of thickness 4 mm with the dimension $1.10 \text{ m} \times 1.10 \text{ m} \times 0.25 \text{ m}$. There was sawdust filled on the bottom of the basin with height of 0.15 m. The sides of the basin are insulated with the glass wool (figure 50).

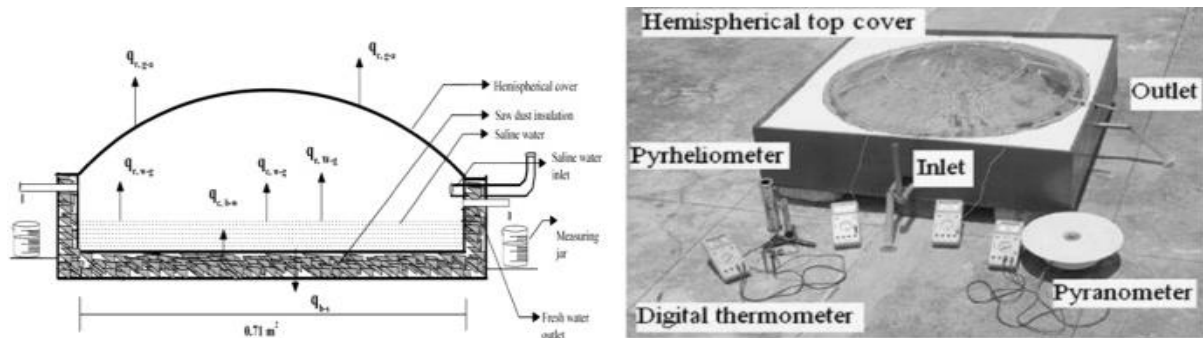


Figure 50: Arunkumar hemispherical solar still [100]

Ismail [101] fabricated domestic type transportable hemispherical solar still (figure 51). The still mainly consisted of the circular basin (Tray) and absorber plate carrying the saline water, the hemispherical cover, the conical-shaped distillate collector, the distillate output plastic container, and the mobile support structure (trolley). The basin was contained the absorber aluminium plate which has a surface area of 0.5 m^2 and a thickness of 4 mm. A hole with diameter of approximately 25.4 mm was drilled into the tray to provide accessibility of saline water into the basin. It was found that over the hours of experimental testing through daytime, the daily distilled water output from the still ranged from 2.8 to 5.7 litre/ m^2 day. The daily average efficiency of the still reached as high as 33% with a corresponding conversion ratio near 50%. It was also found that the average efficiency of the still decreased by 8% when the saline water depth increased by 50%.

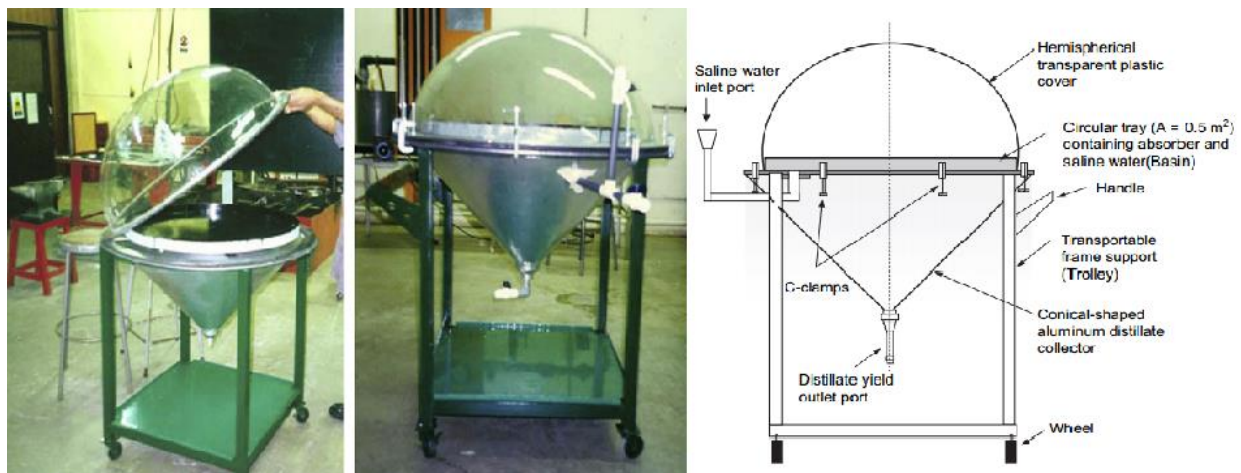


Figure 51: Schematic and picture of transportable hemispherical solar still [101]

Hitesh N. Panchel et al. [102] fabricated hemispheric solar still with basin area of 0.55 m^2 painted in black (figure 52). Theoretical results and practical test was shown that the average productivity of solar still is 3.1 litre/ m^2 day.



Figure 52: Complete fabrication of hemispherical solar still [102]

2.4.5. Miscellaneous Designs of Solar Still

Esfahani et al. [103] used a different nonconventional, portable domestic design of solar desalination system. A photovoltaic 12-volt power supplied was used to run pump, thermoelectric cooler and pump. The 4 litter of evaporation zone was filled with raw water for each experiment. Right side and the bottom of evaporating zone have been fabricated with black coloured Plexiglas and also covered with black wool to absorb maximum solar radiation. The photographic and schematic view is shown in the figure 53.

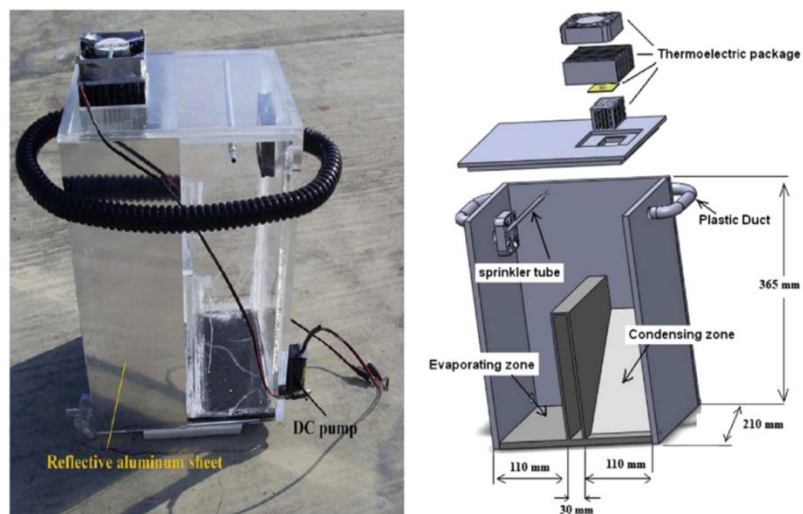


Figure 53: Esfahani's portable design of solar still [103]

The daily performance was evaluated for the 7 sunny hours in winter and 1.7 litre/m² day productivity was obtained. A comparison between theoretical and practical result was shown that the maximum productivity of still was 13%.

T. Arunkumar et al. [104] fabricated a tubular solar still with a rectangular basin for water desalination with flowing water and air over the cover (figure 54).



Figure 54: T. Arunkumar tubular solar still [104]

The daily distillate output of the system is increased by lowering the temperature of water flowing over it (top cover cooling arrangement). The water production rate with no cooling flow was 2.05 litre/ day. However, with cooling air flow, production increased to 3.05 litter/ day, and with cooling water flow, it further increased to 5.0 litre/ day. Despite the increased cost of the water cooling system, the increased output resulted in the cost of distilled water being cut in roughly half.

Ashok Kumar et al. [105] designed and tested a tubular multi-wick solar still (figure 55).

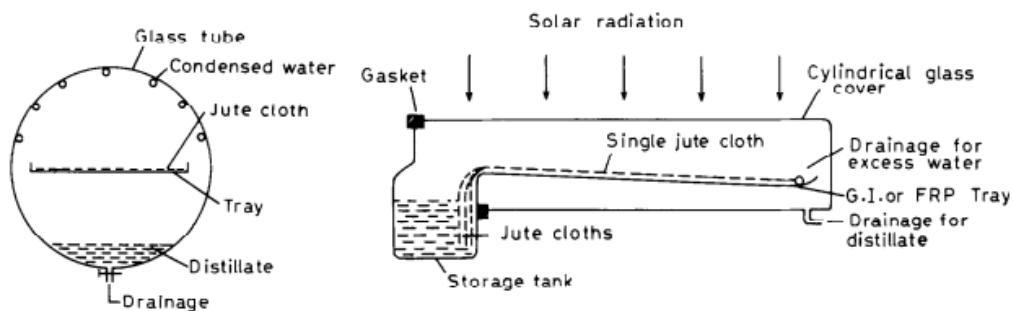


Figure 55: Ashok Kumar front and side schematic of tubular solar still [105]

The results obtained show that the tubular multi-wick solar still can yield more than 3.0 litter/m² day of distillate output, even under typical cold climatic conditions, which is about 13% more than that of the conventional multi-wick solar still and 8% more than that of a simple tubular solar still.

H. Sharon et al. [106] fabricated tilted wick type and stepped solar still (figure 56).

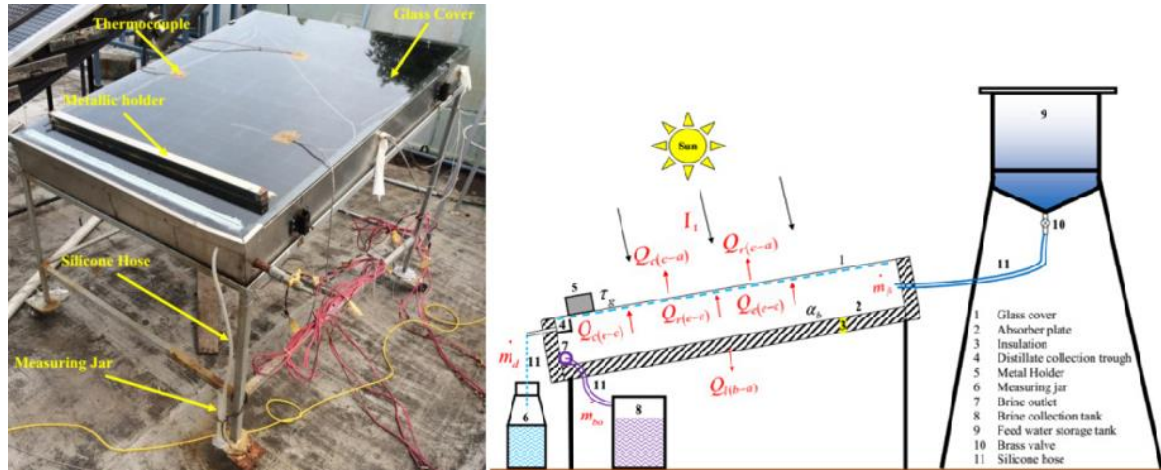


Figure 56: Schematic and practical view of tilted wick type solar still [106]

It was conducted on tilted solar still with basin and tilted solar still with wick to assess their performance, distillate quality, environmental benefits and economic feasibility. Distillate quality of both the tested units was superior. Annual average distillate yield of tilted solar still with basin was nearly 19.76% higher than that of the unit with wick.

B Janarthan et al. [107] built a simple transient performance of floating cum tilted-wick type solar still by incorporating the effects of water flowing over a glass cover, heat capacity of tilted-wick water surface and floating-wick water surface (figure 57).

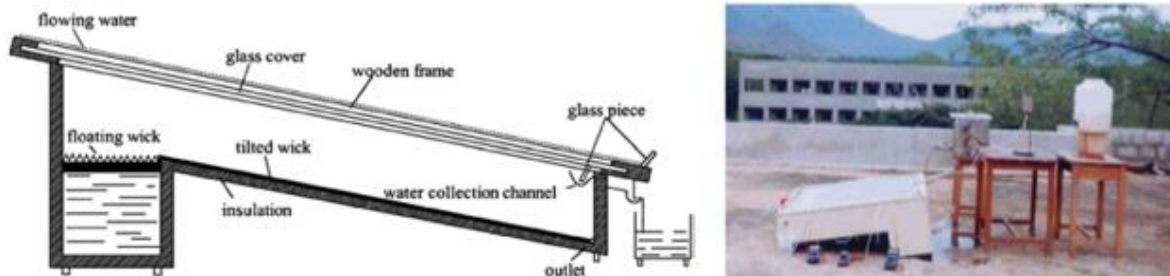


Figure 57: Janarthan's single wick solar still (Schematic and experimental set up) [107]

The results were indicated that the relative standard deviations between theoretical and experimental results are less than 8% (glass cover), 2% (tilted-wick water surface), 1% (floating-wick water surface) and 2% (flowing water at the lower end of the glass cover) an average for the working hours of the day.

M.S. Sodha et al. [108] constructed a multiple wick solar still in which blackened wet jute cloth forms the liquid surface which can be oriented to intercept maximum solar radiation and attain high temperatures on account of low thermal capacity. The wet surface was consisted of a series of jute cloth pieces of increasing length separated by thin black polythene sheets, resting on foam insulation supported by a net of nylon ribbon; these pieces are arranged along an incline and their upper edges are dipped in a saline water tank. On a typical cold sunny day, the distillate output was 2.5 litre/m² day.

Hiroshi Tanaka et al. [109] analysed a tilted-wick solar still with an inclined flat plate external reflector (figure 58).

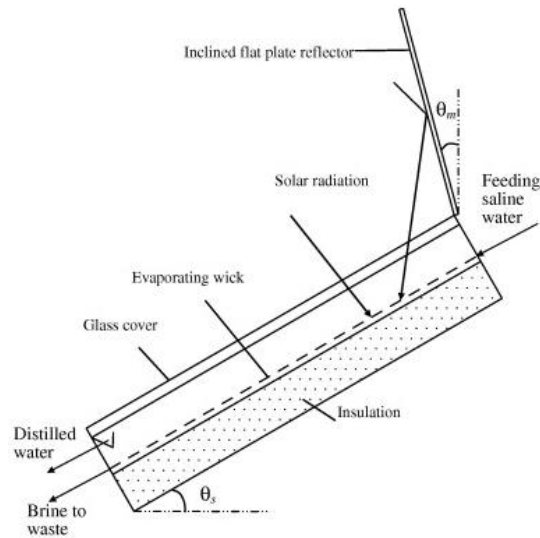


Figure 58: Tanaka's tilted-wick solar still with inclined flat plate external reflector [109]

The daily amount of distillate of a still with an inclined reflector was about 15% or 27% greater than that with a vertical reflector when the reflector's length is a half of or the same as the still's length.

S. B. Sadieneni et al. [110] fabricated a weir-type solar still to recover rejected water from the water purifying systems for solar hydrogen production. It was consisted of an inclined absorber plate formed to make weirs, as well as a top basin and a bottom basin. Water was flowed from the top basin over the weirs to the bottom collection basin. The average distillate productivities for double- and single-pane glass covers are approximately 2.2 and 5.5 litre/m² respectively (figure 59).

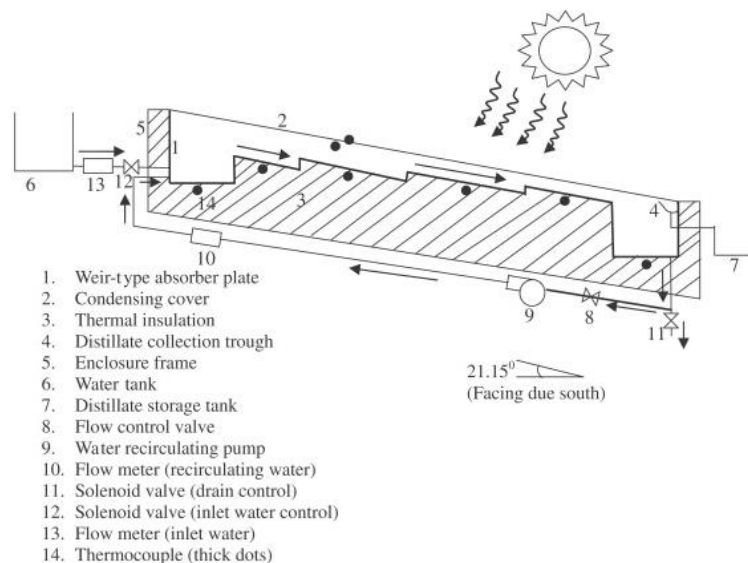


Figure 59: Sadeineni's weir-type solar still [110]

Farshad F. Tabrizi et al. [111] fabricated two cascade solar stills with and without latent heat thermal energy storage (LHTESS) system was constructed for comparison of the stills productivity. The effect of flow rate was also investigated on the total productivity of stills. The total productivity of still without LHTESS is slightly higher than the still with LHTESS in sunny days. The productivity of sola still was 3.4 litre/m² day for still with LHTESS and 2.1 litre/m² day for still without LHTESS (figurer 60).

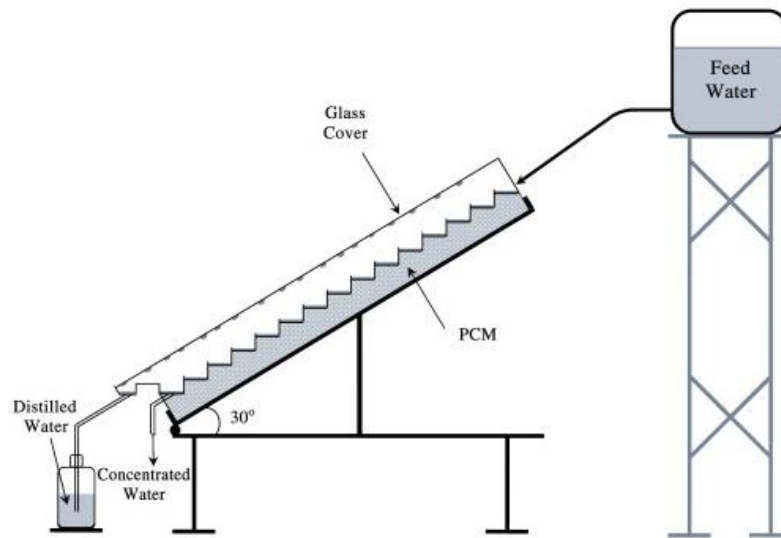


Figure 60: Schematic view Tabrizi's weir-type cascade solar still [111]

Ahsan et al. [112] fabricated on tubular solar stills as shown in figure 61.

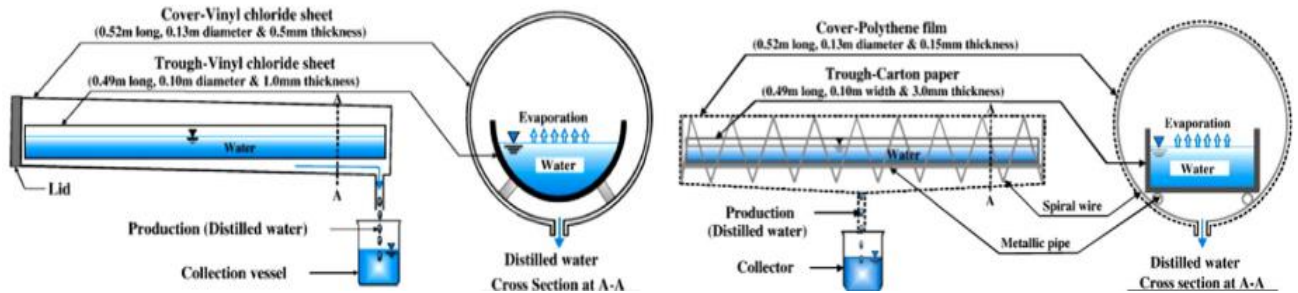


Figure 61: old and new Ahsan's solar still [112]

The results were shown a comparison between an old and new tubular solar still made of different glass covers namely vinyl chloride sheet and polythene film. It was reported that the improved still with polythene film was durable, economical, light weight and easily mould to different sizes. Also, from the experimental results, it was found a linear relation is between the total heat transfer coefficients and evaporation mass transfer coefficients.

2.5. Parameters Affecting the Productivity of Basin Solar Still

The performance of a solar still is generally expressed as the quantity of water produced by basin area in a day. There are numerous influences affecting the solar still productivity that it can be grouped as:

1. *Climatic factors*: solar radiations, intensity, ambient temperature, wind speed, outside humidity and sky condition;
2. *Design parameters*: single/double slope, water depth, cover insulation, basin type, energy absorbing and storing material, external and internal reflector, sun tracking system, insulation system and gap distance;
3. *Operational condition*: colouring of water, water flow, surfactant activities and salt concentration.

Climatic factors cannot be controlled by human because they are metrological factors. The other parameters can be varied to increase the solar still productivity. By considering the numerous factors affecting the solar still productivity, several modifications have been made to improve the solar still productivity. The modifications have direct impact on evaporation and condensation rate that it can be grouped as follow.

Evaporation rate:

1. Basin construction material;
2. Absorption of basin water;
3. Inlet water temperature;
4. Top transparent material angle;
5. Bain water depth;
6. Reflector;
7. Sun tracking;
8. Energy storing material;
9. Temperature of top surface water;
10. Vacuumed technology.

Condensation rate:

1. Water transparent cover temperature difference (transparent cover cooling);
2. Condenser;
3. Wind speed.

2.5.1. Evaporation Rate

2.5.1.1. Basin construction material

Solar radiation that passes through the transparent cover is absorbed by saline water and the basin liner of a solar still. So, the basin liner acts as an absorber of solar radiation and it is important for the liner to have a relatively high absorbance for solar radiation.

P. I. Cooper et al. [113] tested the effect of basin material made by plastic and metal-sheet. It was found that metal-sheet got better productivity comparable to plastic sheet as it heats up the water faster.

John Twidell [114] tested common metal sheets applied in solar collection in the solar still. The solar still was tested with the copper, aluminium and steel on the basin. The important property of a metal for application in solar engineering is thermal conductivity. Copper and aluminium have relatively high thermal conductivities ($k=200 \text{ W m}^{-1} \text{ K}^{-1}$ for aluminium and $k=390 \text{ W m}^{-1} \text{ K}^{-1}$ for copper) while the thermal conductivity of steel is relatively low ($k=48 \text{ W m}^{-1} \text{ K}^{-1}$). Nevertheless, copper and aluminium are more expensive (more than two times the cost of galvanized steel).

A.S. Nafey fabricated solar still with the black rubber and black gravel as basin material. The results were shown that using the black rubber increased the productivity by about 5% in comparison of black gravel.

2.5.1.2. Absorption area of basin water

The evaporation rate of water in the solar still is directly proportional to the exposure area of absorption of the water. Thus the productivity of the solar still increases with the free surface area of the water in the basin. To increase the free surface area of water, sponges are used at the basin water.

Bassam et al. [115] used sponges to increase the free surface area of the water in the solar still as shown in figure 62.

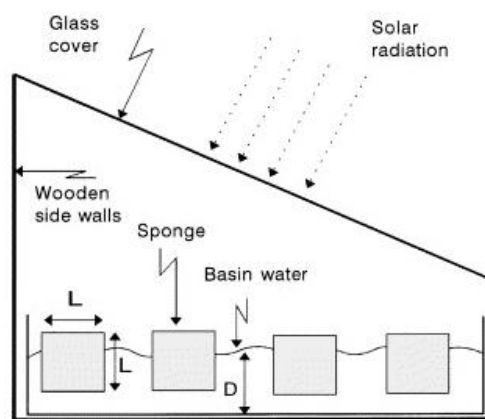


Figure 62: side view schematic of the solar still with sponges cube [115]

The basin water was sucked by the sponges because of capillary action, also, the surface area over increases by using sponge cubes on the basin. The results were shown significant improvement in still production with using sponge cubes. Experiments were carried out with different sizes of the sponge cubes, sponge to basin water volume ratio and water depth. The optimal combination was: sponge cubes with 6 cm (0.06 m) sides, 20% sponge to basin water volume ratio and 7 cm (0.07 m) basin

water depth. It was found that the increase in distillate production of the still ranged from 18% to 273% compared to an identical still without sponge cubes under the same conditions.

Velmurugan et al. [116][117], [118] was tested different solar still by adding sponges to the basin area. It was founded that the productivity of still was increased by 15.3% in stepped solar still integrated with sponges (figure 63).

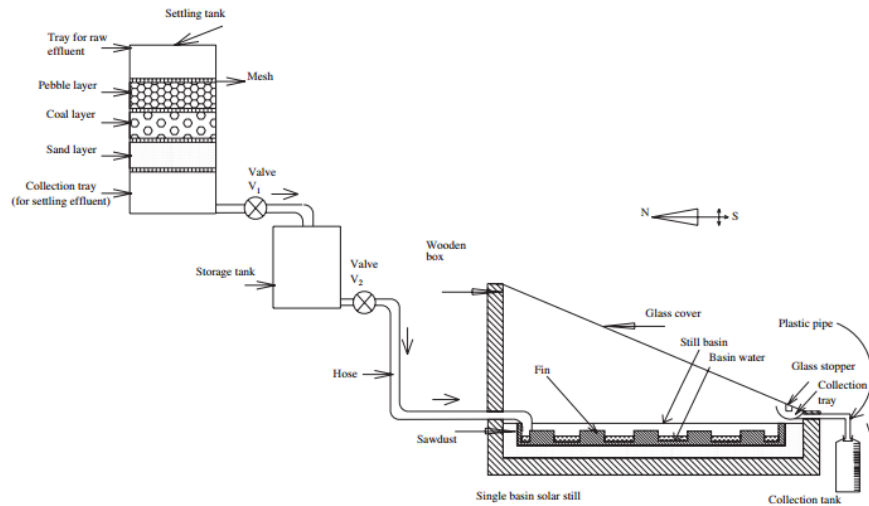


Figure 63: Schematic diagram of the experimental setup of solar still with fin [118]

There are numbers of work with different method to increase absorption area as it shows in table 4 and it does show how it is affecting the productivity of solar still during past.

Table 4: The effect of the absorption area on productivity of solar still

Year	Author(s)	Modification	Observation
1994	Minasian et al. [119]	Wick-Basin Type	Productivity increase by 43% than basin-type
1999	El-Sebaili et al. [120]	Baffle suspended absorber	Productivity increase by 20% than conventional solar still
2002	Naim et al. [121]	Using Charcoal wick on the basin	Productivity increase by 15%
2003	Abu-Hijleh et al. [122]	Sponge cubes in basin	Productivity increase by 18%-273%
2008	Abdallah et al. [122]	Using coated and uncoated metallic wiry sponges and black rocks	Productivity increase by 28%, 43% and 60% respectively
2008	Velmurugan et al.[118]	Using wick, sponges and fins	Productivity increase by 29.6%, 15.3% and 45.5% respectively

2008	Velmurugan et al.[117]	Modify solar still with fin, black rubber, sand, pebble and sponges	Productivity increase by 53%
2009	Velmurugan et al. [116]	Fin, fin and black rubber, fin and sponge, fin and sand, fin sand and sponge	Productivity increase 53%, 67%, 72%, 86% and 96% respectively
2010	Sakthivel et al. [123]	Using jute cloth	Productivity increase by 20%
2011	Omara et al.[124]	Using finned and corrugated absorbers	Efficiency increase by 20-40%
2011	Murugavel et al. [125]	Using light cotton cloth, sponge sheet, coir mate and cotton pieces	N/A
2013	Ayuthaya et al.[126]	Using fin plate at basin	Productivity increase by 15%
2013	Pankaj et al.[127]	Using extended porous fins	Productivity increase by 35.5%
2014	Shukla et al. [128]	Using horizontal and vertical mesh	Productivity increase by 6-13%

2.5.1.3. Inlet water temperature

The evaporation rate of saline water increases with the temperature of inlet the saline water increases. Flat plate collector, storage tank, mini solar pond, multi-source, multi-use environment, greenhouse and, multi-source, multi-use environment heat pipe is integrated with the solar still to increase the temperature of the solar still inlet water. Higher energy may be required to increase the temperature of the entire solar still water. Table 5 shows the works that it has been placed in order to increase the temperature of inlet water in the past.

Table 5: The effect of the inlet water temperature on productivity of solar still

Year	Author(s)	Inlet water temperature difference	Effect of raising temperature of inlet water on productivity
1981	Sodha et al. [129]	15 °C	16%
1984	Madhuri et al.[130]	15 °C	30%
1984	Tiwari et al.[131]	15 °C	40%
1988	Yadav et al.[132]	50 °C	37.5%
2004	Tanaka et al. [133]	5 °C	7%
2007	Garcia Mari et al. [134]	20 °C	35%

2007	Velmurugan et al. [135]	-	27.6%
2007	Abdel-Rehim et al. [136]	10 °C	18%
2008	Tiwari et al. [137]	-	37%
2011	El-Sebaei et al. [138]	5 °C	21%
2012	Karuppusamy [139]	10 °C	49.7%
2013	Singh et al. [140]	-	33%
2013	Sharif abad et al. [141]	20 °C	17%

E. Mathioulakis et al. [142] tested solar still through its incorporation in a multi-source and multiuse environment with different configurations are investigation. Initially the case of coupling solar still with thermal solar system has been examined, the tank of which is thermally coupled with the still basin. Comparison of coupled system productivity was done with its productivity as a solar still only for days with similar climatic conditions. It was found that the productivity of the coupled system is about the double from that of the still only system. Significant raises in distilled water productivity have been obtained not only during the day but also mainly during the night operation of the system, reaching the triple of the solar only system productivity.

Raghendra Singh et al. [143] conducted experiments in a solar still with Evacuated Tube Collector (ETC). The feed water is preheated with the use of an ETC in natural mode as shown in figure 64.

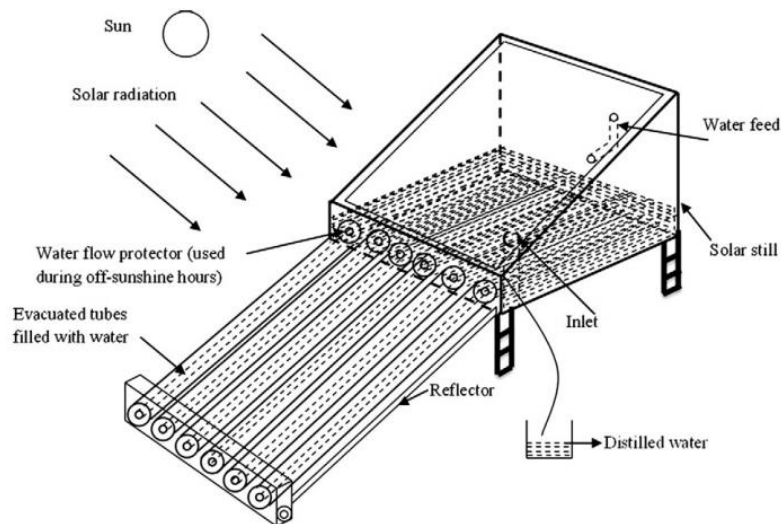


Figure 64: Singh's solar still with evacuated tube collector schematic

Also, the effect of depth of water in the still basin on yield, energy and exergy efficiencies has been estimated. The system has been optimised to find the best combination between the size of the ETC and water depth in the still for increasing the productivity.

Tiwari et al. [144] performed experiments in an active and passive solar still as shown in figure 65.

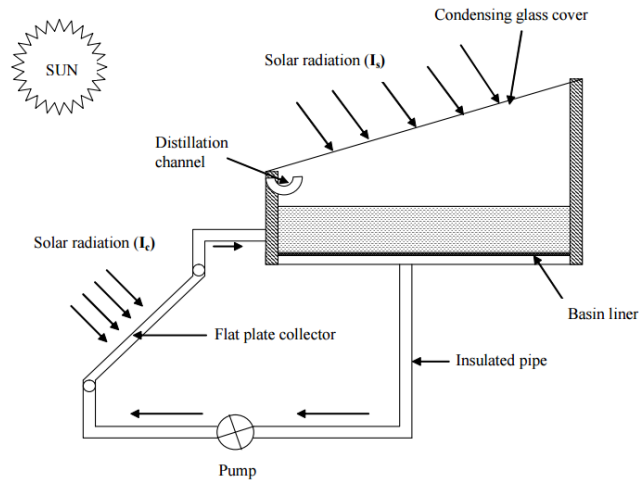


Figure 65: Schematic view of a solar still integrated with a flat plate collector [144]

A flat plate collector (FPC) was coupled to the solar still in the active mode. A water pump was used to circulate the water in the FPC and other piping arrangements. The heated water in the FPC enters the solar still basin. Hence a large temperature difference exists between the water surface and the inner glass cover.

2.5.1.4. Top transparent material angle

One of the main reasons, the productivity of solar still dependent on is top cover tilt angle. The angle depends on solar inclination and the direction the cover is facing, and also its latitude of the site. It is important that top covers inclination aligned with the angle of the latitude location. This is deemed as important due to the fact that evaporation is reliant on intensity of solar radiation. This leads to the adjustment of the angle of inclination with respect to the solar azimuth angle and solar intensity.

Singh and Tiwari [145] investigated a numerical analysis for latitudes of (13–28°N), taking into account the effect of solar radiation, water depths, wind speeds and mainly top cover tilt angle on productivity. They observed that the best optimum tilt angle to achieve maximum annual productivity should be the same as latitude of the location.

A similar study was showed in India (latitude 28.36°N) by Kumar et al. [146], and based on their numerical analysis by a glass tilt angle of 15° resulted in the best performance.

Khalifa and Hamood [147] conducted experiments at latitude 31.57°N in Jordan to measure the effect of cover tilting on the performance of basin solar stills. It was surmised that output could change by almost 63% via tilting the covers alone.

Prasad and Tiwari [148] investigated on a concentrator-assisted solar distillation system, shown in figure 66. They analysed the effect of the inclination of glass covers on the internal heat transfer coefficient, and they found that the daily output increased with inclination.

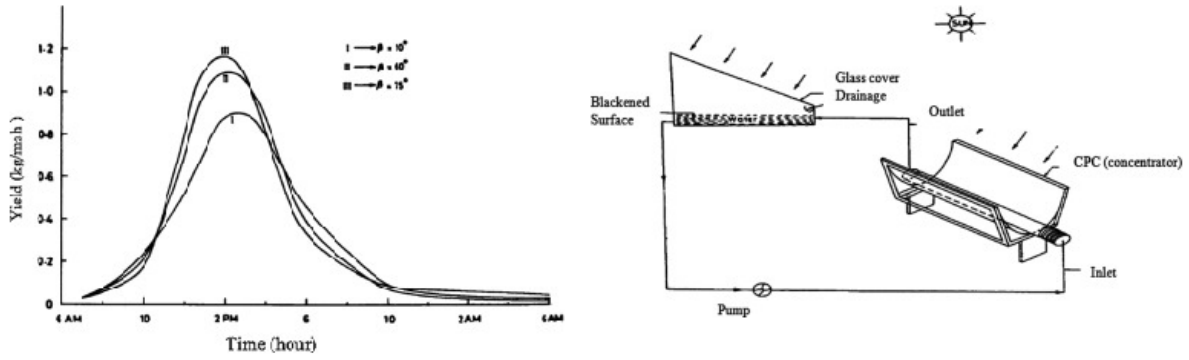


Figure 66: Cross section view of a concentrator assisted solar still and the effect of inclination hourly yield [148]

Tiwari et al. [149] attempted to optimize the condensing cover inclination in a passive solar still for a maximum daily yield under winter climatic conditions. The convective mass transfer relations were determined at three different inclinations of condensing cover. Figure 67 shows a cross-sectional view of the schematic diagram of a single-sloped passive solar still. Under winter climatic conditions, the highest yield was observed at a 45° inclination of condensing cover.

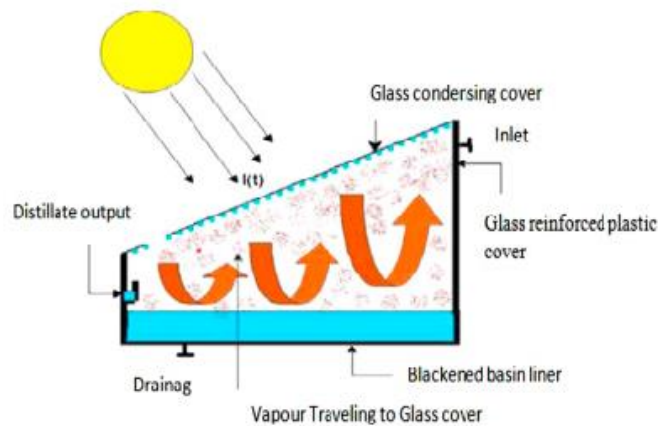


Figure 67: Cross-sectional view of the schematic arrangement of the experiment [149]

Kamal [150] investigated on both experimental and theoretical analyses on a basin-type solar still under spring climatic conditions in Doha (Qatar), at a latitude of 25.3°N . The results were shown the maximum productivity gained at tilt angle of 10° during summer and 15° during winter.

Enein et al. [151] reported that the cover tilt angle should be as low as possible during the summer and 50° during the winter under Egyptian climatic conditions, with latitude of 30.48°N . It was concluded that the daily productivity of solar still increased by 27% by changing incline angle.

Dev and Tiwari [152] conducted a numerical analysis to analyse the impact of cover tilt angle on both winter and summer under Indian conditions (latitude of 28.36°N). They showed the tests in April, June, and November, and concluded that 45° is the optimum inclination angle for the best performance of a solar still.

Hinai et al. [153] carried out mathematical modelling to foresee the annual performance of a solar still under Omani climatic conditions, at a latitude of 23.36°N. Their numerical results presented that the productivity increased with decreasing glass tilt angles during the summer, while the reverse is true during the winter, as shown in figure 68.

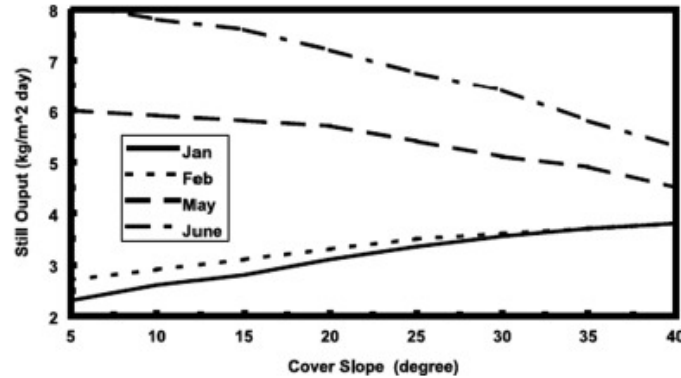


Figure 68: Effect of cover slope on single output in winter and summer months [153]

Khalifa and Ibrahim [154] experimented upon the effects of both internal and external reflectors on a different productivities for simple basin solar stills in all seasons except spring (tilt angles of 0°, 10°, 20°, and 30°, respectively), and this is shown in figure 69.

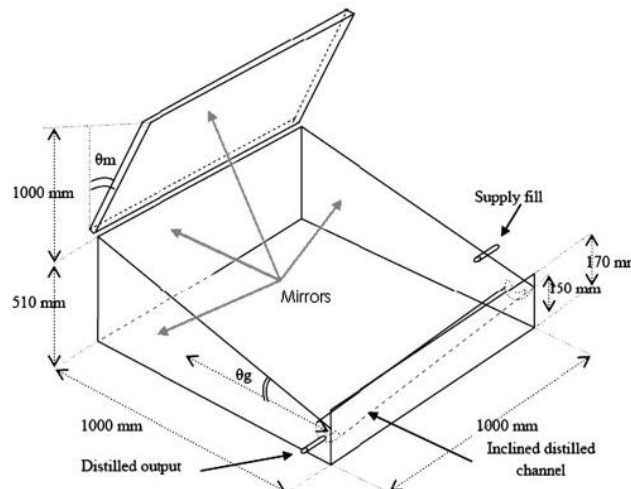


Figure 69: Khalifa and Ibrahim schematic diagram of solar still [154]

They stated on a simple still with a tilting cover angle of 20° and supported up with both internal and external reflectors at a 33.3°N latitude angle. Therefore, a comparable yearly productivity is anticipated for an external reflector angle that ranges from vertical to 20°.

Karaghoulis and Alnaser [155] experimented on single-and double-basin solar stills, as shown in figure 70.

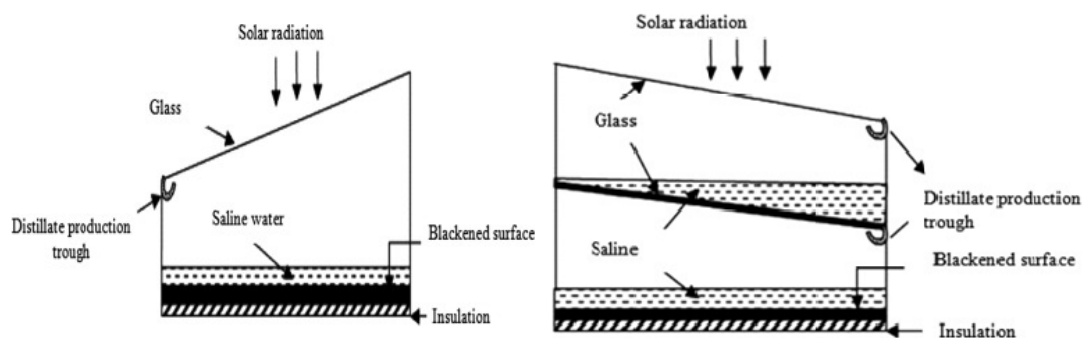


Figure 70: Karaghoulis and Alnaser's Single and double basin solar still [155]

The single basin glass slope angle was maintained at 36° from the horizontal, whereas for the double basin still, it was maintained at 12° from the horizontal. They initiate that the efficiency of the double basin still was 8% more than its single-basin counterpart.

2.5.1.6. Basin water depth

The productivity of solar still is inversely proportional to the water depth on the basin area (see all references in Table 6). The productivity increase within higher heat transfer coefficient, which is happening by minimum water depth. Keeping the water depth at minimum range is difficult job as dry spot may occur because of evaporation that affects the productivity of solar still. The rate of evaporation is different during day as sun radiation varies; therefore, to keep the evaporation process at maximum level depth of water on basin needs to be fluctuating base on sun radiation. Table 6 provides works that has been done on solar still base on different water depth in solar still in the past.

Table 6: Effect of water depth on the productivity of solar still

Year	Author(s)	Water depth on brine	Effect of water depth on productivity
1969	Cooper [156]	1.25-30 cm	-30%
1987	Tiwari et al. [157]	2-8 cm	+34%
1987	Kamal[158]	2-5 cm	-11%
1991	Tiwari et al. [159]	2-10 cm	-62%
1992	Farid et al. [160]	0.5-7 cm	-35%
1996	Yaghoubi et al. [161]	5-15 cm	-72%
1996	Toure et al. [162]	0.5-6 cm	-19%
1998	Aboul-Enein et al. [151]	0.5-8 cm	-10%
2000	Nafey et al. [163]	2-7 cm	-14%
2002	Nafey et al. [164]	3-6 cm	-29%
2004	Singh et al. [165]	1-17 cm	-70%
2005	Tripathi et al. [166]	5-15 cm	+8%

2006	Tiwari et al. [167]	4-18 cm	-27%
2007	Phadatare et al. [168]	2-12 cm	-12%
2007	Tiwari et al. [169]	2-18 cm	-25%
2007	Badran [170]	2-3.5 cm	-26%
2007	Phadatare et al. [168]	2-12 cm	-24%
2012	Rajamanickam et al. [171]	1-7.5 cm	-22%
2014	Ahsan et al. [172]	1.5-5 cm	-28%

Suneja et al. [173] investigated the effect of water depth on the performance of an inverted absorber double basin solar still. It was found that the output of an inverted double basin solar still increases with the decrease of water depth in the lower basin for a given water mass in the upper basin. From figure 71, it is evident that water at minimum depth ($m=20$ kg) gives higher yield at day time and after that it gets reduced.

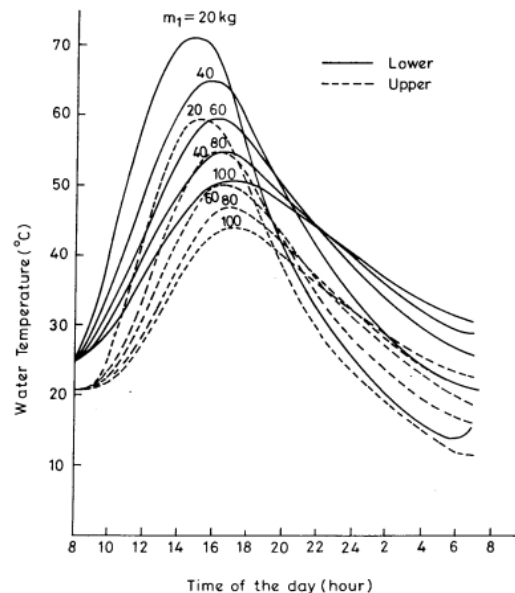


Figure 71: Effect of water depth in the basin on the hourly variations water temperature [173]

Tripathi et al. [174] investigated the effect of different water depth (0.05, 0.1, and 0.15 m) on internal heat and mass transfer for both active and passive solar distillation. The temperature difference between basin water and the glass was accomplished by inserting hot water into the basin from the external collector through. During the sunshine hours, the pump was operated, and was kept off during off-sunshine hours to avoid heat losses caused by reverse flow. The productivity was increased with the water depth in solar still was 0.1 m and 0.15 m.

Phadatare et al. [175] investigated the influence of water depth on internal heat and mass transfer in a plastic solar still. They conducted tests with different depths of water level such as 0.02, 0.04, 0.06, 0.08, 0.1, 0.12 m. At 0.02 m depth of water level the still productivity achieved was as high as

2.1 litre/m² day. The efficiency of the plastic solar still varied from 10% to 34%. The results show that the solar still productivity decreases, when there was an increase in depth of basin water.

Dev et al. [176] investigated relative study of inverted absorber solar still and single slope solar still with dissolved salts and water depth. The daily productivity achieved at water depth of 0.01 m has given higher productivity for both inverted absorber solar still and single slope solar still. The productivity rate of water was 6.302 litre/m² day and 2.152 litre/m² day for inverted absorber solar still and single slope solar still respectively.

2.5.1.7. Reflector

The most recent parameters to be developed that have a direct effect on productivity of solar stills are using reflectors. When using a reflector, the amount of solar radiation into the solar still increases and therefore the evaporation process increases considerably.

To get higher distillate productivity, researchers presented many efforts to make different designs of solar stills. They inferred that the solar still combined with reflectors is efficient and effective. The reflectors with solar stills can be divided into three kinds; internal reflectors, external reflectors (top and bottom), and combination between internal and external reflectors. Using external and/or internal reflectors can be an economical approach to expand the solar irradiation incident on the basin liner to make the productivity high as can as possible. A simple comparison of different solar stills with reflectors is illustrated in table 7. They are compared based on location, daily yield, productivity improvement (%), efficiency, and observations in experiment.

Table 7: Effect of reflectors on the productivity of solar still

Year	Author(s)	Type of reflector	Effect of reflector on productivity
1995	Minasian et al. [177]	Internal stainless steel	35%
2000	El-Sebaai et al. [178]	Mirrors	19% and 30% summer and winter
2001	El-Swify et al. [179]	Internal mirrors	82.6%
2004	Al-Hayeka [180]	Mirrors	20%
2005	Tanaka et al. [181]	Mirrors	13%

2006	Tanaka et al.[182]	Mirrors	48%
2006	Tanaka et al. [183]	Mirrors	9%
2007	Tanaka et al. [184]	Mirrors	13%
2007	Abdallah et al. [185]	Mirrors	20%
2008	Tanaka et al. [186]	Mirrors	15%
2008	Kumar et al. [187]	Mirrors	7.3%
2009	Tanaka [188]	Mirrors	21%
2009	Tanaka [189]	Mirrors	12%
2009	Jabbar, Khalifa et al.[190]	Mirrors	32%
2009	Tanaka [191]	Mirrors	75%
2010	Jabbar, Khalifa et al.[192]	Mirrors	145%
2010	Tanaka [193]	Mirrors	43%
2011	Dev et al. [194]	Steel	200%
2011	Tanaka [195]	Mirror	13%
2011	Al Garni[196]	Mirrors	82%
2011	Boubekri et al. [197]	Mirrors	72.8% in winter
2011	Tanaka [198]	Mirrors	42%
2011	Monow et al. [199]	Aluminium foil	43%
2013	Omara et al. [200]	Mirrors	18%
2013	Srivastava et al. [201]	Mirrors	79%
2014	Omara et al. [202]	Mirrors	68%
2014	El-Samadony et al. [203]	Mirrors	77%

2015	Omara et al. [204]	Mirrors	55%
2016	Estahbanati et al. [205]	Mirrors	34%

Karimi et al. [205] investigated experimentally and theoretically the effect of an internal reflector on the productivity of a single-slope solar still (during the summer and winter) as figure 72.



Figure 72: Karimi's single slope solar still with internal reflectors [205]

Mathematical model was considered the effect of all walls (north, south, west and east) of the still on the amount of received solar radiation to brine. The model was validated with the experimental data. The model can calculate the yield of the still with and without internal reflector on various walls. The results showed that the simultaneous use of internal reflector on front and side walls enhances the still's efficiency by 18%. However, installation of an internal reflector on the back wall can increase the annual efficiency by 22%. The installation of internal reflectors on all walls in comparison to a still without internal reflector can increase the distillate production at winter, summer, and the entire year by 65%, 22%, and 34%, respectively.

El-Bahi and Inan [206] examined a conventional still integrated with an outside condenser, as figure 73.

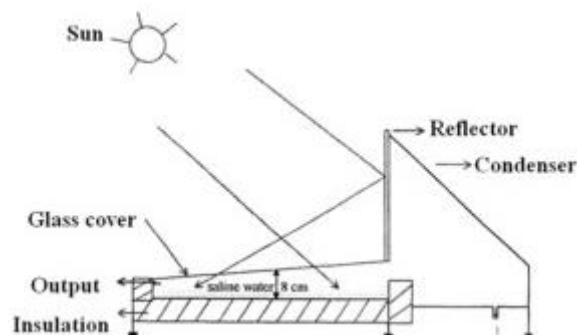


Figure 73: El-Bahi and Ina's schematic of solar still with external top reflector [206]

A reflector made of stainless steel was added to the glass cover to reflect the solar radiation into the still basin through the glass cover and to give a shadow for the condenser. The study led to the conclusion that the efficiency of the solar still was enhanced by about 70% and the daily productivity was up to 7.0 litre/m² day.

Tanaka and Nakatake [207] presented also the results of outdoor experiments for vertical single-effect diffusion solar still, figure 74.

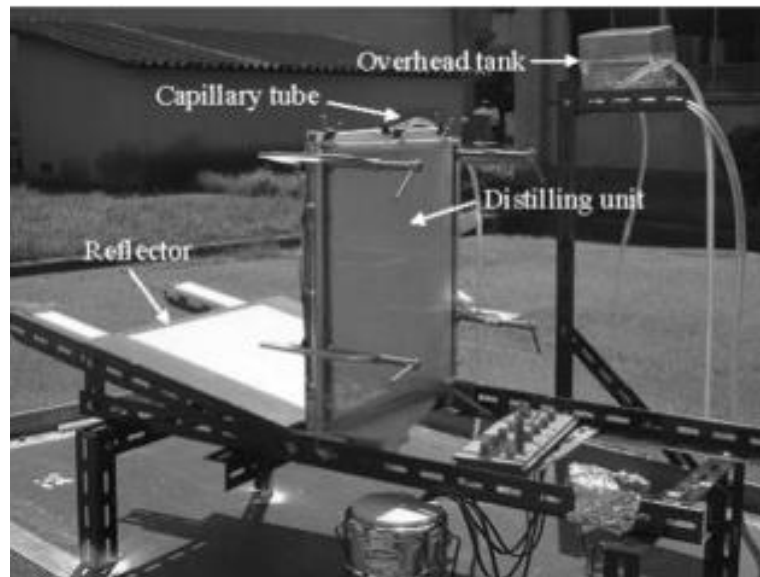


Figure 74: Tanaka and Nakatake's diffusion solar still with external reflector [207]

To know the effect of still orientation deeply, the authors had to make the reflector's inclination angle to be fixed and change the still orientation just one time a day at the south side. They got the result that during the winter and summer seasons, the optimum reflector angles were 0° and 10° respectively. The optimum orientation was varied according to month.

2.5.1.8. Sun tracking

Absorbing sun radiations has direct effect on the productivity of solar still. Sun tracking system helps to track sun at different time of day to absorbed maximum radiation to increase evaporation process.

Abdallah et al. [208] improved the single slope solar still performance through increasing the production rate of distilled water. Design modifications were introduced to the conventional solar still, involving the installation of reflecting mirrors on all interior sides, replacing the flat basin by a step-wise basin, and by coupling the conventional solar still with a sun tracking system. The inclusion of internal mirrors improved the system thermal performance up to 30%, while step-wise basin enhanced the performance up to 180% and finally the coupling of the step-wise basin with sun tracking system gave the highest thermal performance with an average of 380%. A step-wise basin gave higher thermal performance than both with and without mirrors conventional stills. This was due to two

reasons. First, a smaller air volume trapped inside the still chamber than in the traditional still and therefore heating up the trapped air will be much faster. Second, the step-wise basin provides higher heat and mass transfer surface area than the flat basin.

Ibrahim [209] investigated a collector that is made up of six parabolic troughs with tracking system to divert the sun radiation into the solar still. The results were shown the temperature of water on the basin increases faster than system without tracking system.

A. Kalogirou [210] built a tracking system which can be used with single-axis solar concentrating systems. The position and “status” of the Sun are detected by three light-dependent resistors (LDRs), one of which detects whether the collector is focused, whilst a second resistor determines if there is cloud cover, and the third senses whether it is day or night.

Abdallah and Badran [211] developed a sun tracking system for enhancing the solar still productivity. A computerized sun tracking device was used for rotating the solar still with the movement of the sun. A comparison between fixed and sun tracked solar stills showed that the use of sun tracking increased the productivity for around 22%, due to the increase of overall efficiency by 2%. It can be concluded that the sun tracking is more effective than fixed system and it is capable of enhancing the productivity.

Khalifa et al. [212] investigated the effect of using two-axis sun tracking system on the thermal performance compound parabolic concentrators (CPC), with the CPC determined to better performance. Two cases were examined: in the first, a batch feeding was used where no flow through the collector was allowed; in the second, different steady water flow rates were used. In both cases, the variations of water temperature in the systems were monitored. The tracking CPC collector showed a better performance with an increase in the collected energy of up to 75% compared with an identical fixed collector.

Abdallah and Nijmeh [213] designed and constructed two-axis tracking system. The experimental study was investigated the effect of using two axes tracking on the solar energy collected. The collected energy was measured and compared with that on a fixed surface tilted at 32° towards the south. The results indicate that the measured collected solar energy on the moving surface was significantly larger than that on a fixed surface. The two axes tracking surface showed a better performance with an increase in the collected energy of up to 41.34% compared with the fixed surface.

Hiroshi Tanaka et al. [214] presented on a vertical multiple-effect diffusion-type solar still consisting of a flat plate reflector, a number of vertical parallel partitions in contact with saline-soaked wicks with narrow air gaps between partitions, and casters for manual azimuth tracking. Theoretical

parameters were investigated to determine the effect of these factors that could cause a decrease in the distillate productivity of the still, and found that although the distillate productivity of the still under practical conditions considering possible poorness of construction and operation skills would be about half of that under optimum conditions, the actual productivity under practical conditions would still be significantly greater than that of the conventional single-effect stills. The overall daily productivity of the proposed still under practical conditions assuming poorness of construction and operation skills is predicted to be about 18.0 and 21.5 liter/m² day.

H. Tanaka et al. [215] investigated the optimum angle of a flat plate reflector and the optimum orientation of a vertical multiple-effect diffusion solar still coupled with a flat plate reflector throughout the year are numerically determined with the assumption that the still is located at the equator and at 10°, 20°, 30° and 40° northern latitude. The optimum orientation of the still which maximizes the distillate productivity of the proposed still was calculated assuming that the orientation of the still is changed once during daytime at of the sun. The proposed still was assumed to be rotated manually just twice a day (at near noon and before sunrise) to change its orientation and absorb more solar energy on the first partition. It was found that the angle of the flat plate reflector should be basically fixed at 10° from horizontal and changed to be 0° during the winter season (around December) at higher latitudes, and the orientation of the still should be adjusted according to month at any latitude. The daily productivity of the proposed still was predicted to be more than 30 liter/m² day at any latitude throughout the year except for the winter season.

Hisanori Tanaka et al. [216] investigated a theoretical analysis of a one-step azimuth tracking tilted-wick solar still with a vertical flat plate reflector is studied. The still was assumed to be rotated manually just once a day at a aligning with a sun. The theoretically determined the optimum tilt angle of the still and the optimum orientation of the still on these 4 days were presented. The results show that the increase in the daily amount of distillate of a tilted-wick still would average about 41% for 4 days and can be achieved by the simple modification of using a flat plate reflector, setting the still at a proper tilt angle according to seasons and rotating the still just once a day.

2.5.1.9. Energy storing material

Sun radiations are main power source of solar still, but it is unpredictable and intermittent. Using material such as sponge cubes, gravel, wicks and phase change materials are used in the basin of solar still to store energy (heat) when the sun radiations are available and using it during the time that sun is not available. These materials are used in solar still basin increase the basin solar radiation absorption but also increase the heat capacity of basin, due to their property of high heat storage capacity. Table 8 details the thermal storage material in solar still and the effect of it on productivity of solar still.

Table 8: Effect of energy storing material on the productivity of solar still

Year	Author(s)	Heat Storage Material	Effect of energy storage material on productivity
1999	El-Sebaili et al. [178]	Baffle suspended absorber	20%
2000	Nafey et al. [217]	Black rubber – Gravel	20% - 19%
2003	Radhwan[218]	Paraffin wax	57%
2007	Sakthivel et al.[219]	Black granite gravel	20%
2007	Badran [220]	Asphalt	51%
2008	Velmurugan et al. [221]	Wick – Sponges – Fins	29.6% - 15.3% - 45.5 %
2008	Murugavel [222]	Black rubber	20%
2009	El-Sebaili [223]	Stearic acid	27%
2009	Abdallah et al. [224]	Coated sponges – uncoated sponges – black rocks	28% - 43% - 60%
2010	Tabrizi et al. [225]	Sand	75%
2011	Omara et al. [226]	Fin	40%
2013	Srivastava et al. [227]	Porous fin	23%

Abu-Hijle and Rababa'H [228] studied solar still by using sponge cubes in the basin. Figure 75 shows a schematic of the still with sponge cubes used in the study.

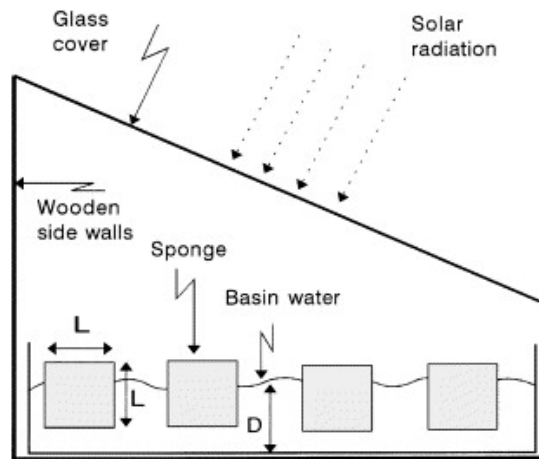


Figure 75: Side view schematic of solar still with sponges [228]

The experimental study depends mainly on the ratio of the overall distillate still yield in case of using sponge cubes to that of the reference still. The addition of sponge cubes in the basin water causes major enhancement in still production (up to 273%). The sponge cubes increase the surface area over which water evaporation occurs.

Murugavel et al. [229] evaluated the performance of the solar still with various spreader materials such as jute cloth, cotton cloth, a sponge sheet and porous materials such as quartzite rock and natural rock. The results confirmed that the use of the black light cotton cloth gave the most productivity.

Nafey et al. [217] fabricated single slope solar still with storage medium material such as black rubber, black gravel material and sand (figure 76).

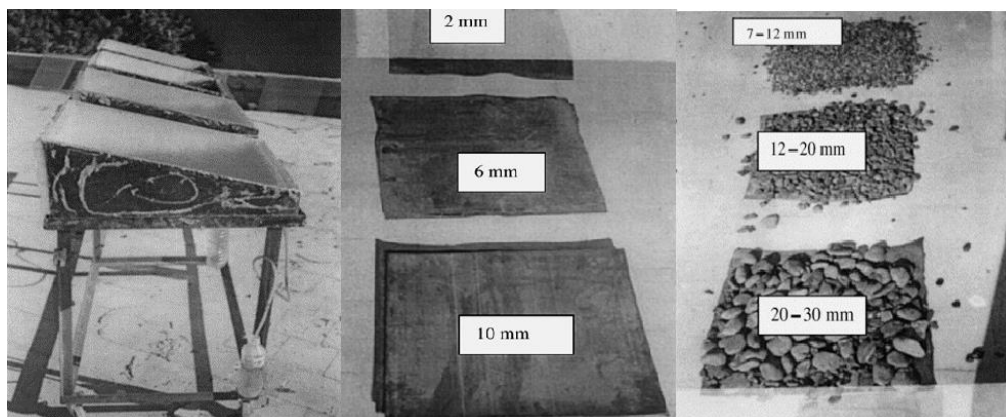


Figure 76: Nafey et al. experimental work with energy storing material [217]

Four identical still units were designed and constructed. From the results, the addition of 10 kg sand as storage material enhanced the daily productivity to reach a value of almost 4.005 (litre/m²/day) with a daily efficiency of about 37.8%. When sand was not used, the daily productivity reduced to a level of 2.852 litre/m²/day with a daily efficiency of 27%. The annual average daily yield of the still with storage has been found to be 23.8% greater than that without storage.

Abdallah et al. [224] fabricated solar still to test different type of absorbing material such as coated and uncoated porous media (called metallic wiry sponges) and black volcanic rocks (figure 77).

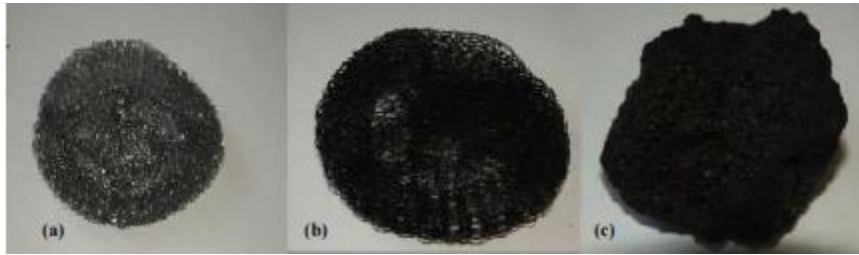


Figure 77: Various absorbing materials used in solar stills a) uncoated metallic wiry sponge b) coated metallic wiry sponge c) black rocks [224]

The results showed that the uncoated sponge has the highest water collection during day time, followed by the black rocks and then coated metallic wiry sponges. On the other hand, the overall average gain in the collected distilled water taking into the consideration the overnight water collections were 28%, 43% and 60% for coated and uncoated metallic wiry sponges and black rocks respectively.

El-Sebaai et al. [230] conducted experiments in a single basin solar still by combining a thin layer of stearic acid as a Phase Change Material (PCM) under the basin liner to increase the productivity of the still. The outcomes were compared with the still without PCM. The productivity was found to decrease with the increase of the mass of the PCM. But, the overnight productivity increased with the increase of the mass of the PCM. The productivity of the still was found to be 9.0 litre/m² day and 4.9 litre/m² day for the still with PCM and without PCM respectively.

T. Rajaseenivasan et al. [231] fabricated double basin double slope and single basin single slope stills have been fabricated and their performances were compared for various basin conditions. It is also noted that, provision of wick or porous or energy storing material in the basin increases the distillate output. Maximum water production was 5.68 litre/m² day for double basin still. Production increase was 85% for the same basin condition. Production increase was 169% when compared with minimum production condition of the single basin still (figure 78).



Figure 78: Double basin double slope and single basin single slope stills with (1) Black cotton cloth (2) Jute cloth (3) Waste cotton pieces (4) Clay pot- facing up (5) Clay pot- facing down (6) Mild steel pieces [231]

Murugavel and Srithar [232] tested a basin type double slope solar still equipped with different wick materials, such as light cotton cloth, coir mate, sponge sheet, and waste cotton pieces in the basin (figure 79).



Figure 79 basin different basin wick material was used by Murugavel and Srithar [232]

It was discovered that stills with Aluminium fins covered with cotton cloth is more effective. A single basin double slope passive type solar still is tested in a layer of water (approximately 2 mm depth) under controlled input conditions.

Pankaj et al. [233] used low thermal inertia porous absorbers were made up of ordinary blackened jute cloth in single sloped basin type solar still. Low thermal inertia of the porous absorber increased

higher operating temperature and higher productivity. Also the increase in the evaporation surface area further aided the performance. They got about 68% more distillate output on clear days, whereas it was nearly 35% more on cloudy days (figure 80).

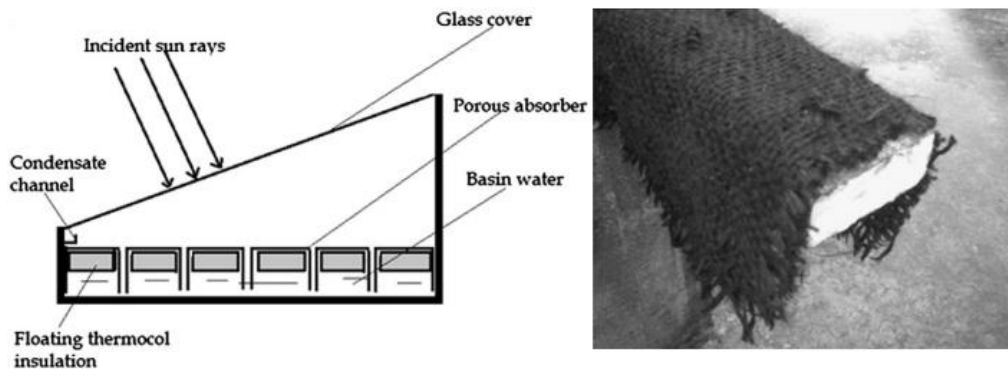


Figure 80: Pankaj et al. modify solar still with porous absorber [233]

Tiris et al. [234] improved the performance of solar still by using absorbing materials. Three types of absorbing materials were tested under natural solar radiation. They were charcoal, blackened rock-bed, and black-paint. Results shown that charcoal gave the best efficiency (11–18% more than black-paint, 23–92% more than blackened rock-bed). During the summer months water level in the still also plays an important role in the productivity.

Naim et al. [235], [236] designed a solar still with charcoal as heat absorbing medium and wick material. They used three different charcoal sizes such as coarse, intermediate and fined. At higher flow rates both coarse and intermediate sizes gave better productivity. At moderate and low flow rates fine charcoal gave slightly better productivity. The reason for this may be attributed to the fact that coarser the charcoal is, glossier is its surface resulting in light reflection through the cover with consequent heat loss. It was found that charcoal can be used as absorbing medium successfully instead of wick type, black butyl rubber, and asphaltic absorber. A 15% improvement in productivity over wick type stills has been attained.

2.5.1.10 Temperature of top surface water

In a conventional still, the base absorbs a large amount of solar radiation, rendering it to be the hottest area of the still and around 11% of solar radiations reflect back. Heat is transferred from the bottom surface to the water via convection and to the outside atmosphere via conduction through the insulating layer. There are number of techniques in order to increase absorption rate of sun radiation on top surface water.

S. Nijmeh et al. [237] fabricated a single-basin solar still using various absorbing materials. The materials used to enhance the absorptivity of water for solar radiation include dissolved salts, violet dye, and charcoal. The salts were potassium permanganate (KMnO_4) and potassium dichromate

($K_2Cr_2O_7$). Significant increase in still efficiency and productivity was obtained. For example, the addition of potassium permanganate resulted in 26% improvement in efficiency. Also, a comparison between theoretical and measured water productivity is presented. It was found that there is a good agreement between theory and experiment.

Bilal A. Akash et al. [238] tested single basin solar still with improvement of some material to increase maximum solar radiations to increase evaporation rate. Experimental results showed that the productivity of distilled water was enhanced for some materials. For example, using an absorbing black rubber mat increased the daily water productivity by 38%. Using black ink increased it by 45%. Black dye was the best absorbing material used in terms of water productivity. It resulted in an enhancement of about 60%. The still used in the study was a single-basin solar still with double slopes and an effective insolation area of 3 m^2 .

Anil K. Rajvanshi et al. [239] studied an analytical and experimental study of the effect of adding dyes to a solar distillation unit. The dyes used are black methylaniline, red carnosine and dark green, at various concentrations. Test results showed that a dye solution is able to increase the distillate output by as much as 29% (for black dye with 172.5 ppm concentration). Based on these tests, a method of calculating the percentage increase in evaporation effected by a specific dye over that from the control unit is developed. Among the dyes tested black methylaniline dye was found to be most suitable from two points of view: increased evaporation and no photochemical degradation. The analytical model subsequently used to study the effect of ambient temperature, wind velocity and dye concentration on still productivity.

M.S. Sodha et al. [240] analysed the effects of dye on the output of a solar still. Black and violet dyes were found to be more effective than other dyes, and the performance with a dye present was found to improve (by 48%), the deeper the still.

2.5.1.11. Vacuumed technology

The effect of vacuum inside the still is to avoid any heat transfer due to convection in the still. The heat loss from the water in an insulated still is due to evaporation and radiation only. In the presence of vacuum, the effect of the non-condensable gas, which reduces the rate of condensation, was also avoided.

H. Al-Hussaini et al. [241] studied the effect of applying vacuum inside the solar still on its productivity. The effect of vacuum inside the still was to avoid any heat transfer due to convection in the still. So, the heat loss from the water in an insulated still is due to evaporation and radiation only. Hence, the air mass transfer is not included in the analysis. In the presence of vacuum, the effect of the non-condensable gas, which reduces the rate of condensation, is also avoided. The results show that applying vacuum inside the solar still increases the water productivity about 100%.

Al-Kharabsheh et al. [242] conducted experiments in a water distillation system using low grade solar heat as shown in figure 81.

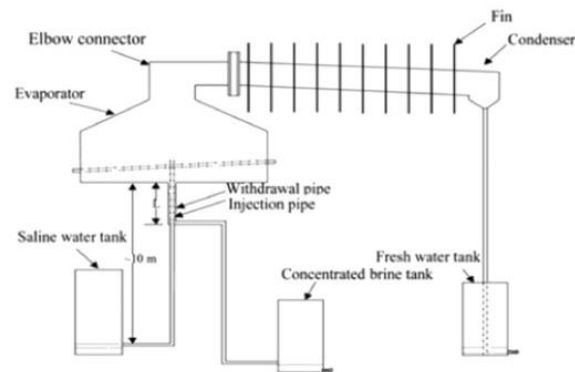


Figure 81: Schematic diagram of vacuum distillation [242]

The system uses the gravity and atmospheric pressure to create a vacuum. The water evaporates at lower temperatures and pressure in the vacuum conditions. The set-up consists of an evaporator connected to the condenser. The vapour produced in the evaporator was condensed in the condenser and the distillate was collected. The productivity of the above system was 6.5 litre/m² day and 3–4 litre/m² day for the conventional still.

Nassar et al. [243] conducted experiments in a solar desalination system working on the basis of evacuation (figure 82).

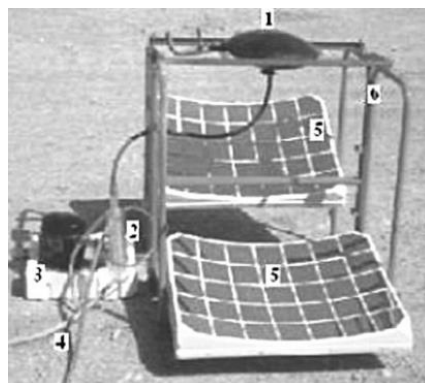


Figure 82: Nassar et al. experimental solar still using vacuum technology [243]

There are two concave mirrors were placed to concentrate the solar radiations into the still. The still works under vacuum conditions (25 kPa absolute) to reduce the boiling point of the saline water. A condenser condenses the outlet vapour and the distillate was collected. The productivity of the still was found to be 20 litre/m² day of the reflector compared to 5 litre/m² day for the conventional still. The results showed that the productivity of the still was about 303% compared with the other stills. The performance ratio was found as 900%. The vacuum pump in the still may be operated by means of photovoltaic system to provide potable water to the nearby villages.

2.5.2. Condensation Rate

2.5.2.1. Transparent cover cooling

Condensation rate can be increased by reducing the inner glass temperature of the cover. The natural circulation of air mass inside the still is increased by maintaining the temperature difference between the glass cover and the basin water.

Tiwari et al. [244] investigated single basin solar still performance with water flowing over the glass top cover (figure 83) and the following results have been obtained: first, by introducing an even flow of water over the glass cover, the daily productivity of the still is almost doubled. Secondly, the distillate output slightly decreases with the increase of water flow over the glass because of temperature reduction in basin water.

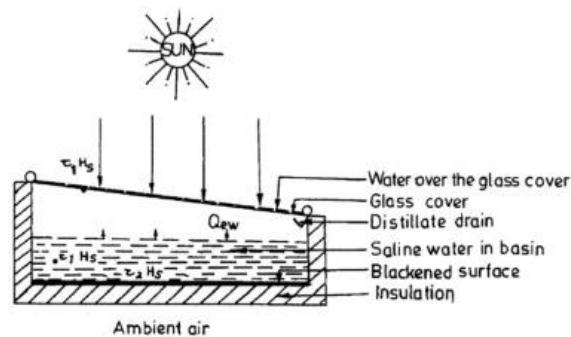


Figure 83: Schematic representation of the single basin solar still with water flowing over the glass [244]

Tiwari et al. [245] reduced temperature of top glass cover by an intermittent cooling water flow on the cover of solar still. The glass cover temperature was slightly higher than the ambient temperature and the flowing water temperature over the glass cover remains of the same order as ambient temperature (figure 84).

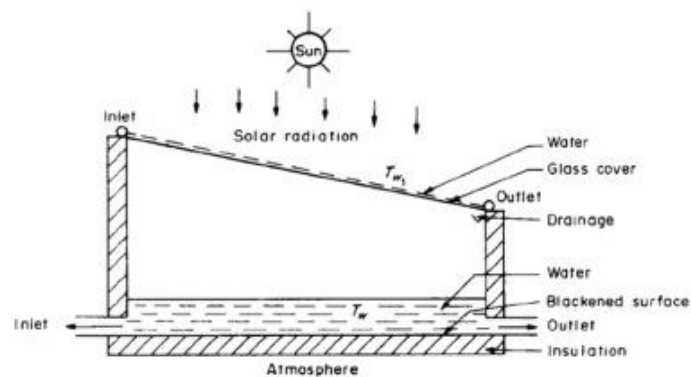


Figure 84: Schematic representation of single basin solar still with water flowing over the glass cover and inside the basin [245]

Lawrence et al. [246] investigated the effect of heat capacity on the performance of solar still with water flow over the glass cover. It was clear that, water flow above the glass cover reduces the temperature of water as well as glass temperature. Reduction in basin water temperature slightly

reduces the evaporation rate. Reduction in glass temperature increases the condensation rate, due to which productivity of the still improved (figure 85).

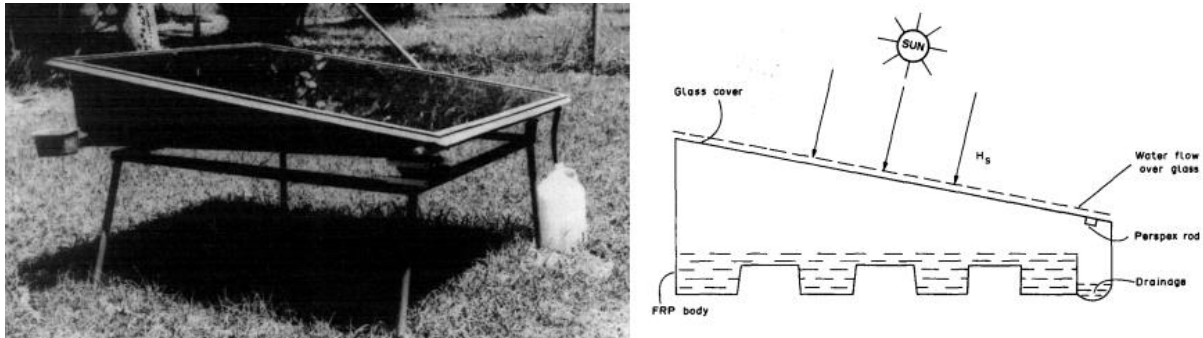


Figure 85: Lawrence solar still with water flow on top of the glass [246]

Singh et al. [247] found the analytical expression for thermal efficiency of a passive solar still by using energy balance equations for the different components of a passive solar still (glass cover, basin liner and water mass) with water flowing over the glass at uniform velocity. On basis of the analytical results obtained, it was found that there is a significant increase in the efficiency of the solar still due to water flow over the glass cover at higher depths of water in the basin.

Abu-Hijleh [248] fabricated a solar still with the glass cover temperature reduction by a film of cooling water continuously over the glass cover (figure 86).

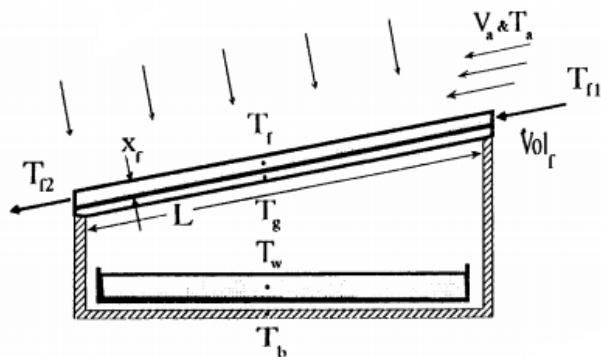


Figure 86: sketch of solar still with film cooling [248]

By proper use of film cooling the efficiency of solar still was increased by 6%, but poor combinations of film cooling lead to reductions in still efficiency. Temperature of flowing water over the glass cover and that of glass are always nearly equal.

Arunkumar et al. [249] fabricated a solar still with a hemispherical top cover with and without flowing water over the cover (figure 87).

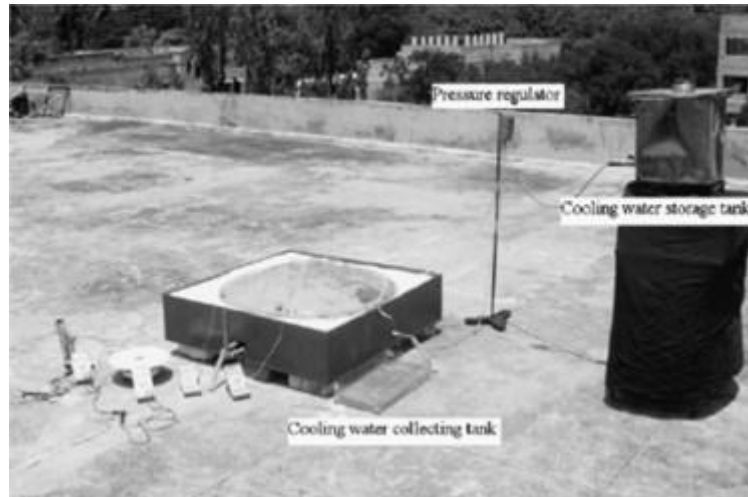


Figure 87: Solar still showing cooling water system [249]

They found that the daily distillate output of the system increased with water flowing over the glass cover. The efficiency was 34% without top cover cooling and 42% with top cover cooling.

Second method that was used to reduce the glass cover temperature is by passing water between double-glass cover. This method is used to eliminate the glass cover heat by flowing of water in among them.

Abu-Arabi et al. [250] investigated the solar still unit performance analysis with double glass cover cooling technology. They designed a glass cover technology with no space between the upper glass cover and flowing water. The advantage of the system was that no evaporation takes place from the cooling water.

Zurigat et al. [251] designed a regenerative solar still with provision of cooling water to flow in and out of the second effect (figure 88).

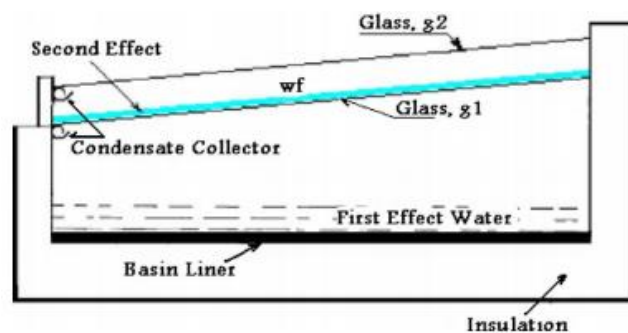


Figure 88: Zurigat et al. schematic solar still [251]

It was just opposite to earlier technique with providing the space between water and glass cover. This technique has the advantage of cooling the lower basin glass cover by upper basin and condensed water collected at the upper basin. The heated water from the upper basin was given to the lower basin to improve the evaporation rate and productivity. The productivity of regenerative solar still was 20% higher than conventional solar still.

2.5.2.2. Condenser

A. Rahim [252] suggested the utilization of a forced condensing technique in a moving film inclined solar desalination (figure 89).

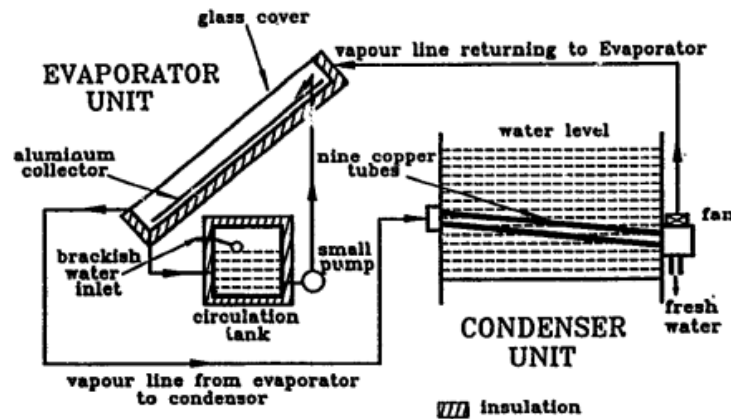


Figure 89: A. Rahimi's schematic solar still with external condenser [252]

The solar still consists of four main parts. The water vapour is extracted as soon as it is formed before it reaches the glass cover and is allowed to condense in a separate unit kept at a much lower temperature. In a study to find optimum performance of the system, the thermal and overall efficiency were found to be about 70% and 60%, respectively.

S. T. Ahmed [253] evaluated the effect of using an internal condenser on the performance of a single-effect solar still. The still was tested in two different ways (figure 90): first, it was used for water vapour condensation without condenser, and second, it was used for water vapour condensation with condenser.

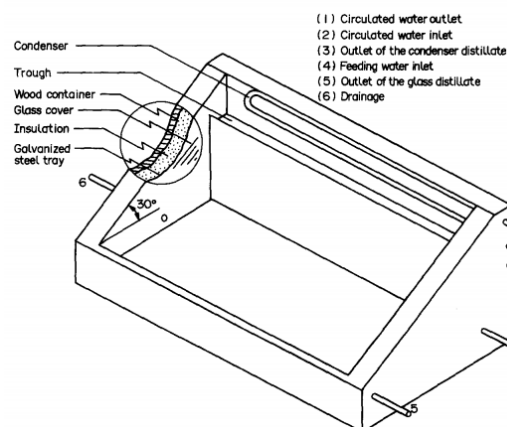


Figure 90: Ahmed's solar still with external condensation [253]

The still was single-sloped with a double pass internal condenser. The results showed that combining an internal condenser with basin type solar still caused an improvement in the still performance. The still daily productivity was increased from 5.5 litre/m² day for the first test to 5.9 litre/m² day for the second test.

El. Bahi's et al. [254] fabricated single slope solar still to improve the efficiency of solar still by adding an outside passive condenser (figure 91).

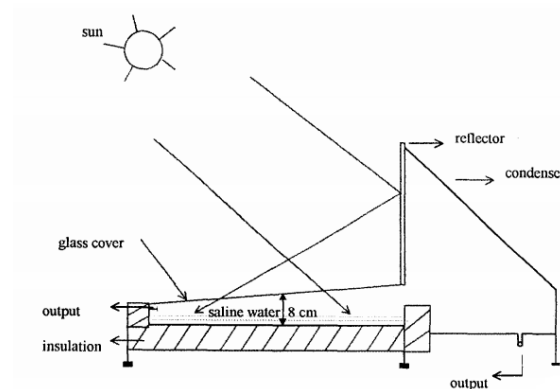


Figure 91: El. Bahi's solar still with external condenser [254]

The solar still yielded a daily output of up to 7 liter/m² and efficiency of 75% during the summer months. The solar still was operated without a condenser, it yields decreased to 70% of that with a condenser.

Nikolat Nuegorodov et al. [255] studied the effect of adding a passive condenser on the performance of the single slope, basin type solar still (figure 92).

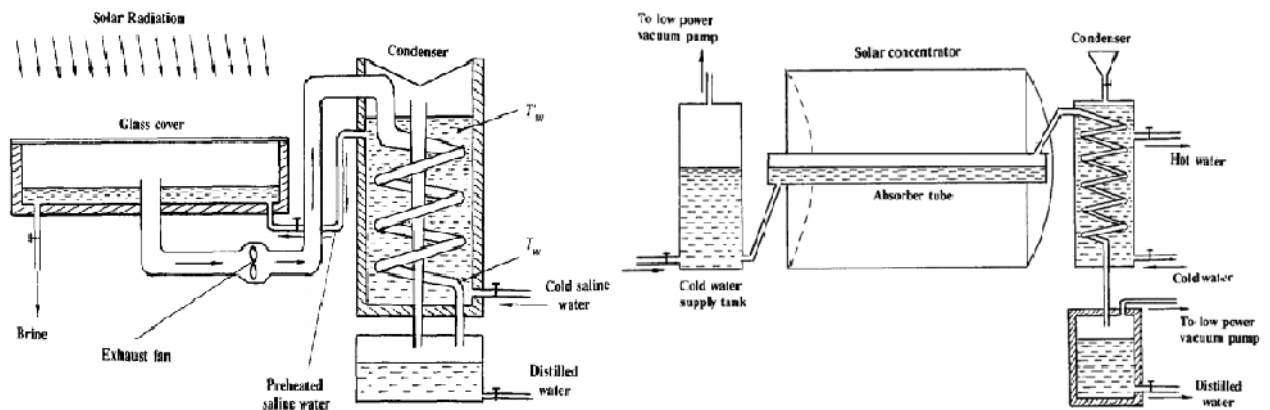


Figure 92: Left, the basin type still with exhaust fan and a condenser. Right, a concentrator collector with vacuum pump to lower the boiling temperature of water [255]

Two solar thermal–electrical methods are defined to purify water by distillation method. In the first method, air saturated with water vapour is removed from a basin type still by using a low power exhaust fan and is passed through a condenser. The thermal efficiency of the still is increased more than twice the thermal efficiency of the conventional still. In the second design, a concentrator–collector is used to boil water in the absorber tube. A low power vacuum pump is employed to lower the boiling temperature of water by about 10 °C. The yield of distillate from the still is nearly doubled.

A. Madhlopa et al. [256] fabricated a passive solar still with separate condenser and its performance was evaluated (figure 93).

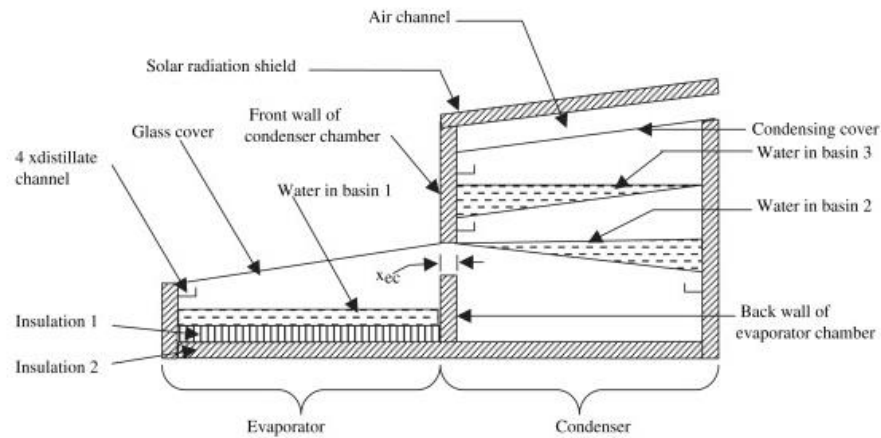


Figure 93: Cross section of Madhlopa's solar still with external condenser [256]

The performance of the system was evaluated and was compared with that of a conventional solar still under the same meteorological conditions. Results show that the distillate productivity of the present still is 62% higher than that of the conventional type. The first, second and third effects contribute 60, 22 and 18% of the total distillate yield respectively. It is also found that the productivity of the solar still with separate condenser is sensitive to the absorbance of the liner of basin 1, and the mass of water in basins 1 and 2. The mass of water in basin 3 and wind speed have marginal effect on distillate production. Table 9 summarize the works that increase the condensation process by different methods:

Table 9: Effect of condenser on the productivity of solar still

Year	Author(s)	Type of condenser	Effect on productivity
1989	Kumar et al. [257]	Heat exchanger	20%-25%
1989	Lawrence et al.[258]	Water flow over glass cover	7%-10%
1990	Tiwari et al.[259]	Separating condenser	30%
1993	Yadav [260]	Heat exchanger	40%
1996	Abu-Hijlah [261]	Water film cooling of the glass cover	2.5%-3%
1996	Abu-Qudais [262]	External condenser	42%
1999	El-Bahi [263]	Separating condenser	5%
2002	Fath et al.[264]	Built-in additional condenser	55%
2002	Abu-Arabiet et al.[265]	Double-glass cover cooling	34%

2004	Zurigat et al.[266]	Double-glass cover cooling	20%
2008	Kumar et al.[267]	Enhance condensation	30%
2009	Madhlopa et al.[256]	Separate condenser	62%
2012	Arunkumar et al.[268]	Top cover cooling	8%
2012	Ahmed[269]	External condenser	40%
2014	Suneesh et al.[270]	Top cover cooling	24%-29%

2.5.2.3. Wind speed

The effect of wind speeds is insignificant concerning productivity in compare with other operational configuration but it still has positive impact on solar still output. Productivity of solar still increases with decreasing cover temperatures. The temperature difference between glass and water widens with decreasing cover temperature, which consequently improved the natural circulation of air mass within the still. Moreover, the convective heat transfers from the cover to the atmosphere increases when both evaporative and convective heat transfers between the basin water increases to compensate for high wind speeds [266] [271].

Soliman [272] investigated roof-type solar stills under forced convection conditions to determine the effect of wind velocity on the output in detail by integrating heat and mass transfer modes. The variation in the output against the water temperature increases when the temperature gradient between the water temperature and cover temperature is enhanced. The rate of evaporation increases with increasing wind velocity.

El-Sebaii [273] investigated the effect of wind velocity on the outputs of active and multi-effect passive stills, and concluded that the yield increases with increasing wind speed. El-Sebaii [274] also analysed the influence of wind speed on the performance for multiple masses of water in basins, and he concluded that performance improves with increasing wind speeds.

A. Safwat Nafey et al. [275] investigated the main parameters affecting solar still productivity. Four solar still units are designed and constructed to operate under the same weather conditions with different design parameters. It was consulted that with the increase in wind velocity, the productivity is decreased. The numerical calculations showed that when the wind velocity changes from 1 to 9 m/s, the productivity decreases by 13%.

Y. Zurigat [266] fabricated solar desalination unit to measure performance by increasing wind speed. This arrangement has the advantages of increasing the temperature difference between water and glass cover in the first effect and utilizes the latent heat of water vapour condensing on the glass of the first effect to produce more fresh water in the second effect. The performance of the regenerative still is evaluated by comparison with the performance of the conventional still under the same weather conditions. The wind speed has a significant effect on the productivity of the stills; it can increase the productivity by more than 50% if the wind speed is increased from 0 to 10 m/s.

2.6. Literature Review Summary

As summary, a full literature review was carried to discuss different shapes of solar still and how the shape affected the productivity of solar stills. It was found that designing the unit shape to pass maximum solar radiation into the basin area with direct angle make the solar still productivity increases its productivity based on various designs (e.g. single slope, double slope, pyramidal and hemispherical solar stills). Therefore, the solar still unit introduced in this thesis was planned with the top cover at zero angle in order to pass solar radiation directly into the basin area while the sun is at its highest point during day time (noon period).

There are also climatic factors, which have a direct impact on the productivity of solar still such as solar radiations, intensity, ambient temperature, wind speed, outside humidity and sky condition. These factors cannot be controlled by humans. The experiments for the introduced solar still unit were placed in the laboratory, which keeps aforementioned factors at constant parameters.

By considering the numerous factors affecting the solar still productivity, operational parameters (e.g. colouring of water, water flow, surfactant activities and salt concentration) are also a main key element to improve the solar still productivity. The modifications have a direct impact on both evaporation and condensation rate that was presented in this chapter. There are also numbers of applied modifications in the introduced solar still with its new geometry. These modifications and their impact on evaporation and condensation rate are presented in table 10 as follows:

Table 10: Operational facts used in the introduce solar still

Operational factors	Present solar still	Evaporation rate	Condensation rate
Basin construction material	Isolated black ponds	✓	-
Absorption of basin water	Ink and lava stone	✓	-
Top transparent material angle	15° angle (two sides cover) and 0° (top cover)	✓	-
Basin water depth	80 mm	✓	-
Solar radiation concentrator	Two linear focuses Fresnel lenses	✓	-
Energy storing material	Lava stone	✓	-
Water transparent cover temperature difference	Internal extraction ventilation fan	✓	✓
Condenser	Heat-exchanger	✓	✓

3. Research Aim and Objectives

3.1. Introduction

Water and energy are two most essential parameters as regards to international and development planning. Therefore, desalination plants and renewable energy are two different technologies that can be combined in many ways to aid both water and energy crises.

The design and testing of a portable (to be tested in the solar field) lab scale solar still unit, to be capable of being enlarged in scale size (to community scale), in addition with a solar still concentrator for desalination purposes, is one of the key solutions to provide fresh water without harming environment.

A comprehensive literature review in regard to desalination and its technologies, such as solar still with different modifications was described in chapter 2. Modifications were categorized in two groups based on geometry shape (type) of solar still and operational parameters, focusing to increase either evaporation or condensation rate in solar stills.

Several researchers have developed simple models to study daily productivity depending on construction geometry of the solar still (chapter 2.4). It was found that the double slope single basin shape solar still is the best concept that could be configured to use solar radiation concentrator (chapter 5), and it is also capable to of being enlarged in scale size with market available parts in inaccessible areas (scale up cost analysis chapter 6.4).

This present research investigated new modifications in order to increase both evaporation and condensation rate which are two key thermodynamic elements to increase the productivity of a solar still. Through this approach, the following priority actions were used to enhance optimum operation conditions, in order to maximise the productivity:

1. **Fresnel lenses:** The geometry of the introduced solar still was designed to custom two linear focus Fresnel lenses, as the top cover of the solar still, to concentrate and direct solar radiations on top of the basin area in order to increase evaporation rate;
2. **Internal Ventilation fan:** It was used in order to take vapour out of unit before it starts to become saturated. The fan shroud was also used to avoid air turbulence inside solar still box;
3. **Heat exchanger pipes:** A ventilation fan extracts the vapour throughout the solar still's enclosed area and directs it into heat exchange copper pipes that sit on top of the basin area thus transferring vapour heat to the basin water, which causes it to change its phase to condense as liquid water.

4. **Heat storing material:** Lava stones were used in the basin area as one of many types of volcanic rock that could store heat and release it when its needed.

A portable laboratory scale double slope solar still unit was designed and constructed in order to use Fresnel lenses concentrator in the field. Other modifications such as ventilation fan airflow ratio with/without shroud and heat storing material and their outcome were measured to find the best operational conditions.

The laboratory experimental results (water was heated in an external tank and then exported to the basin area) were then compared to the theoretical values in order to measure the productivity of the unit to be used for two locations (Almeria, Spain; Qeshm, Iran) as case studies. The solar still unit could be tested at either of the aforementioned locations in order to compare results for further study.

3.2. Research Aim

The aim of this work was to explore a new method of direct solar distillation to increase the daily productivity of fresh water per unit of area to generate fresh water from brackish water for small communities in inaccessible areas. The devised method is a single basin double slope solar still enhanced with an internal ventilation fan and heat exchanger. This unit was also designed and constructed to use linear focused Fresnel lens in order to concentrate and direct solar radiation into the basin area.

3.3. Research Objectives

The objectives of this research were as follows:

- I. Review and understand the state of the art in direct solar water distillation (Chapter 2);
- II. Create an analytical model of a novel solar still to increase the unit yield (Chapter 5.1.1 and 5.1.2);
- III. Design and construct a laboratory scale unit to test different parameters such as effects of a ventilation fan, heat exchanger and thermal storage materials (Chapter 5.1.3 and 5.1.4);
- IV. Analyse theoretical and laboratory scale experimental results of solar still (Chapter 5.2 and 5.3);
- V. Develop a case study to evaluate the solar still unit productivity in Almeria (Spain) and Qeshm Island (Iran) (Chapter 6).

3.4. Research Scope

This research investigated modifications of a direct solar still in order to increase the yield of the unit for desalinate purposes. The scopes of this research include:

- I. A new geometry of direct solar still to absorb most radiation during day time. Linear focused Fresnel lenses were integrated on the roof of the solar still (figure 94);

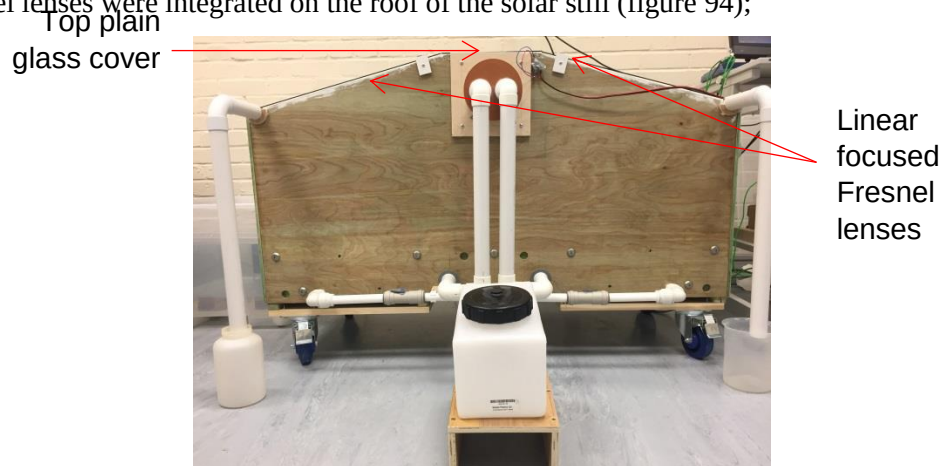


Figure 94: The new solar still to apply two Fresnel lenses

- II. A ventilation fan (with and without shroud) was used to pull vapour out of unit, in order to prevent saturation of water vapour inside the solar still (figure 95);

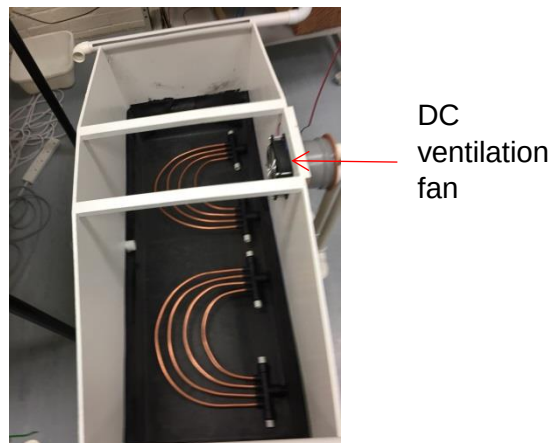


Figure 95: DC ventilation fan to direct vapour into copper pipes

- III. The vapour is passed through the basin water inside copper pipes. This acts a thermal heat exchanger, in order to utilise the latent heat from water phase change to vapour liquid, to raise the temperature of basin water (figure 96);

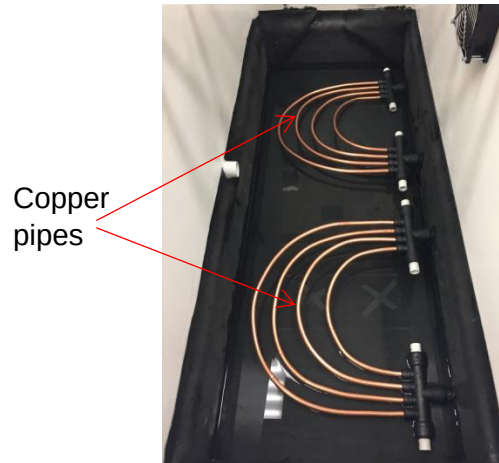


Figure 96: Copper pipes (acting heat exchanger)

- IV. Lava stones were used as thermal storage material, in order to offset decreasing temperature rate during sunset period. Their effect on yield of solar still unit was measured in the laboratory (figure 97).



Figure 97: heat storing material o the basin area (Lava stone)

While this unit of solar still was designed to use PMMA (poly methyl methacrylate) linear focus Fresnel lenses as a concentrator, no experimental test was carried out as part of in this work due to lack of sun in United Kingdom.

3.5. Research Methodology

The main objective of this work was to investigate the performance of a solar still integrated with a ventilation fan and heat exchanger. The solar still was also constructed to apply Fresnel lenses as a dual sloping top cover in order to direct and concentrate solar radiation into the basin area.

A new packable shape single basin double slope solar still was designed and fabricated using plywood material (L1.2 m × W0.5 m× h 0.5 m). Productivity of the solar still were measured and tested with

different basin water temperatures under different operational conditions such as the presence of a ventilation fan, heat exchanger and heat storing material (Lava stone) on the basin area.

A theoretical and experimental study was directed to investigate the effect of fan flow rate with/without shroud (to avoid air turbulence in the unit) connected to the heat exchanger pipes, which sit on top of basin area to help vapour to change its phase to condense water while heat energy transfers to the basin water in addition with energy storing material (lava stone) on the performance of the solar still.

A theoretical model based on different authors (Cooper & Dunkle, Clark & Schrader's Model) was developed for both internal and external heat transfer. Evaporation, convective and radiative heat transfer coefficients are three types of heat transfer that are placed internally, and top, bottom and sides heat transfer coefficient are placed externally. Each of these terms are calculated separately to discover evaporation and condensation rate of solar still at different temperatures. The theoretical results of solar still yield then calculated in order to be comparable to experimental results.

The experimental results were compared with theoretical results obtained. As part of simulations, experimentally determined operational and metrological parameters were used. Based on results obtained, a case study was developed using available data to estimate productivity of solar still at Almeria (Spain) and Qeshm Island (Iran). These locations were selected as potential experimental outdoor locations to compare with the results achieved in the laboratory.

3.6. Research Structure

Figure 98 presents the structure of work in order to achieve the aim of this project.

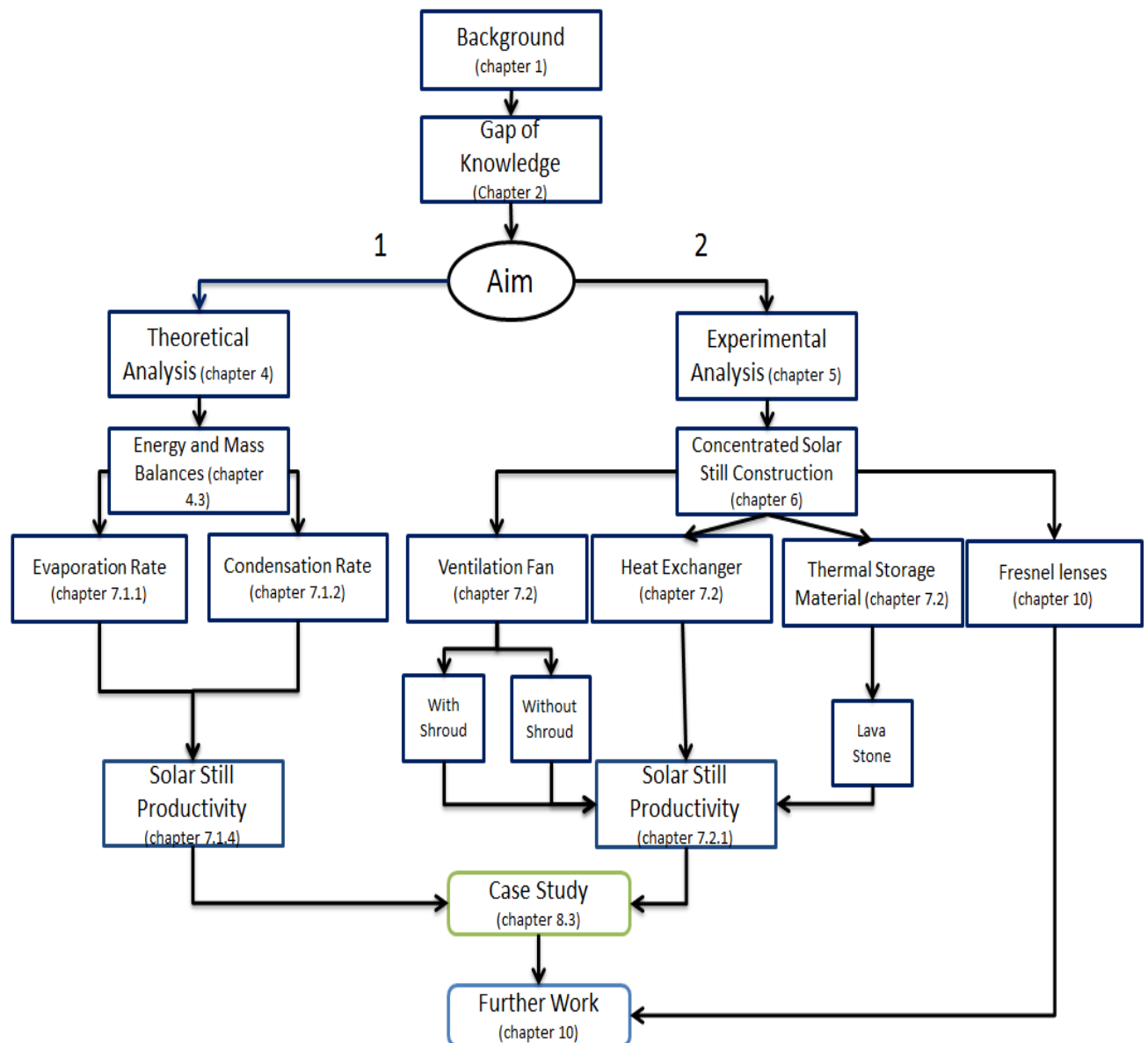


Figure 98: Flow chart illustrating the route to achieve the aim of the project

4. Thermal and Heat Principle of Solar Still

4.1. Solar Radiations

The earth, almost round in shape with a diameter of about 13,000 km, came into existence some 4.6×10^9 years ago [276]. The eruption of the volcanos generally occurs at plate boundaries of the earth. During eruption of the volcanos, various greenhouse gases, namely, carbon dioxide (CO_2), methane (CH_4), nitrous oxide (NO_x), ozone (O_3) and water vapour (H_2O) etc. available inside ground were discharged through the plate boundary. These discharge gases at boundary of the plate moved upwards towards the sun due to its low density. These gases formed a layer between the sun and earth. This layer is commonly stated to as the earth's atmosphere. Approximately 70% of the earth is covered by water and the remaining 30% is land. The earth reflects one-third of the sunlight that falls on to it. This is known as the earth's albedo. The earth is spinning about its axis at a constant rate. Its axis is inclined at an angle 23.5° . As a result, the length of day and nights keep changing.

The sun, which has an effective black body temperature T_s of $5,777^\circ\text{K}$, is the largest member of the solar system with other members revolving around it. The sun is a sphere of intensely hot gaseous matter with a diameter of 1.39×10^9 m and is, on an average 1.5×10^{11} m away from the earth [277].

Figure 99 shows the spectral distribution of the solar irradiance at the mean distance between the sun and earth is similar to the black body radiation at the temperature about $5,777^\circ\text{K}$. Additionally, the area under the curve is the solar constant (G^*), which is about 1.367 kW/m^2 .

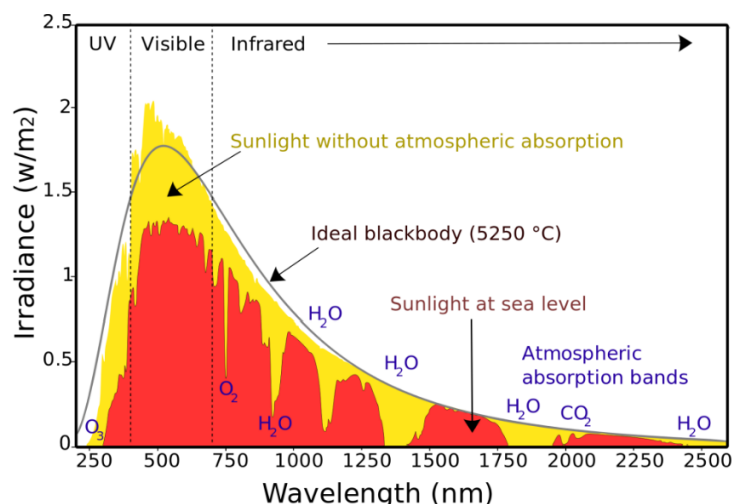


Figure 99: Spectral distributions of the solar irradiance at the earth [278]

Using a plane that directly faces the Sun and is located outside the atmosphere collects this value. Furthermore, the solar spectrum can be separated into three principal categories, the ultraviolet region, the visible region and the infrared region. The proportion of three sorts of spectral distribution can be seen in the table 11.

Table 11: The table shows different spectral distribution region together with their wavelength [279]

Region	Wavelength	Proportion of the irradiance
Ultraviolet	$\lambda < 0.40 \mu\text{m}$	8.73%
Visible	$0.40 \mu\text{m} < \lambda < 0.70 \mu\text{m}$	38.15%
Infrared	$\lambda > 0.70 \mu\text{m}$	53.12%

Solar radiations while passing through the earth's atmosphere are subjected to the mechanism of the atmospheric absorption and scattering. The X-rays and extreme ultraviolet radiations of the sun are absorbed highly in the ionosphere by nitrogen, oxygen and other atmospheric gases; ozone and water vapour largely absorb ultraviolet ($\lambda < 0.40 \mu\text{m}$) and infrared radiations ($\lambda > 2.3 \mu\text{m}$). There is almost complete absorption of short wave radiations ($\lambda < 0.29 \mu\text{m}$) in the atmosphere. Therefore, the energy in the wavelength radiation below $0.29 \mu\text{m}$ and above $2.3 \mu\text{m}$, of the spectra of the solar radiation, incident on earth's surface is insignificant.

The solar radiation, which is outside the earth atmosphere, is extra-terrestrial beam radiation. Below the atmosphere, the radiation is that observed at the earth's surface directly from the sun is known as the direct beam, and from other directions called the diffuse radiation, which can be seen in figure 100.

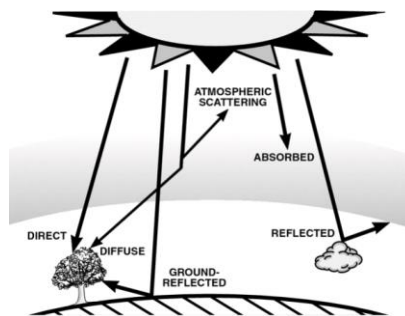


Figure 100: The total radiation on the Earth' surface has direct, scattered and reflective [280]

Since there are some molecules of the air or dust in the atmosphere, although on the clear sky or a cloudless day, there will be at least 10 percent of diffusion. As for the atmospheric effects, there are various kinds of effects on solar energy at the surface of the earth such as the absorption; scattering and reflection in the atmosphere can make the power of the solar radiation subside. Moreover, these situations can also affect the spectral content of the solar radiation for some wavelengths.

According to the figure 101, the Earth rotates twenty-four hours on its own axis, which is the line from drawn from the point N to S referred to the North Pole and the South Pole respectively.

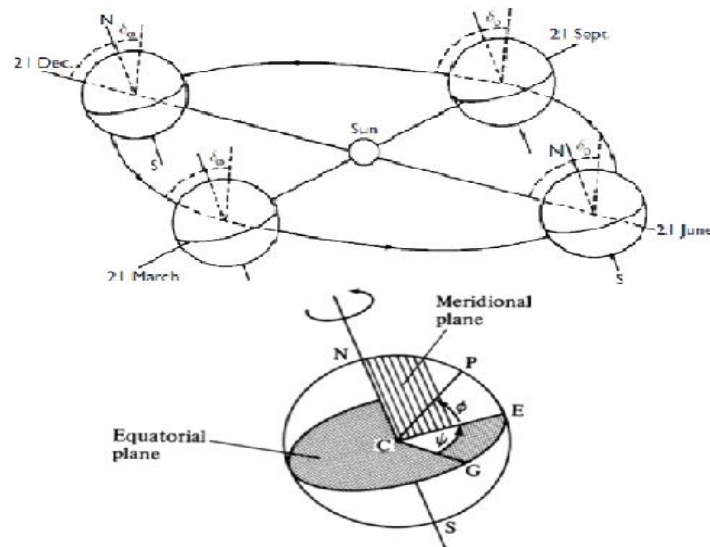


Figure 101: The earth revolving around the sun in a year with the sketch of latitude and longitude [281]

The axis (C) is perpendicular to the equatorial plain and passes through the middle of the Earth. The point P, which is located on the Earth's surface; can be described by its own latitude (Φ) and longitude (Ψ). The latitude will be positive, if we consider any points above the equator. Conversely, if the point is located under the equatorial plane, the latitude is negative. Turning to the longitude, it is measured positive eastwards from the Greenwich, U.K. and vice versa. The vertical plane that places from the north to south through the point P is usually called the local meridian plane. Additionally, the point E and G shares the similar longitude with the point P and the Greenwich respectively.

The hour angle (ω) at the point P is the angle through which the earth has to rotate to bring the meridian plane of any place or location under the sun. This angle continuously decreases from the sunrise to the noon; become zero at noon and then starts increasing when its value becomes positive. At sunset the hour angle is maximum positive and at sunrise it is maximum negative for any place. Therefore, the hour angle is the measure of the angular displacement of the sun through which the earth has to rotate to bring the meridian of the place directly under the sun. Thus, it is very clear that ω will vary with the time of the day.

The angle between an observer's (at a particular place on earth) meridian and the hour circle on which some celestial body lies is known as hour angle. This angle is conventionally expressed in units of time, which gives the time elapsed since celestial body's last transit at the observer's meridian (for positive hour angle), or the time expected for the next transit (for a negative hour angle). As the Earth rotates 360° in a day, twenty four hours, which means it rotates 15° in an hour.

At sunrise, the value of " ω " will be maximum; then slowly and steady reduce and keep on reducing with the passage of time till solar noon. At this point of time " ω " become zero. It starts increasing moment after solar noon and will be maximum at sunset. The values at the sunrise and sunset are numerically same but have opposite signs. The hour angle can be express as:

$$\omega = (15^\circ h^{-1})(t_{solar} - 12 \text{ hour}) \quad (1)$$

Where:

ω is the hour angle;

t_{solar} is the time solar (the local solar time).

Our planet orbits around the Sun, however, the axis of the Earth stays fixed in space, the δ_0 of which is 23.45° from the normal axis to the revolution plane (figure 102).

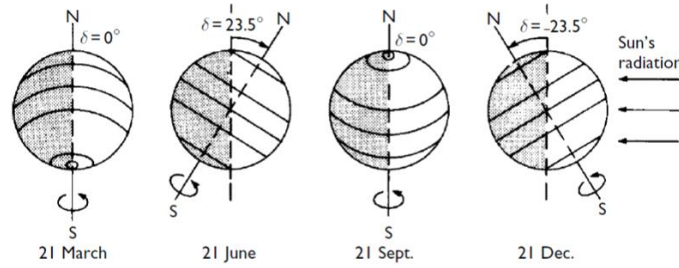


Figure 102: the earth observed from a point far along its orbit [281]

The angle between the equatorial plane and the Sun's direction is usually known as the declination (δ), which is changed throughout the year. Moreover, the line access that pass through the Sun to the centre of the Earth at the point P, this would make δ equal to Φ . For example, the inclination will have the same value as the latitude of any point when the Sun is precisely above at solar noon.

As can be seen in the pictures above, the inclination changes smoothly from $-\delta_0 = -23.45^\circ$ at northern midwinter, to $+\delta_0 = +23.45^\circ$ at midsummer in the upper hemisphere. In other word, the solar rays hit to the earth at a certain angle (-23.45° to $+23.45^\circ$) with respect to the equator. For any day, δ is taken as constant which changes on next day. Cooper's empirical relation for calculating the solar declination angle is [282]:

$$\delta = 23.45 \sin[(284 + n) \times \frac{360}{365}] \quad (2)$$

As 'n' is the daytime in the year, for instance, 'n' will equal to 1 on the first on January.

According to the figure 103, the angle between the horizontal and the plane surface is called the slope (β). For a surface heading towards the equator, the β is in the range between 0° and 90° , and for the surface heading away from the equator, the slope will be in the range from 90° and 180° .

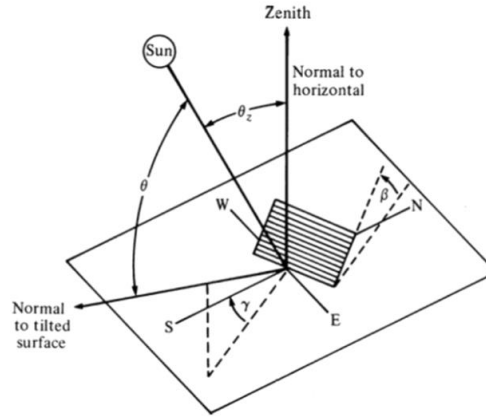


Figure 103: The geometry of solar panel and the solar beam [283]

The surface azimuth angle (γ) is the angle among the projected normal to the tilted surface and the local longitude meridian on the horizontal plate (figure 103). The azimuth angle will be 0° , if the panel faces to the south. The azimuth angle will equal to 180° , if the panel faces to the north. By facing the panel westwards, ' γ ' will be in the range between 0° to 180° , and If the panel facing eastwards, ' γ ' will be in the range between 0° to -180° . For a horizontal surface, the azimuth angle is constantly 0° .

Moving on to the angle of incidence (Θ), it is the angle between the normal to the tilted surface and the solar beam. Regarding the zenith angle or Θ_z , it is the angle between the vertical line and the solar beam. The relationship between each angle and the surface can be derived from the following equations :

$$\cos \theta = (A - B) \sin \delta + (C \sin \omega + (D + E) \cos \omega) \cos \delta \quad (3)$$

Where:

$$A = \sin \phi \cos \beta$$

$$B = \cos \phi \sin \beta \cos \gamma$$

$$C = \sin \beta \sin \gamma$$

$$D = \cos \phi \cos \beta$$

$$E = \sin \phi \sin \beta \cos \gamma$$

4.2. Heat and Mass Transfer of Solar Still

The heat transfer in the solar still unit can be classified as internal and external heat transfer. The internal heat transfer occurs within the solar still, which mainly consists of radiation, convection and evaporation (figure 104).

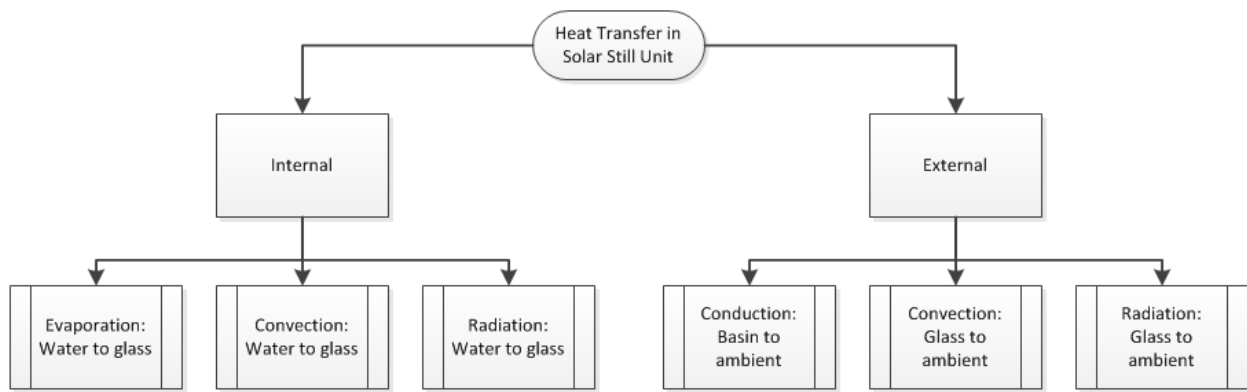


Figure 104: Classification of heat and mass transfer in a conventional solar still.

Within the solar still, heat transfer is accompanied by transport of the vapour formed above the water surface through an air-vapour mixture. Convective heat transfer occurs, simultaneously, with evaporation heat transfer and the two are independent of radiative heat transfer. Radiative heat transfer occurs within as well as outside solar still unit. The external heat transfer is mainly governed by conduction, convection and radiation processes, which are independent of each other. These external heat transfers occur outside the solar still from the glass cover and sides of insulation to ambient, and from bottom to ambient or ground depending, respectively, on whether the solar still unit is placed on a stand or on the ground.

The internal heat transfer is responsible for the transportation of pure water in vapour form leaving behind all the impurities in the basin, whereas, the external heat transfer through condensing cover is responsible for the condensation of pure vapour as distillate. Both of the heat transfers are most desired heat transfers in a solar still, But external heat transfer through the sides and bottom of a solar still is very undesirable.

The temperature difference, normally known as temperature gradient is the driving force for all the modes of heat transfer. The temperature difference between any hot surface and the fluid in contact with it cause density variation in the fluid above the surface, resulting in resistance. The motion of fluid above the surface, thus produced, called free or natural convection. However, if forces arise from externally imposed pressure difference, it is referred to as forced convection. These two process may, sometimes occur simultaneously.

The rate of heat transfer ($\dot{Q}$) by convection between a hot surface and reasonably cooled fluid in contact within the boundary layer is described by a general equation [284]:

$$\dot{Q} = h_c \cdot A \cdot \Delta T \quad (4)$$

Where:

“ $\dot{Q}$ ” is the convective heat transfer (W);

“ h_c ” is the convective heat transfer coefficient ($\text{Wm}^{-2} \text{ } ^\circ\text{C}^{-1}$);

“ A ” is the area of responsible for the heat transfer (m^2);

“ ΔT ” is the temperature difference between the fluid and inner surface of condensing cover ($^\circ\text{C}$).

Equation 4 appears to be simple, but the main problem sets in evaluation the convective heat transfer coefficient “ h_{cw} ”, which is a complicated function of the following parameters:

- a) Geometry of the surface;
- b) Flow characteristic of the fluid;
- c) Physical properties of the fluid at operating temperature;
- d) Operating temperature range.

In most practical cases, the heat transfer coefficient are evaluated from empirical relations obtained by correlation the experimental results using the method of *dimensional* analysis. However, the convective heat transfer is considered in terms of four dimensionless numbers, which are given as follows [285]:

- i. Nusselt number (Nu)

$$Nu = \frac{h_{cw}}{\left(\frac{k}{d}\right)} = \frac{\text{Convective heat transfer coefficient}}{\text{Conductive heat transfer coefficient}} \quad (5)$$

Where:

“ h_{cw} ” Convective heat transfer coefficient (W/m^2);

“ k ” is the thermal diffusivity ($\text{W/m}^\circ\text{C}$);

“ d ” is the fluid later of thickness (m^2).

The Nusselt (Nu) number characterizes the process of heat transfer at the solid-fluid boundary. It is the ratio of convective heat transfer to heat transfer by conduction in the fluid. This is also regarded as *non-dimensional* convective heat transfer coefficient. It is usually unknown in problems of convection, since it includes h_{cw} , which is an unknown parameter.

In order to understand the physical significant of “Nu” number, a fluid layer of thickness “ d ” and temperature-difference “ ΔT ” should be considered. Heat transfer through the fluid layer will be by convection when the fluid involves some motion (natural or forced) and by conduction when the fluid layer is motionless. Heat flux, which is the rate of heat transfer per unit time per unit surface area “ q ” (Wm^{-2}), in either case, will be:

$$\dot{q}_{conv} = h_{cw} \cdot \Delta T \quad (6)$$

$$\dot{q}_{cond} = \left(\frac{k}{d}\right) \cdot \Delta T \quad (7)$$

Taking ratio of equation 6 and 7, gives:

$$\frac{\dot{q}_{conv}}{\dot{q}_{cond}} = \frac{h_{cw} \cdot \Delta T}{\left(\frac{k}{d}\right) \cdot \Delta T} = \frac{h_{cw}}{\left(\frac{k}{d}\right)} = Nu \quad (8)$$

Thus, “Nu” number represents the enhancement of heat transfer through a fluid layer as a result of convection relative to conduction across the same fluid layer. The layer the “Nu” number, the more effective is the convection. Nu = 1 for a fluid layer represent heat transfer by pure conduction only.

ii. Grashof number (Gr)

$$Gr = \frac{g \cdot \beta \cdot d^3 \cdot \rho^2 \cdot \Delta T}{\mu^2} = \frac{\text{Buoyancy force}}{\text{Viscouse force}} \quad (9)$$

Where:

“g” is the acceleration due to earth gravity (m/s²);

“β” is the coefficient of thermal expansion (equal to approximately 1/T, for ideal gases) (1/°C);

“ρ” is the fluid density (kg/m³);

“μ” is the viscosity of fluid (Pa.s).

It represents the flow regime in natural convection. Low “Gr” number denotes laminar flow and a large value denotes turbulent flow in natural convection.

iii. Prandtl number (Pr)

$$Pr = \frac{\mu \cdot C_p}{k} = \frac{\text{Momentum diffusivity}}{\text{Thermal diffusivity}} \quad (10)$$

The “Pr” number provides a measure of relative effectiveness of momentum transport in the velocity boundary layer over the thermal energy transport in the thermal boundary layer by the diffusion mechanism. For gases, “Pr” number is near unity.

iv. Rayleigh’s number (Ra)

$$Ra = Gr \cdot Pr \quad (11)$$

In natural convection, transition in a boundary layer depends on the relative magnitude of the buoyancy and viscous forces in the fluid. It is correlated in terms “Ra” number, which is the product of “Gr” and “Pr” numbers, where “Gr” looks after the type of flow and “Pr” the type of fluid. The temperature dependent physical properties of vapour (humid air) used in equation 9 to 11 are given in table 12.

Table 12: Temperature dependent physical properties of vapour

Quantity	Symbol	Expression
Specific heat	C_p	$999.2 + 0.1434 \times T_v + 1.101 \times T_v^2 - 6.7581 \times 10^{-8} \times T_v^3$
Density	ρ	$353.44 / (T_v \times 273.15)$
Thermal conductivity	k	$0.0244 \times 0.7673 \times 10^{-4} \times T$
Viscosity	μ	$1.718 \times 10^{-5} + 4.620 \times 10^{-8} \times T_v$
Latent heat of vaporization of water	L	$3.1615 \times 10^6 \times [1 - (7.616 \times 10^{-4} \times T_v)]; \text{ for } T_v > 70^\circ\text{C}$ $2.4935 \times 10^6 \times [1 - 9.4779 \times 10^{-4} \times T_v + 1.3132 \times 10^{-7} \times T_v^2 - 4.7974 \times 10^{-9} \times T_v^3]; \text{ for } T_v < 70^\circ\text{C}$
Partial saturated vapour pressure at condensing cover temperature	P_{ci}	$\exp[25.317 - \frac{5144}{T_{ci} + 273}]$
Partial saturated vapour pressure at water temperature	P_w	$\exp[25.317 - \frac{5144}{(T_w + 273)}]$
Expansion factor	β	$1 / (T_v + 273.15)$

4.2.1. Internal Heat Transfer

4.2.1.1. Evaporation Heat Transfer

1. Cooper and Dunkle Model

The mass of air transferred per unit area per unit time by free convection is given by [285], [286]:

$$M_a = \frac{q_{cw}}{C_{pa}(T_w - T_{ci})} = \frac{h_{cw}}{C_{pa}} \quad (12)$$

It is assumed that the air next to water surface is saturated at the water temperature and, therefore, the specific humidity (or mass of water per mass of dry air) may be written as:

$$\frac{M_w}{M_a} \cdot \frac{P_w}{P_t - P_w} \quad (13)$$

Thus, the mass of water vapour transferred per unit area per unit time from the water surface is:

$$\frac{M_w}{M_a} \cdot \frac{P_w}{(P_t - P_w)} \cdot \frac{h_{cw}}{C_{pa}} \quad (14)$$

Similarly, the mass of water vapour transferred per unit area per unit time from the glass surface is given by:

$$\frac{M_w}{M_a} \cdot \frac{P_{ci}}{(P_t - P_w)} \cdot \frac{h_{cw}}{C_{pa}} \quad (15)$$

Baum [287] found that the bulk of the air did not have any significant rate of exchange of water vapour with the boundary layers at the water and glass surface, so the net mass of water vapour transferred per unit area per unit time is given by the difference equations 14 and 15.

$$\frac{M_w}{M_a} \cdot \frac{h_{cw}}{C_{pa}} \cdot \left[\frac{P_w}{P_T - P_w} - \frac{P_{ci}}{P_T - P_{ci}} \right] \quad (16)$$

The rate at which heat is transferred from the water surface to the glass cover on account of the mass transfer of the water is:

$$q_{ew} = \frac{M_w}{M_a} \cdot \frac{(P_w - P_{ci})}{C_{pa}} \cdot L \cdot h_{cw} \cdot \frac{P_T}{(P_T - P_w)(P_T - P_{ci})} = h_{ew} \cdot (P_w - P_{ci}) \quad (17)$$

In practical situation, the values “ P_w ” and “ P_g ” are considerably smaller as compared to the values of “ P_T ” and, therefore, it is justified to assume that $(P_T - P_w)(P_T - P_{ci})$ is approximately equal to “ P_T^2 ”. The equivalent mass transfer coefficient “ h_{ew} ” may then be written in terms of heat transfer coefficient “ h_{cw} ” as:

$$\frac{h_{ew}}{h_{cw}} = \frac{L}{C_{pa}} \cdot \frac{M_w}{M_a} \cdot \frac{1}{P_T} \quad (18)$$

Equation 18 can also be obtained from Lewis relation [288].

$$\frac{h_{cw}}{h_D \rho_a C_{pa}} = 1 \quad (19)$$

In other word, the ratio of the heat transfer coefficient to mass transfer coefficient is equal to the specific heat per unit volume at constant pressure of the mixture. “ h_D ” is defined as the mass transfer rate per unit area from the water surface is:

$$\frac{\dot{m}}{A} = h_D (\rho_w - \rho_a) \quad (20)$$

Where “ $\dot{m}$ ” is the mass transfer rate (kg/h), “ h_D ” the mass transfer coefficient (kg h⁻¹ m²/kgm³) and “ ρ ” the partial mass density of water vapour (kgm⁻³).

Using the perfect gas equation ($P \cdot V = R \cdot T$, $V = M/\rho$) for water vapour and substituting h_D from equation 19 to equation 20 give:

$$\frac{\dot{m}}{A} = \frac{h_{cw}}{\rho_a C_{pa}} \cdot \frac{M_w}{R \hat{T}} \cdot (\rho_w - \rho_a) \quad (21)$$

It has been assumed that $\hat{T} \approx T'_w \approx \hat{T}_a$, which is reasonable approximation. Now, the amount of heat transferred on account of the mass transfer of the water vapour per unit area per unit time is:

$$q_{ew} = \frac{\dot{m}L}{A} = L \cdot \frac{h_{cw}}{\rho_a C_{pa}} \cdot \frac{M_w}{R \hat{T}} \cdot (\rho_w - \rho_a) = h_{ew} (\rho_w - \rho_a)$$

Where:
$$\frac{h_{ew}}{h_{cw}} = \frac{L}{\rho_a c_{pa}} \frac{M_w}{R\hat{T}}$$

Using the perfect gas equation for air:

$$R\hat{T} = \frac{M_a P_a}{\rho_a} \quad (P_a = \text{atmospheric pressure})$$

$$\frac{h_{ew}}{h_{cw}} = \frac{L}{\rho_a c_{pa}} \cdot \frac{M_w}{R\hat{T}} \cdot \frac{1}{P_T} \quad (22)$$

Since $P_T \approx P_a$ for small “ P_w ”, discussed earlier, the equation 22 is identical to equation 18. Substituting the appropriate values for different parameters yields [289]:

$$h_{ew} = 0.013 h_{cw} \quad (23)$$

It must be remembered that in the formulation of equations 12 to 23, the vapour assumed to obey the perfect gas equation and, consequently, the gas constant “R” is a universal constant.

The value of “ h_{ew}/h_{cw} ” given by equation 23. The value of “0.013”, is smaller than the value obtained by Bown and Dunkle [290]. This is due to the approximation made earlier in expanding the factor $(P_T - P_w) \cdot (P_T - P_g)$ and neglecting terms involving “ P_w ” and “ P_g ”. The best representation of the mass heat transfer phenomena is obtained if the value of “ h_{ew}/h_{cw} ” is taken to be 16.273×10^{-3} . Thus, the heat transfer per unit per unit time by evaporation from the water surface to the glass cover can be given by:

$$q_{ew} = 16.273 \times 10^{-3} \times h_{cw} (P_w - P_{ci}) \quad (24)$$

Or

$$h_{ew} = 0.016273 \times h_{cw} \times \left(\frac{P_w - P_{ci}}{T_w - T_{ci}} \right) \quad (25)$$

$$P_w = \exp \left[25.317 - \left(\frac{5144}{273 + T_w} \right) \right]$$

And

$$P_{ci} = \exp \left[25.317 - \left(\frac{5144}{273 + T_{ci}} \right) \right] \quad (26)$$

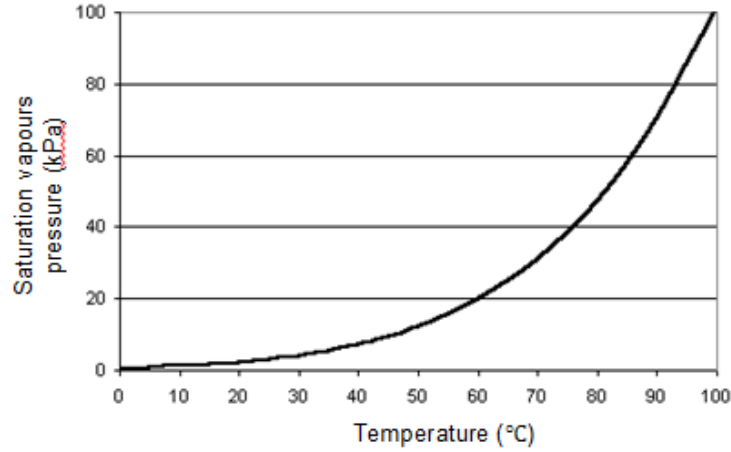


Figure 105: Various of saturation vapour pressure with temperature [291]

Equation 24 can also be written as:

$$\dot{q}_{ew} = h_{ew}(T_w - T_{ci}) \quad (27)$$

The rate of mass transfer $\dot{m}_e$ is given by:

$$\dot{m}_e = \frac{\dot{q}_{ew}}{L} \quad (28)$$

2. Clark and Schrader's Model

The rate of evaporation heat transfer from the water-air front to the front far away can be written by using the rate of evaporative mass flux in an air-water humidification situation as [292]:

$$\dot{q}_{ew} = \dot{k}h_{cw}(P_i - P_\infty) \quad (29)$$

Where “ P_i ” is the partial pressure of water at air-water front, “ P_∞ ” the partial pressure of water vapour far from the front, and “ $\dot{k}$ ” is a constant.

In case of solar still, it is justified to assume that the partial water vapour pressure at the water-air front is equal to the partial vapour pressure at water temperature i.e. $P_i \cong P_w$. Thus, equation 29 can be written as:

$$\dot{q}_{ew} = \dot{K}h_{cw}(P_w - P_\infty) \quad (30)$$

Similarly, condensation heat flux at vapour-glass interface can be written as:

$$\dot{q}_{cw} = \dot{K}h_{cw}(P_\infty - P_{ci}) \quad (31)$$

It is better to understand here that the glass cover is an interface far removed from the water-air interface discussed in equation 29. If the rate of evaporation is equal to the rate of condensation in a steady-state condition, then:

$$\dot{q}_{ew} = \dot{q}_{cw} \quad (32)$$

$$P_{\infty} = \frac{P_w + P_{ci}}{2} \quad (33)$$

Now, to find the rate of evaporation heat transfer, substitute the expression “ P_{∞} ” in equation 33 into equation 30 that it gives:

$$\dot{q}_{ew} = (\dot{K}/2)h_{cw}(P_w - P_{ci}) \quad (34)$$

Equation 34 is similar to equation 24 by Dunkle, with the only difference that “ $\dot{K}/2$ ” is half of “ $\dot{K}$ ” (=0.016). Equation 34 is generally valid when:

- a) Spacing between evaporating and condensing surface is large (more than 1 meter);
- b) Rate of evaporation and condensation are equal, which is only possible for high operating temperature range (> 80 °C) of the distillation system.

This condition is not valid with high operating temperature range and small spacing between the water and glass surface since the release of latent heat of vaporisation after vapour condensation at the inner surface of the glass cover is not immediately transferred from the glass cover to the ambient because of large heat capacity of the glass cover. The thicker the glass cover, higher is the heat capacity of the glass and higher will be the energy stored within it. In normal operating temperature range (10-45°C) and small spacing in comparison to the above situation, the approximations ($P_i = P_w$ and $P_{\infty} = P_g$) made by Dunkle are justified and, hence, equation 25-27 are valid for normal conditions.

Clark [293] has validated equation 34, experimentally, for operating temperature range greater than 55°C. He performed the experiments in an air conditioned room (20°C), which provides large heat transfer from the glass cover to the room ambient. This is normally not the situation in real operating conditions of solar distillation system under natural climatic conditions.

4.2.1.2. Convective Heat Transfer

1. Dunkle's Relation

Heat is transported across the bulk of humid air inside solar still, within the space between water surface and glass cover, by free convections. In free convection the fluid motion is caused by the action of buoyancy forces arising because of the density variations in the space that, in-turn, exists whenever there is a temperature gradient in the fluid. However, the forced convection arises due to externally applied pressure gradient.

The humid air that has transported the heat to the glass cover, releases its enthalpy to glass upon coming into contact, which is, comparatively, at a lower temperature. The coefficient of heat transfer is usually incorporated in the “Nu” number. In the case of heat transfer by free convection, the “Nu” number is related to the “Gr” and “Pr” numbers as follow:

$$Nu = f(Gr, Pr) \quad (35)$$

For heat flow from the horizontal water surface in the upward direction, i.e. against the forces of gravity, Jakob [294] has suggested the following relationship by correlating the experimental data of Mull and Reiher [295]:

$$Nu = C(Gr, Pr)^n \quad (36)$$

Equation 36 can be extended by considering equation 8 as follows:

$$Nu = \frac{h_{cw} \times d}{k} = C(Gr, Pr)^n \quad (37)$$

Here, “C” and “n” are constants, the values of which for various ranges of “Gr” numbers are given as follows [294]:

- a) For $Gr < 10^3$, $C = 1, n = 0$;
- b) For $10^4 < Gr < 3.2 \times 10^5$, $C = 0.21, n = 1/4$;
- c) For $3.2 \times 10^5 < Gr < 10^7$, $C = 0.075, n = 1/3$.

In case (a) above, the magnitude of convection is negligible. In case (b), the airflow is laminar and, in (c), airflow is in the turbulent command.

In the case of convective heat transfer by humid air in the presence of mass transfer of a fluid of lower molecular weight, i.e. water vapour, it becomes necessary to use Grashof number “ $\hat{Gr}$ ”. For non-isothermal evaporation as it has been shown by Sharpley and Boelter that [296]:

$$\hat{Gr} = \frac{x_1^3 \rho_f^2 g}{\mu_f^2} \left[\frac{M_\infty \hat{T}_o}{M_o \hat{T}_\infty} - 1 \right] \quad (38)$$

Where the subscripts “o” and “ ∞ ” refer to the condition, at the surface, at which the evaporation originated and to a point far away from the surface, respectively. The subscript “f” refers to air saturated with water vapour. For $M_\infty = M_o$ the term in brackets reduces to:

$$\hat{\beta} \Delta T; \hat{\beta} \approx \hat{T}_\infty^{-1}$$

Let subscript “w” and “a” refer to the diffusing (water vapour) and inert (air) gases, respectively. Assuming these to be ideal gases, which is a necessary condition for the modified equation 38, and remembering that $P_{w\infty} + P_{a\infty} = P_{wo} + P_{ao} = P_T$ (total gas pressure), we can obtain:

$$\begin{aligned} \frac{M_\infty \hat{T}_o}{M_o \hat{T}_\infty} - 1 &= \frac{M_\infty P_{w\infty} \hat{T}_o + M_a P_{a\infty} \hat{T}_o}{M_w P_{wo} \hat{T}_\infty + M_a P_{ao} \hat{T}_\infty} - 1 = \frac{M_\infty (P_{w\infty} \hat{T}_o - P_{wo} \hat{T}_\infty) + M_a (P_{a\infty} \hat{T}_o - P_{ao} \hat{T}_\infty)}{\hat{T}_\infty (M_w P_{wo} + M_a P_{ao})} = \\ &= \frac{(M_\infty P_{wo} + M_a (P_T - P_{wo})) (\hat{T}_o - \hat{T}_\infty) + (M_w - M_a) (P_{a\infty} - P_{ao}) \hat{T}_o}{\hat{T}_\infty (M_w P_{wo} + M_a (P_T - P_{wo}))} = \frac{\hat{T}_o - \hat{T}_\infty}{\hat{T}_\infty} + \frac{(M_w - M_a) (P_{a\infty} - P_{ao}) \hat{T}_o}{\hat{T}_\infty (M_w P_{wo} + M_a (P_T - P_{wo}))} \end{aligned} \quad (39)$$

For air water vapour system at normal atmospheric pressure [295]:

$$M_w = 18$$

$$M_a = 28.96$$

$$P_T = 98.07 \times 10^3 Pa$$

Substituting in equation 39, gives:

$$\frac{M_\infty \dot{T}_o}{M_o \dot{T}_\infty} - 1 = \frac{\dot{T}_o - \dot{T}_\infty}{\dot{T}_\infty} + \frac{(P_{wo} - P_{w\infty}) \dot{T}_o}{\dot{T}_\infty (268.91 \times 10^3 - P_{wo})} = \beta (\Delta T + \frac{(P_{a\infty} - P_{ao}) \dot{T}_o}{(268.91 \times 10^3 - P_{wo})}) = \beta \Delta \dot{T} \quad (40)$$

Where $\Delta \dot{T}$ is equivalent temperature difference, thus:

$$\dot{G}r = x_1^3 \rho_f^2 g \beta \Delta \dot{T} / \mu_f^2 \quad (41)$$

It is the same relationship used by Dunkle model. For a mean air temperature of 50°C, an equivalent temperature difference of 17°C and assuming saturated air, “ $\dot{G}r$ ” given by equation 41 is $2.81 \times 10^7 \times x_1^3$. Over the normal operating temperature range, for values of the mean water to cover spacing “ x_1 ” being too small, “ $\dot{G}r$ ” may be seen to lie in the range, for $C = 0.075$ and $n = 1/3$ in equation 37. For this value of exponent “ n ”, the length parameter conveniently cancels out so that the heat transfer coefficient becomes substantially independent of the spacing “ x_1 ”. Dunkle has chosen those values of the physical parameter (occurring in the dimensionless variables), which are applicable over the normal range of operation of the still, to arrive at the relation:

$$q_{cw} = 0.884 \left[T_w - T_{ci} + \frac{(P_w - P_{ci})(T_w + 273)}{(268.9 \times 10^3 - P_w)} \right]^{1/3} \cdot (T_w - T_{ci}) = h_{cw} (T_w - T_{ci}) \quad (42)$$

Where:

$$h_{cw} = 0.884 \left[T_w - T_{ci} + \frac{(P_w - P_{ci})(T_w + 273)}{(268.9 \times 10^3 - P_w)} \right]^{1/3} \quad (43)$$

2. Clark's Models

Within the enclosure of solar still these two heat transfers (convective and evaporative) take place simultaneously. As discussed in the working principle of solar distillation, the expressions derived with convective heat transfer coefficient “ h_{cw} ” (equation 43) and evaporative heat transfer coefficient “ h_{ew} ” (equation 25) have many limitations. This model with limitation is known as Dunkle model and uses the constants as for $C = 0.075$ and $n = 1/3$. Hence it is felt necessary to examine the validity of the Dunkle model at least for the conditions not falling within its limitation.

Clark [297], amongst others, had made attempts in this respect by conducting steady-state indoor experiments on a basin type solar still using a solar simulator. He pointed out that Dunkle's heat transfer model for such a still is valid but for an additional factor 1/2 (to account of saturation) that has to be introduced in the expression of evaporation heat transfer coefficient “ h_{ew} ”. The reason for introducing this factor was attributed to the fact that the rate of evaporation is equal to the rate of condensation in an ideal condition. This condition is achieved by using a fan across the condensing

cover. It is impracticable for solar distillation system, operating in actual field conditions. Based on steady-state experiments and their results, the following values of “C” and “n” were proposed for different “Gr” number ranges:

- i. $C = 0.21, n = 1/4$ for $10^4 < Gr < 2.5 \times 10^5$
- ii. $C = 0.1255, n = 1/3$ for $2.51 \times 10^5 < Gr < 10^7$

$$q_{ew} = \frac{k}{2} \cdot h_{cw} \cdot (P_w - P_{ci}) \quad (44)$$

Where $k = 0.016273$.

The equation 44 is generally valid when the spacing between evaporating and condensing surface is large and the rate of evaporation and condensation are equal, which is only possible for high operating temperature range ($> 80^\circ\text{C}$) of the distillation system.

Shawagfeh and Farid [298] did simulation studies to develop empirical relation based on the best fit. Their correlations provided expressions for convective heat transfer coefficients independent of solar geometry. A value of $n = 1/3$, as suggested by Dunkle, to account for turbulent flow inside solar still and reduced value of C (0.067) were used. All these correlations are developed for the steady-state conditions and indoor simulations. For a single slope solar still, Kumar and Tiwari [299] has proposed the values of $C = 0.0322$ and $n = 0.4144$ for $1.794 \times 10^6 < Gr < 5.724 \times 10^6$ using regression analysis by performing experiments in actual field conditions.

It is reported that the same values of “C” and “n” are used for the analysis of double slope solar still as well. However, the values of “C” and “n” proposed for single slope solar stills are not valid for double slope solar still due to the following reasons:

1. There are two condensing surfaces for one evaporating surface in double slope solar still.
2. Temperature of both the condensing surfaces are different at any given point time.
3. The solar intensity falling on both condensing surfaces are also different at any given point time.

Taking these facts into account, Shruti [300] has made an attempt to develop a thermal model and its experimental validation for evaluating “C” and “n” with the help of regression analysis for the following, conventional single slope solar still, congenital double slope solar still, double condensing chamber solar still and active single slope solar still.

The methodology used by Tiwari and Suneja [301] and Kumar and Tiwari [299] for evaluating “C” and “n” is as follows:

Substituting “ h_{cw} ” from equation 37 into equation 25 and substituting “ q_{ew} ” from equation 26, equation 28 becomes:

$$\dot{m}_w = 0.0163 (P_w - P_{ci}) \left(\frac{k}{d}\right) \left(\frac{3600}{L}\right) C. (Ra)^n \quad (45)$$

Where $Ra = Gr.Pr.$

Equation 45 can be rewritten as:

$$\dot{m}_w = R.C. (Ra)^n \quad (46)$$

Or

$$\frac{\dot{m}_w}{R} = C. (Ra)^n \quad (47)$$

$$\text{Where } R = 0.0163 (P_w - P_{ci}) \left(\frac{k}{d}\right) \left(\frac{3600}{L}\right) \quad (48)$$

Equation 47 can be rewritten as:

$$y = a.x^b \quad (49)$$

Where

$$y = \frac{\dot{m}_w}{R}; x = Ra; a = C; b = n$$

Equation 49 can be reduced into an equation of straight line by taking log on both the sides.

$$\ln(y) = \ln(a) + b.\ln(x) \quad (50)$$

Or

$$\hat{y} = \hat{a} + \hat{b}.\hat{x} \quad (51)$$

Where

$$y = \ln(y); \hat{a} = \ln(a); \hat{b} = b; \hat{x} = \ln(x)$$

From equation 51, values of coefficient “ $\hat{a}$ ” and “ $\hat{b}$ ” are calculated by using linear regression analysis.

The expressions for “ $\hat{a}$ ” and “ $\hat{b}$ ” are given by:

$$\hat{b} = \frac{N(\sum \hat{x}.\hat{y}) - (\sum \hat{x}).(\sum \hat{y})}{N(\sum \hat{x}^2) - (\sum \hat{x})^2} \quad (52)$$

$$\hat{a} = \frac{(\sum \hat{y})}{N} - \hat{b} \frac{(\sum \hat{x})}{N} \quad (53)$$

Where “ N ” is the number of experimental observations. From equations 52 and 53, after knowing “ $\hat{a}$ ” and “ $\hat{b}$ ” we can get “ C ” and “ n ” by the expressions:

$$C = \exp(\hat{a}) \quad (54)$$

And

$$n = \hat{b} \quad (55)$$

The values of “ C ” and “ n ”, proposed and tested, take into account the following, which have not been considered explicitly in previous models:

- Effect of solar cavity;
- Operating temperature ranges;
- Orientations of the condensing covers.

It can be concluded that in order to predict the performance of solar still precisely, evaluation of “ C ” and “ n ” values are very essential. The values of “ C ” and “ n ” evaluated under simulated conditions are no longer valid for the still operating in the actual field conditions. This is due to the fact that in the laboratory conditions variations of climatic parameters are under human control, whereas, the same condition is not true for actual operating condition of the solar still at the users end.

The analysis of Shruti [302] strongly supported that there is definite need for estimation of convective mass transfer for each type of solar still to predict their performance in the actual field conditions. The values of “ C ” and “ n ” differ for different shape of condensing cover and operating temperature range. Hence, use of any given standard values of “ C ” and “ n ” evaluated under simulated conditions will result in invalid results. Therefore, it is recommended that before predicting the performance theoretically, experiments must be carried out on a particular model of still for given climatic conditions to evaluate the value of “ C ” and “ n ” from the thermal models. Thus, the values of “ C ” and “ n ” experimentally from equations 54 and 55, respectively, without any limitations, “ h_{cw} ” and “ h_{ew} ” can be obtained by:

$$h_{cw} = \left(\frac{k}{d}\right) \cdot C \cdot (Gr \cdot Pr)^n \quad (56)$$

And

$$h_{ew} = \left(\frac{\dot{q}_{ew}}{(T_w - T_{cl}) \times 3600}\right) \quad (57)$$

4.2.1.3. Convective Heat Transfer from Basin Linear to Water

The convective heat transfer coefficient for heat flow from the horizontal basin liner (hottest region in the still) to the water mass in the basin, and vice versa is determined from the following relation [303]:

$$Nu = \frac{h_3 x_1}{k_f} = C \cdot (Gr \cdot Pr)^n \quad (58)$$

The values of “ C ” and “ n ” in equation 58 for different cases are as follows:

$$C = 0.54, n = \frac{1}{4}, \text{upward direction of heat flow (hot surface facing upward)}$$

$$C = 0.27, n = \frac{1}{4}, \text{downward direction of heat flow (hot surface facing downward)}$$

By substituting the values of “Nu”, “Gr” and “Pr”, the convective heat transfer coefficient “ h_3 ” between basin liner and water (upward) can be written as:

$$h_3 = \frac{0.54k_f}{x_1} \left[\frac{x_1^3 \rho_f^2 g \beta \Delta T}{\mu_f^2} \times \frac{c_{pf} \mu_f}{k_f} \right]^{1/4} \quad (59)$$

The unit of “ h_3 ” is in $W/m^2^\circ C$.

4.2.1.4. Radiative Heat Transfer Coefficient

In order to understand radiative heat transfer, the surface of water as well as glass cover of solar still is treated as the case of infinite parallel planes. The validity of this consideration is justified because of the small inclination of glass cover and larger width of distiller unit. The rate of radiative heat transfer “ $\dot{q}_{rw}$ ” (W/m^2) from the water surface to glass cover for the considered infinite parallel planes is given by:

$$\dot{q}_{rw} = \varepsilon_{eff} \cdot F_{12} \cdot \sigma [(T_w + 273)^4 - (T_{ci} + 273)^4] \quad (60)$$

Or

$$\dot{q}_{rw} = h_{rw} \cdot F_{12} \cdot [T_w + T_{ci}] \quad (61)$$

Where “ F_{12} ” is the view factor that is considered unity for the glass cover inclination, being small. For large inclination of glass cover, the view factor is not unity. Therefore, the radiative heat transfer coefficient “ h_{rw} ” from the water surface to the glass cover can be expressed as:

$$h_{rw} = \varepsilon_{eff} \cdot \sigma \cdot [(T_w + 273)^2 + (T_{ci} + 273)^2] \cdot [T_w + T_{ci} + 546] \quad (62)$$

Where

$$\frac{1}{\varepsilon_{eff}} = \frac{1}{\varepsilon_w} + \frac{1}{\varepsilon_g} - 1 \quad (63)$$

The value of “ h_{rw} ” is almost independent of temperature for normal operation temperature range ($< 80^\circ C$) and varies between 7 and 10 $W/m^2^\circ C$.

4.2.1.5. Total Internal Heat Transfer

The total internal heat transfer coefficient is the combination of convective, evaporative and radiative heat transfer coefficient from water surface to inner surface of condensing cover. Its expression is given by [304]:

$$h_{1w} = h_{cw} + h_{ew} + h_{rw} \quad (64)$$

Where “ h_{cw} ”, “ h_{ew} ” and “ h_{rw} ”, respectively, are given by equations 56, 57 and 62. The absolute value of the total rate of internal energy transfer from water to the glass can be obtained by the summation of all heat transfer rates between the two. This includes summation of evaporative,

convective and radiative rates of heat transfer. This is obtained by the addition of the corresponding values of respective heat transfers obtained by equations 17, 42 and 61. Thus,

$$\dot{Q}_1 = \dot{Q}_{cw} + \dot{Q}_{ew} + \dot{Q}_{rw} \quad (65)$$

The relative significance of these three modes of heat transfer can be better understood by the energy fractions of each mode. The heat transfer by each mode is expressed as a fraction of the total to understand the relative significance of the magnitudes of each mode of heat transfer. Thus, evaporative, convective and radiative energy fraction can be calculated by:

$$F_e = \frac{\dot{Q}_{ew}}{\dot{Q}_1}; F_c = \frac{\dot{Q}_{cw}}{\dot{Q}_1}; F_r = \frac{\dot{Q}_{rw}}{\dot{Q}_1} \quad (66)$$

Figure 106 shows the variation of these three energy fractions with respect to water temperature for indoor simulation as found by Cooper [305]:

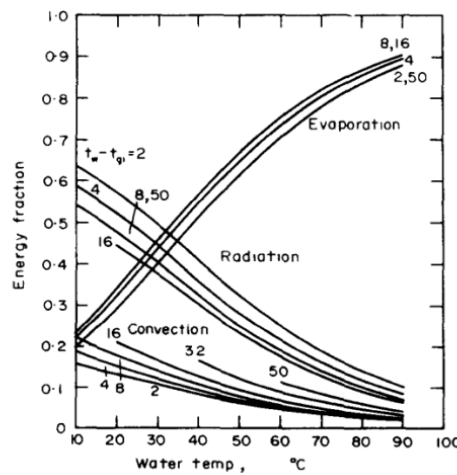


Figure 106: Variations of evaporative, convective and radiative energy fraction with respect to the water temperature as found by Cooper [305]

Effect of water depth on variation of three energy fractions (evaporative, convective and radiative) with respect to the water temperature is shown in figure 107.

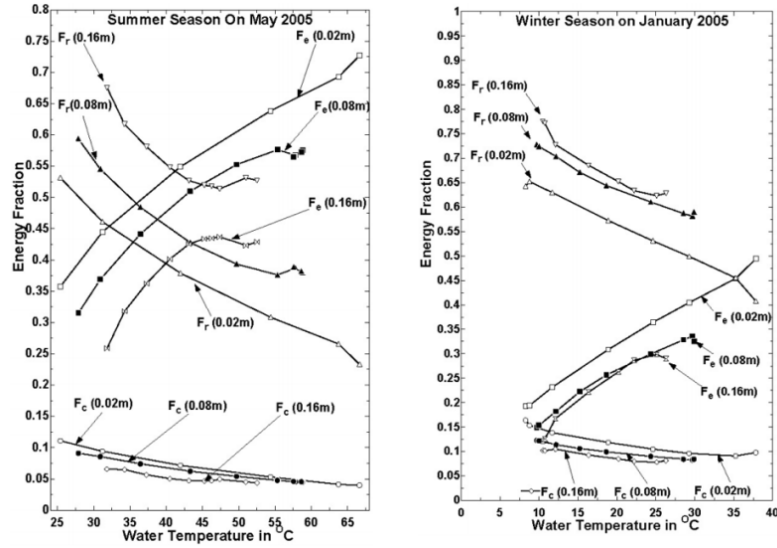


Figure 107: Variation of evaporative, convective and radiative energy fractions with respect to the water temperature as carried out by Cooper [304]

It is to be noted that the fraction increases when water depth decreases. Also, it can be noted that the water depth has more effect on radiative and evaporative fraction. The evaporative fraction dominates before water temperature range of 35-40°C and radiative fraction dominates after the same water temperature range.

4.2.1.6. Yield Calculation

The output from the solar still can be calculated by equation 28 after evaluating “ $\dot{q}_{ew}$ ”. The hourly distillate output (m^{-2}) from a distiller unit can be obtained as:

$$\dot{m}_{ew} = \frac{\dot{q}_{ew}}{L} \cdot 3600 = \frac{h_{ew}(T_w - T_{ci})}{L} \cdot 3600 \quad (67)$$

It is clear from equation 67 that the values of “ h_{ew} ”, “ T_w ” and “ T_{ci} ” must be known for calculating the amount of the hourly output. The expression for “ h_{ew} ” represented by equation 25 is used by many researchers to validate either their indoor simulation or outdoor field experimental observations. It is observed that most of the experimental results are good agreement with the theoretical results obtained. There are various available methods to evaluate “ h_{ew} ”, analytically and numerically, so that the use of equation 67 becomes straightforward.

4.2.2. External Heat Transfer

The heat transfer from the solar still to the atmosphere is known as external heat transfer. It is of two types: one is the heat transfer from the condensing cover made of glass to the ambient and another is from the body of the solar still to the ambient. The higher the former the higher will be the yield. The former is known as top heat loss whereas the latter is known as bottom and side loss.

3.2.2.1. Top Heat Loss Coefficient

The temperature of glass (condensing) cover is assumed to be uniform due to small thickness of the glass cover. The external radiative and convective losses from glass cover to outside atmosphere $\dot{q}_g (W/m^2)$ can be given by [143]:

$$\dot{q}_g = \dot{q}_{rg} + \dot{q}_{cg} \quad (68)$$

Where

$$\dot{q}_{rg} = \varepsilon_g \cdot \sigma \cdot [(T_g + 273)^4 - (T_{sky} + 273)^4] \quad (69)$$

Or

$$\dot{q}_{rg} = h_{rg} [T_g - T_a] \quad (70)$$

And

$$\dot{q}_{cg} = h_{cg} [T_g - T_a] \quad (71)$$

Where

$$h_{rg} = \frac{\varepsilon_g \cdot \sigma \cdot [(T_g + 273)^4 - (T_{sky} + 273)^4]}{[T_g - T_a]} \quad (72)$$

The $T_{sky} = T_a - 6$, $T_a = \text{ambient temperature } (^{\circ}\text{C})$.

Substituting equations 70 and 71, in equation 68, we get:

$$\dot{q}_g = h_{1g} [T_g - T_a] \quad (73)$$

Where

$$h_{1g} = h_{rg} + h_{cg} \quad (74)$$

The correlation for “ h_{1g} ” and “ h_{cg} ”, respectively, have been reported in following cases:

Case (i)

A direct expression for “ h_{1g} ” is given by:

$$h_{1g} = 5.7 + 3.8 \times v \quad (75)$$

Where v is the wind velocity parallel to the condensing surface, i.e. glass. The effect of radiation and free convection from the condensing cover has been considered in this expression.

Case (ii)

Calculating the value of “ h_{cg} ” and “ h_{rg} ”, separately, the evaluation of radiation and convection losses, i.e. “ h_{cg} ” and “ h_{rg} ” can be obtained. “ h_{rg} ” can be calculated from equation 72 and convective heat transfer coefficient h_{cg} can be obtained from:

$$h_{cg} = 2.8 + 3.0 \times v \quad (76)$$

In the expressions shown by equations 75 and 76, it has been observed that there is no significant change in the performance of the distillation system by considering “ h_{1g} ” as represented by case (i) or (ii).

Now, one can define the overall top loss coefficient U_t from the water surface to the ambient through the glass cover by combining the total internal heat loss coefficient “ h_{1w} ”, conductive heat transfer coefficient “ k_g/l_g ” of the glass and top loss coefficient “ h_{1g} ” from glass to the ambient. The expression for “ U_t ” is given by:

$$U_t = \left[\frac{1}{h_{1w}} + \frac{l_g}{k_g} + \frac{1}{h_{1g}} \right]^{-1} \quad (77)$$

Where “ l_g ” is the thickness of glass cover (m) and “ k_g ” thermal conductivity of glass ($W/m^\circ C$).

3.2.2.2. Bottom and Sides Loss Coefficient

The heat is lost or transferred from the water mass in basin to ambient through the insulated walls and from the basin liner to ambient through the insulated bottom. In case of solar still mounted on stand, the bottom and side heat losses occur in sequence- first convection, then conduction and, finally, convection- and radiation losses to the ambient. However, in case of grounded solar still the bottom heat loss is first in the form of convection and then conduction only. Hence, the bottom heat transfer coefficient U_b from water mass to the ambient through the bottom can be written as [143]:

$$U_b = \left[\frac{1}{h_3} + \frac{1}{k_i/l_i} + \frac{1}{h_{rb}} \right]^{-1} \quad (78)$$

Or

$$U_b = \left[\frac{1}{h_3} + \frac{1}{h_b} \right]^{-1} \quad (79)$$

Where

$$h_b = \left[\frac{1}{k_i/l_i} + \frac{1}{h_{cb} + h_{rb}} \right]^{-1} \quad (80)$$

Hence “ l_i ”, “ k_i ”, “ h_{cb} ”, “ h_{rb} ” and “ h_3 ” are thickness and thermal conductivity of the insulation/body material, convective and radiative heat transfer coefficients from bottom to ambient and convective heat transfer coefficient between basin liner and water mass, respectively.

It is pertinent to mention here that the marginal change in the value of “ h_3 ” has no significant effect as far as the performance of the solar still is concerned. In equation 79, if the contribution from first and last terms is not significant the heat transfer can be considered only by conduction through the bottom of the solar still and it can be approximated as:

$$U_b = \left(\frac{k_t}{l_t}\right) \quad (81)$$

Similarly, the loss through vertical walls of the still that can be called as edge or side loss is also, mainly, caused by conduction through the insulation/body of still and can be written as:

$$U_s = \left(\frac{A_{ss}}{A_s}\right) \cdot U_b \quad (82)$$

Where “ A_s ” is the basin area (m^2) and “ A_{ss} ” the sides area in contact with water mass (m^2).

If “ A_{ss} ” is very small in comparison to “ A_s ”, for lower water depth, “ U_s ” can be neglected in the energy balance equation for water mass. In general, total bottom and sides loss coefficient from water to ambient can be given by:

$$U_{bs} = U_b + U_s \quad (83)$$

The overall heat transfer coefficient from water to ambient through top, bottom and sides can be given by:

$$U_L = U_t + U_{bs} \quad (84)$$

Where, “ U_t ” and “ U_{bs} ” are given by the equations 77 and 83, respectively.

4.3. Heat Transfer Mechanisms in a Solar Still

Thermal modelling of solar distillation system is based on energy balance equation for each component of distillation unit, namely, glass cover, water mass and basin liner. These energy balances mainly depends on the design and climatic parameters of distiller unit. The design parameters are as follows:

- i. The thickness of glass cover and insulating material;
- ii. Absorptivity of glass cover and basin liner;
- iii. Heat capacity of glass cover, absorbing surface and water mass;
- iv. Reflectivity of glass cover, water surface and basin liner surface;
- v. Quality of water to be distilled.

The climatic parameters mainly depend on the following locations:

- i. Solar radiations;
- ii. Ambient temperature;

- iii. Wind velocity;
- iv. Sunshine (day length) hours.

By thermal modelling, we can design a solar distiller unit for a given capacity. Thermal modelling can be used to make a decision regarding shape of distiller unit for maximum yield as per requirement.

4.3.1. Working Principle

Figure 108 shows various components of energy balance and thermal energy loss in a conventional solar distiller unit. It is an airtight basin, usually constructed of concrete/cement, galvanized iron sheet (GI) or fibre reinforced plastic (FRP) with top cover of transparent material like glass, plastic etc.

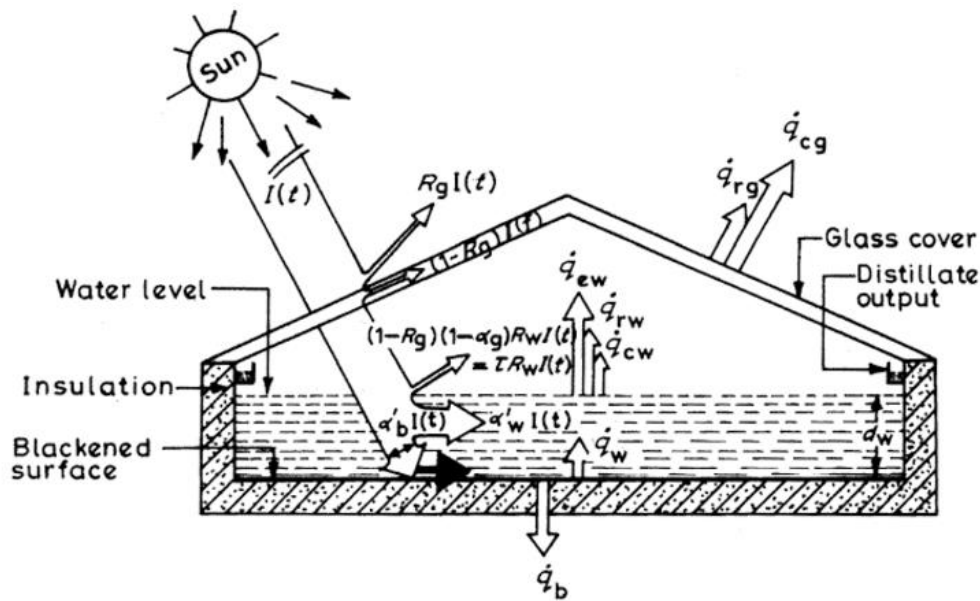


Figure 108: Energy flow diagram of conventional solar still [55]

The inner surface of the rectangular base is blackened to efficiently absorb the solar radiation, incident at the surface. There is a provision to collect the distillate at lower end of the glass cover. The brackish or saline water is fed into the basin for purification. The working principle of distiller unit in terms of energy flow is discussed as follows.

The solar radiation, after reflection and absorption by the glass cover is transmitted inside an enclosure of the distiller unit. The transmitted radiation ($\tau_g I(t)$) is further partially reflected ($\dot{R}_w I(t)$) and absorbed ($\dot{\alpha}_w I(t)$) by the water mass. The attenuation of solar flux in water mass depends on its absorptivity and depth. Finally, the solar radiation reaches the blackened surface where it is mostly absorbed. Following absorption of solar radiation at the blackened surface, generally known as the basin liner, most of the thermal energy is converted to water mass and a small quantity is lost to the atmosphere by conduction. Consequently, the water gets heated, leading to an increased difference of water and glass cover temperature. There are basically three modes of heat transfer, radiation (q_{rw}), convection (q_{cw}) and evaporation (q_{ew}) from the water surface to the glass cover. The evaporated

water gets condensed on the inner surface of the glass cover after releasing the latent heat. The condensed water tickles into the channels provided at the lower ends of glass cover, under gravity force. The collected water in the channel is taken out of the system for further use. The thermal energy received by the glass cover, through radiation, convection and latent heat, is lost to the ambient by radiation and convection.

The fraction of solar flux, at different components of the distiller unit is shown in figure 108 and can be mathematically expressed as [306]:

Solar flux absorbed by the glass cover:

$$\dot{\alpha}_g = (1 - R_g)\alpha_g \quad (85)$$

Solar flux reflected by the water mass:

$$\dot{R}_w = (1 - R_g)(1 - \alpha_g)R_w \quad (86)$$

Solar flux absorbed by the water mass:

$$\dot{\alpha}_w = (1 - \alpha_g)(1 - R_g)(1 - R_w)\alpha_w \quad (87)$$

Solar flux absorbed by the basin liner:

$$\dot{\alpha}_b = \alpha_b(1 - R_g)(1 - \alpha_g)(1 - R_w)(1 - \alpha_w) \quad (88)$$

Solar Flux lost to the ambient, through water and glass cover will be:

$$(1 - \alpha_b)(1 - R_g)(1 - \alpha_g)(1 - R_w)(1 - \alpha_w) \quad (89)$$

If however, attenuation of solar flux within the water mass is considered, then equation 87 to 89 becomes:

Solar flux absorbed by the water mass:

$$\dot{\alpha}_w = (1 - R_g)(1 - \alpha_g)(1 - R_w)[1 - \sum \mu_j \exp(-\eta_j d_w)] \quad (90)$$

Solar flux absorbed by the basin liner:

$$\dot{\alpha}_b = \alpha_b(1 - R_g)(1 - \alpha_g)(1 - R_w) \sum \mu_j \exp(-\eta_j d_w) \quad (91)$$

Therefore, energy lost to the ambient, through water mass and glass cover:

$$(1 - \alpha_b)(1 - R_g)(1 - \alpha_g)(1 - R_w) \sum \mu_j \exp(-\eta_j d_w) \quad (92)$$

The basin heat flux components at various points have been shown in figure 104. The following assumptions are made in writing the energy balance in terms of J/s/m²:

- i. There is no vapour leakage in the solar still;
- ii. The water mass in the solar still basin is assumed to be constant;

- iii. The evaporative loss of water mass is negligible;
- iv. The temperature gradient along water mass depth is negligible;
- v. The heat capacity and absorbance of the glass cover and insulating material is negligible;
- vi. The inclination of the glass cover with horizontal is small;
- vii. The area of water surface, glass cover, and basin are equal.

The energy balance for different component of introduce solar still are as follow:

Glass cover

Rate of energy absorbed + Rate of energy received from water surface by radiation, convection and evaporation = Rate of energy lost to the air

$$\alpha_g I(t) + [\dot{q}_{rw} + \dot{q}_{cw} + \dot{q}_{ew}] = \dot{q}_{rg} + \dot{q}_{cg} \quad (93)$$

Water mass

Rate of energy absorbed + Rate of energy converted from basin liner = Rate of energy stored + Rate of energy transferred to glass cover

$$\alpha_w I(t) + \dot{q}_b = (MC)_w \frac{dT_w}{dt} + [\dot{q}_{rw} + \dot{q}_{cw} + \dot{q}_{ew}] \quad (94)$$

Basin liner

Rate of energy absorbed + Rate of energy received from heat exchanger = Rate of energy transferred to the water + Rate of energy lost by conduction through bottom/sides

$$\alpha_b I(t) + \dot{q}_{hex} = \dot{q}_b + [\dot{q}_{bg} + \dot{q}_s(A_{ss}/A_s)] \quad (95)$$

Where “ α_g ”, “ α_w ” and “ α_b ” are given by equations 85, 87 and 88. The various $\dot{q}$'s in terms of respective heat transfer coefficient are given in section 2.6.2. The side area “ A_{ss} ” being very small in comparison to the basin liner area of solder still, hence the term “ A_{ss}/A_s ” can be neglected.

By substituting of the expressions for all $\dot{q}$'s, equations 96 to 97 can be rewritten as:

$$\alpha_g I(t) + h_{lw}(T_w - T_g) = h_{lg}(T_g - T_a) \quad (96)$$

$$\alpha_w I(t) + h_w(T_b - T_w) = (MC)_w \frac{dT_w}{dt} + (T_w - T_g) \quad (97)$$

$$\alpha_b I(t) = h_w(T_b - T_w) + h_b(T_b - T_a) \quad (98)$$

4.3.2. Thermal Efficiency of distiller Unit

The thermal efficiency of distiller unit can be defined as the ratio of the amount of thermal energy utilized to get certain amount of distilled water to the incident solar energy within given time interval.

If the evaporation process inside the distiller unit can be considered as an isobaric atmospheric process at thermal equilibrium, then all the absorbed solar radiation is utilized for evaporation thermal losses. An energy balance for steady state around the water basin can be written as [308]:

$$[\dot{\alpha}_w + \dot{\alpha}_b] I(t) A_s = \dot{Q}_{ew} + \dot{Q}_{losses} \quad (99)$$

$$(Rate\ of\ energy\ in) = (Rate\ of\ energy\ out)$$

Where $\dot{Q}_{ew} = \dot{m}_w L$, $\dot{Q}_{losses} = U_L (T_w - T_a) A_s$ and U_L is the overall heat transfer coefficient from water to the ambient through top, bottom and sides of the distiller unit. It is assumed that $(\dot{\alpha}_w + \dot{\alpha}_b) = (\alpha\tau)_w$.

Here in the Tamini model [309], $\dot{Q}_{losses}$ does not include evaporative heat loss. The analysis has been compared with that of flat-plate collector. However, it may be noted that in a flat-plate collector the upward losses should be minimum whereas in a solar still the upward losses should be maximum in order to get a higher yield. In the conventional solar still, to be discussed later, the radiative, convective and evaporative losses from the water to the condensing cover (glass) are grouped together and taken as the total internal heat transfer coefficient from water to glass.

Equation 93 can be rewritten as:

$$\dot{Q}_{ew} = \dot{m}_w L = (\alpha\tau)_w I(t) A_s - U_L (T_w - T_a) A_s \quad (100)$$

The expression for instantaneous efficiency η_i , can be given as [310]:

$$\eta_i = \frac{\dot{m}_w L}{I(t) A_s} = (\alpha\tau)_w - U_L \frac{(T_w - T_a)}{I(t)} \quad (101)$$

The overall thermal efficiency of the distiller unit in the passive modes of operation can be mathematically expressed as [310]:

$$\eta_{passive} = \frac{\sum \dot{m}_w L}{A_s \int I(t) dt} \times 100 \text{ (without storage effect)} \quad (102)$$

And

$$\eta_{passive} = \frac{\sum \dot{m}_w L}{\sum I(t) \times A_g + M_w \times C_w \times (T_{ini} - T_{amb})} \times 100 \text{ (with storage effect)} \quad (103)$$

5. Design and Construction of Double Slope Solar Still

The performance of a solar still is generally expressed as the quantity of water produced by basin surface area in a day. This amount varies due to, in order of importance, solar radiation available, ambient temperature, sky condition and atmosphere wind speed, which cannot be controlled as they are metrological parameters. Design parameters such as orientation of the solar still, area of absorber plate, inclination of glass cover, slopes of the cover, insulation materials, depth of water, inlet temperature of water and the temperature difference between the glass cover and basin water affect also the production rate.

The suggested approach described in following section 5.4 is to use a design based on solar water desalination while improving its low productivity in comparison with conventional solar stills while keeping it easy to operate at a reasonable cost as the main challenges for community scale desalination purposes in remote areas. The suggested strategies in the new design of the solar still are as follows:

1. Applying solar radiation concentrator to focus solar radiation into the solar still to speed up the evaporation process by directing radiation onto the basin inside the solar still. These novel solar stills should have a direct effect on still productivity (section 5.1).
2. Applying a ventilation fan to take out the evaporated water before it becomes saturated inside the solar still (section 5.2).
3. Applying heat exchanger pipes, from ventilation fan, to cool down evaporated water by passing it through the basin area. By using this method, the temperature of basin water increases (or reducing cooling rate) while the evaporated water inside the pipes condenses. This uses latent heat available in vapour water (section 5.3).

The average daily fresh water required per person is 20 litres per day (World Health Organisation [325]) including drinking, cooking and washing. Therefore, providing enough drinkable water for a community of 1,000 people necessitates a production of 20,000 litres per day. A conventional solar still has an average fresh water productivity of 5 litre/m² per day, thus the size of land it requires is approximately 12,000 m². Solar energy and brackish water are two main elements that are freely available to be used for desalination purposes in solar stills, consequently land requirement is one of the main capital costs that could be decreased by increasing the solar still productivity.

Based on the literature review and objectives of this research, a single basin double slope solar still was selected as the main concept of design that can be easily disassembled and carried around the globe to be tested with different environmental conditions. The laboratory scale concentrated solar

still (L1.2 m × W0.5 m× h 0.5 m) needed to be designed so as to increase its productivity in comparison with the conventional solar still.

5.1. Concentrated Solar Still Unit Concept Designs

Using solar concentrators to direct sun radiations into the solar still has one of the key modifications to solar still design to improve productivity. Selecting the best concentrator or reflector to deliver radiations area onto a small area of solar still basin has an important feature in terms of cost, construction, time and risks.

Selecting the best sun radiation concentrator is significant in solar still as it will act as a power supply generator for each single unit. There are mainly six concepts that can be used for a solar still. As any other system, each concept had advantages and disadvantages. The best concept was selected in terms of cost, maintenance, cleaning and productivity. Solar concentrating technologies in solar still can be divided into three main forms such as:

1. Fresnel lenses;
2. Mirrors and reflector;
3. Parabolic-through.

5.1.1. Fresnel Lenses

The top cover of a simple solar still is made of transparent material (i.e. glass) to pass the solar radiation to the basin water. In the field of concentrated solar energy applications, Fresnel lenses have recently been one of the preferred choices. Their advantages are small volume required, light-weight, and mass production with low cost as well as effectively increasing the energy density. There are two main types of Fresnel lens: imaging and non-imaging. Imaging Fresnel lenses use segments with curved cross-sections and produce sharp images, while non-imaging lenses have segments with flat cross-sections, and do not produce sharp images. Using non-imaging Fresnel lenses as cover of a solar still would direct sun radiation into the system, therefore the evaporation process and productivity would increase significantly.

Concept 1

Figure 109 illustrate solar still with line focus PMMA material Fresnel lenses as a top cover of solar still.

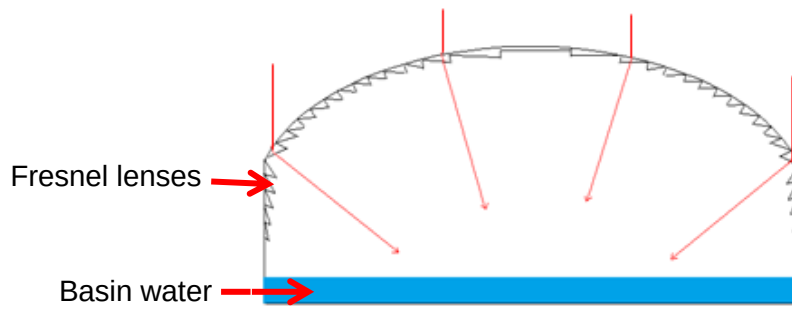


Figure 109: Direct concentrated solar still using Fresnel lenses.

Using this scheme, the weight of glass is reduced by using a plastic Fresnel lenses leading to a lighter structure. Therefore, the cost of structure support reduces by approximately 10-15%. However, the cost of Fresnel lenses is higher than normal transparent material such as glass. By using a top cover of Fresnel thin lenses, the sun can be tracked throughout the day without the complexity of moving mirrors (tracking system) commonly associated with large solar power unit. The temperature of basin water could be raised at a higher rate with this method than simple solar still. Therefore, the productivity, which is directly proportional to evaporation rate, would increase considerably.

Concept 2

In order to supply enough fresh water for small community, multiple solar still units have to be constructed. This causes shadows to sides of unit that has a direct impact on productivity. To minimize land requirement and avoiding shadows, compact mirrors or walls are suggested in this concept (figure 110).

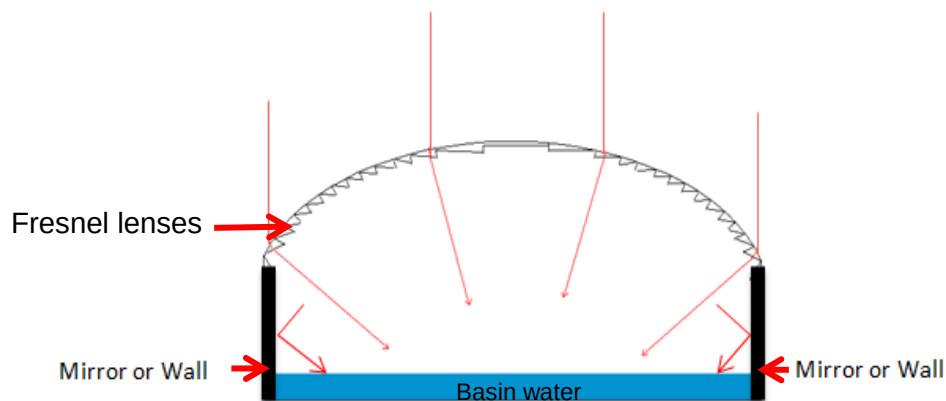


Figure 110: Using mirror or wall at side of Fresnel lenses solar still.

For this configuration, the capital cost of structure (side Fresnel lenses) could decrease slightly as side Fresnel lenses are replaced by mirrors or wall. By adding mirror at sides, the amount of loss of sun radiation directed into the system can be reduced; therefore it helps to increase productivity.

5.1.2. Mirrors and Reflector

Three additional concepts were developed using combination of Fresnel lens and reflectors (mirrors) as the top cover of the solar still. The main advantage of using reflectors is to direct more sun radiation into the basin water to accelerate evaporation process, while the main disadvantage is additional costs of structures and land area requirement. Using reflectors also requires large land area as they have to be installed next to the solar still and a tracking system. Therefore, these concepts are expected to be very costly with a lot more maintenance work.

Concept 3

The solar still has top and side reflectors (Figure 111), to direct surrounding sun radiation into the basin water.

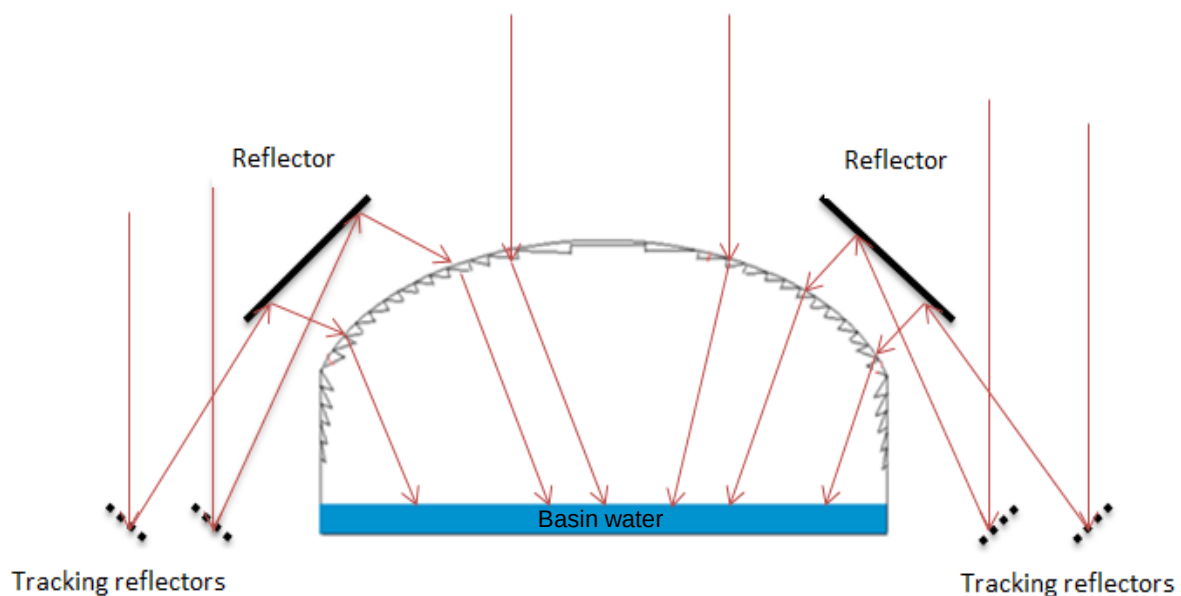


Figure 111: Using mirrors and reflector as concentrator factors in solar still.

Installing solar still with top and side reflector require large land area and lots of structural work that makes the capital cost increase significantly. However, a tracking system for the “side” reflectors is necessary to reflect the sun radiation onto the top reflectors to direct it to the basin water. It is a very complex system as it requires lots of structural work for reflectors. Maintenance and cleaning are other aspects that make this concept significantly costly to provide fresh water.

Concept 4

An additional disadvantage created by concept 3 is the shadow generated by top reflectors on the basin. Therefore to avoid making shadow, the solar still units can be raised from ground. Sides reflectors can be used to direct the surrounding sun radiation into the basin water as shown in figure 112.

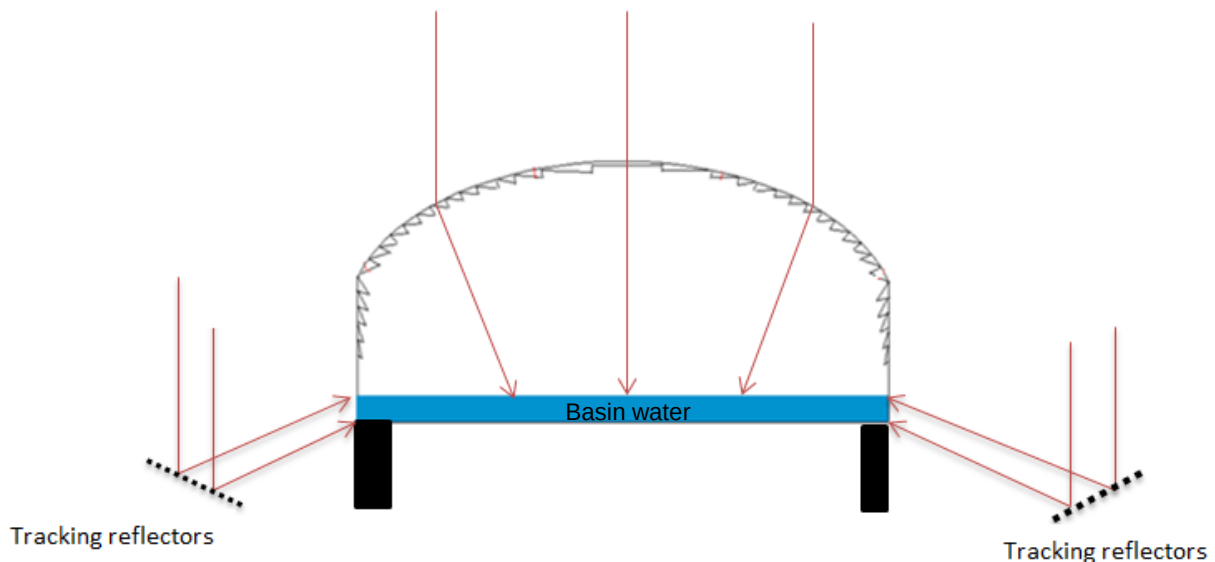


Figure 112: Using reflector to reflect the surrounding sun radiation into the lifted solar still

The basin water heats up by the sun's radiations transmit directly through the Fresnel lenses and reflect from the reflector at the side of system into the basin water. The amount and depth of water inside the basin has to be increased to allow larger side area to absorb the sun radiation coming from side reflectors. However, the structure costs increases significantly as the whole system (solar still unit) has to be lifted.

Concept 5

In order to reduce overall cost, small changes can be made to concept 4 while having a small effect on the water productivity as shown in figure 113.

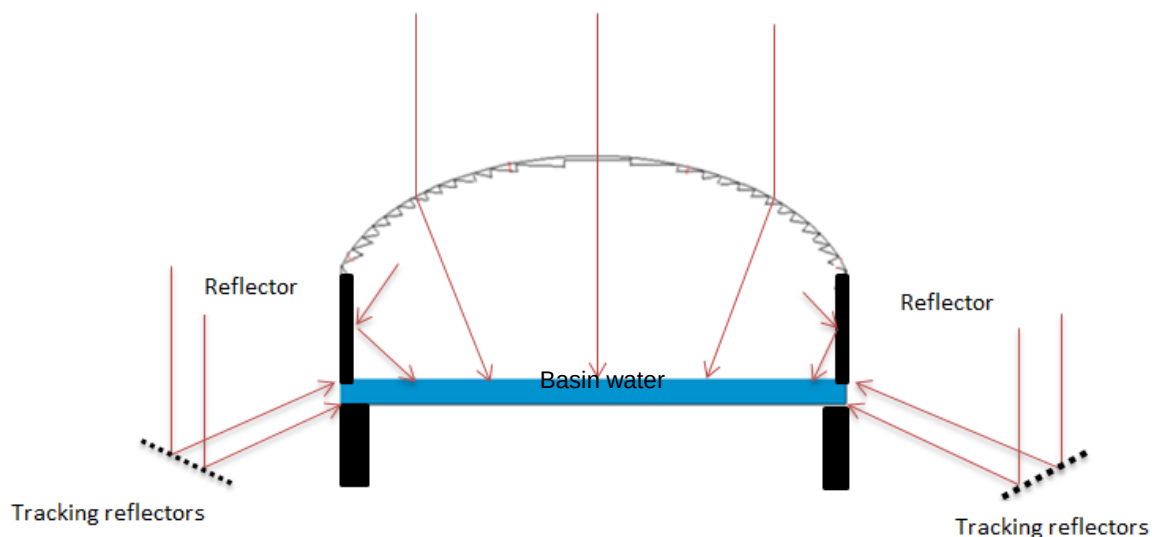


Figure 113: Using reflector at side to concentrate larger amount of solar radiation into the basin water.

While this concept solar still requires a lift up the solar still unit and using tracking reflectors on the sides, Fresnel lenses have been replaced by flat plate mirror walls at sides of solar still. This reduces slightly overall cost. One of the main challenges in this concept is the water level in the basin is

reduced. It has to be control to keep water depth constant during the day while evaporation rate varies throughout day time.

5.1.3. Parabolic trough

Concept 6

As mentioned in literature review part 2.5.1, heating up the inlet water prior to feeding the solar still could have direct effect on productivity. This process can be achieved by installing a parabolic trough with a receiver tube with salty water flowing through the tube before the water gets into the solar still as shown in figure 114.

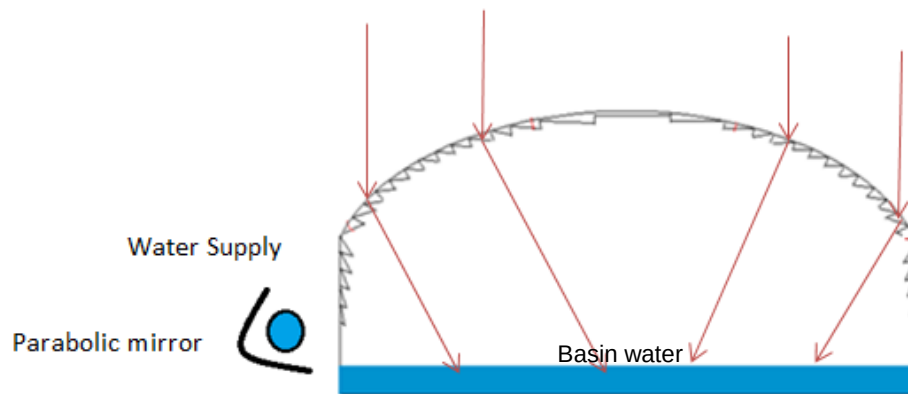


Figure 114: Using parabolic through to pass heat through basin of solar still

This concept is mostly suitable for small scale desalination units. The capital cost for a scale up system is significant in terms of land and equipment requirement.

5.1.4. Evaluating of Concentrated Solar Still Unit Concepts Design

In order to select the best concept of single unit solar still an evaluation matrix was employed to allow concepts to be assessed and ranked through quantifying the important aspect of the design.

A selection of criteria considered important for the design, build and function of the concept were selected and weighted judging by their criticality in order for the project to be successful and productive.

All calculations and designs are for a single unit of solar still with dimension area of $1.2 \text{ m} \times 0.5 \text{ m}$ and a height of 0.5 m . The target is to provide fresh water for a small community of 1,000 people. The measurement and weighting of each criterion are listed on table 16.

Table 13: Criteria and weighting for use in evaluation matrix.

Criteria	Weighting (1-5)
<i>Construction</i>	
Number of units	5
Size of each unit	5
Solar still structure	4
Concentrator factor	4
Complexity of the system	4
<i>Financial</i>	
Cost to build	4
Cost of concentrator	4
Cost of operation	2
Cost of maintenance and cleaning	2
<i>Time</i>	
Design time	4
Build time	3
<i>Risk</i>	
Structural risk	3
Technical risk	2

Higher weighting values were assigned to reflect the importance of each criteria to the design of solar still. The description for each of the criteria is as follow:

Construction

- *Number of units*: The number of units can be varied based on productivity of each unit to provide fresh water for small community.
- *Size of each unit*: The size of each unit is depending on several factors such as evaporation and condensation rate, concentrator and land available.
- *Solar still structure*: This includes foundation, support structure and optical structure.
- *Concentrator factor*: Amount of sun radiation concentrated by the system.
- *Complexity of the system*: Possible difficulties to construct the system.

Financial

- *Cost of build*: The capital cost required to build the system.
- *Cost of concentrator*: The cost of concentrator varies based on type and number.
- *Cost of operation*: This cost is expected to increase depending on the complexity of the system.
- *Cost of maintenance and cleaning*: Both the solar still and reflector require maintenance and cleaning.

Time

- *Design time*: The design time will vary depending on the complexity of the system.
- *Build time*: The amount of time necessary to build the solar still. It is an important parameter which is directly related to the cost of build.

Risk

- *Structural risk*: Risks related to the resistance of system to its environment.
- *Technical risk*: It is risk directly associate with design and builds concentrator solar still.

These concepts were ranked 1 to 5 against each criteria, with “1” and “5” being the least preferable (1) the most preferable (5) outcomes respectively as table 17 shows.

Table 14: Explanations of ranking system in the matrix evaluation

Ranking	1	2	3	4	5	6	7
Performance	Significantly worse than single solar still	Moderately worse than single solar still	Slightly worse than simple solar still	Same as simple solar still	Slightly better than single simple solar still	Moderately better than single solar still	Significantly better than simple solar still

A simple solar still (Figure 109) is the original concept, which is used as a comparison to other designs. It was given the ranking 4 for each of the criteria. The rest of the concepts were ranked in relation to the main concept. The sum of the product of the rankings and criteria weights produced a total score for each concept. The matrix shown in table 18:

Table 15: Completed Matrix

Criteria	Weighting (1-5)	Concept 1	Concept 2	Concept 3	Concept 4	Concept 5	Concept 6
Construction							
Number of units	5	5	5	7	6	6	6
Size of each unit	5	4	4	1	2	2	3
Solar still structure	4	5	5	1	2	2	6
Concentrator factor	4	6	6	7	7	7	6
Complexity of the system	4	5	3	1	2	1	3
Financial							
Cost to build	4	3	2	1	1	1	2
Cost of concentrator	4	3	3	1	1	1	2
Cost of operation	2	4	3	1	1	1	2
Cost of maintenance and cleaning	2	4	4	1	2	2	3
Time							
Design time	4	3	3	1	2	2	2
Build time	3	4	4	1	2	2	3
Risk							
Technical risk	3	4	4	1	2	2	3
Structural risk	2	4	4	1	2	2	3
Total		<u>193</u>	179	100	122	118	163

A higher total score represents a better concept in terms of construction, financial, time and risk of design. The matrix shows that concept “1” scores is the best overall with score of 193. There are still some disadvantages such as operation cost and structural risk but it meets requirement to produce fresh water with multiple unit. Concept “5” scores the worse due to its high capital cost and high construction difficulty requirement that make this concept unsustainable. Concept “2” and “6” are closed to Concept “1” in terms of ranking the matrix but there are direct modifications with added complexity, which make concepts unjustifiable.

Accordingly, concept “1” as main model was chosen to design the shape of the solar still in a way to use flat plate linear focus Fresnel lenses. Using solar concentrators (Fresnel lenses) help to direct solar radiation on top of basin water while the sun is not at its highest point (noon) of day. The evaporation process starts from the top surface of water; therefore the shape of solar still needed to be design to make focal point of Fresnel lenses directed in the basin area. Consequently, a double slope solar still shape was founded as outline by considering construction, financial and risk criteria which are extremely keys for scaling up the unit size.

5.2. Extraction System

A ventilation fan system needed to be installed in the solar still to extract evaporated water throughout the system. The ventilation fan needed to be indicating in a way that it is capable of extracting the forecasted volume of evaporated water over a large ceiling area before it gets saturated and drops back to the basin water.

Forecasting the amount of water that undergoes the evaporation process is a complex procedure and would require consideration on the site specifications and proposed operational plan. It takes into account the evaporation efficiency that is dependent on the daily temperature, seawater density and pureness, sun heat energy level, evaporation tank area and water level height. The followings include the steps and assumptions required in order to account for the specification of the ventilation fan for the proposed system.

In order to convert the volume of water subjected to evaporation, it is required to calculate the evaporation from water surface. Based on the water surface evaporation formula commonly used by fluid mechanics experts is implemented as [311]:

$$g_h = \theta A (X_s - X) \quad (104)$$

where humidity ratio X_s can be express as [312]:

$$X_s = 0.62198 \frac{P_{ws}}{(P_a - P_{ws})} \quad (105)$$

Maximum specific humidity at some common temperature is shown on Psychometric chart as figure 115 [312]:

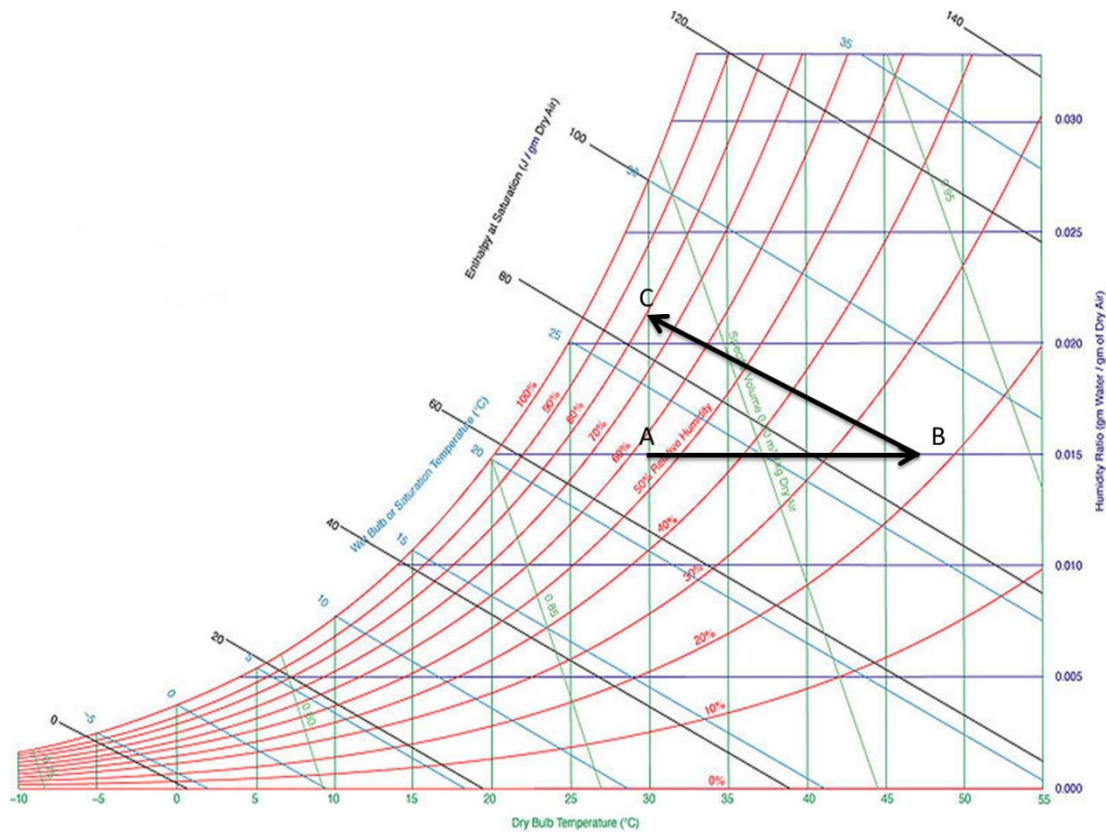


Figure 115: Psychrometric chart for temperature – humidity after [312]

As figure 115 presents, cooling down the point “B” without any changes in moisture content, the illustrative point moves straight to point “A”. Alternatively the air can be cooled by evaporating liquid water. Within this procedure in close area system with no other heat transfer, the humidity of air increase and its demonstrative point moves upwards from “B” to “C”.

By using ventilation fan in the solar still design to pull out the water vapour out, the temperature of vapour water decreases and phase change placed to condensed clean water. With this method the production rate of drinkable water increases significantly compare with similar designs.

Under ideal conditions, the operating point is represented as the intersection between the fan and loss curves, regardless of whether the fan is positioned at the air intake or exhaust side of the device. In addition to ensuring the required flow rate, several additional aspects must be considered for determining an appropriate fan concept. The intake air currents of a fan are mainly laminar, comprising nearly the entire suction area. By contrast, the exhaust air of a fan is generally turbulent, while it flows on a preferred direction, e.g. axial for an axial fan. The turbulences of the exhaust intensify the heat transfer from components within the air currents, so that mounting the fan at the air intake side of the device is recommended for cooling and heating. Mounting the fan at the device intake is also advantageous because the fan will not be subjected to the dissipated heat of the device. Therefore, it operates at low ambient temperatures and has a higher life expectancy.

There are two main types of ventilation fans that they are commonly used. The two general types of fans are axial-flow and centrifugal. Each type has many different blade diameters, materials, blade shape and motor power. With axial-flow fans, the air passes through the fan parallel to the drive shaft. With centrifugal fans, commonly used for grain drying applications, the air makes a right angle turn from the fan inlet to outlet.

The 12-nominal voltage DC axial-fan with diameter of 119×119×32 mm by internal and external temperature sensor were used in the present solar still to pull out vapour from the system before they get saturated into the basin water (figure 116).

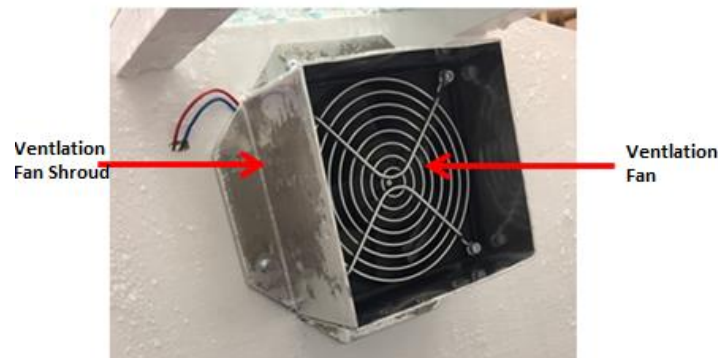


Figure 116: Schematic of 12 volt DC fan [313]

The introduce solar still unit has to be tested in inaccessible areas without access to electricity, thus, it is important to run the fan with 100-watt photovoltaic (PV) panel as power supply (figure 117). The test was placed in Cranfield University during December time, and the fan was running at its maximum air flow ratio.



Figure 117: Testing the fan with the photovoltaic panel.

5.3. Heat Exchanger

As mentioned earlier evaporation and condensation are the two main thermodynamic processes that have direct effect on productivity of solar still. Connecting a heat exchanger pipes to the ventilation fan to direct the evaporated water through basin water could make evaporated water become

condense, simultaneously it helps the basin water to raise its temperature to make evaporation process rate higher.

A heat exchanger transfers heat efficiently from one fluid to another, without allowing them to mix. Most solar water heaters have a separate fluid circuit through the collector, with a heat exchanger within the storage tank to transfer the collected heat to the potable water. Figure 118 shows the principle of a counter-flow heat exchanger.

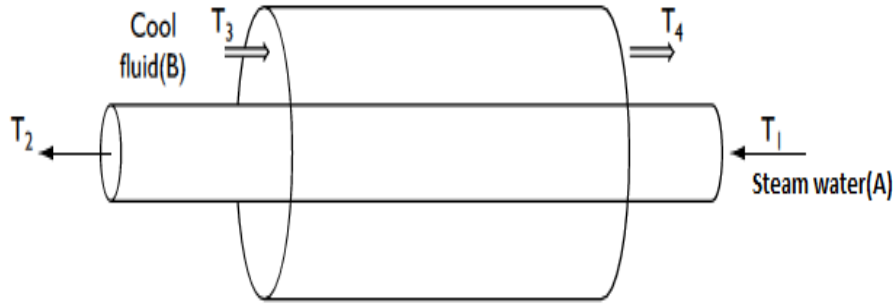


Figure 118 Sketch of counter-flow heat exchanger principle

In Figure 108, consider a fluid, “A”, losing heat in the inner pipe (Steam water), and fluid, “B”, gaining heat in the outer tube (Seawater in the basin). Using symbols “ ρ ” for density, “ c ” for heat capacity and “ V ” for rate of volume flow, if these are considered constants with the relatively small changes of temperature [314]:

$$\begin{aligned} \text{heat lost by fluid A} &= \text{heat gained by fluid B} + \text{losses} \\ \rho_A c_A V_A (T_1 - T_2) &= \rho_B c_B V_B (T_4 - T_3) + L \end{aligned} \quad (106)$$

The efficiency is:

$$\epsilon_{he} = \frac{\rho_B c_B V_B (T_4 - T_3)}{\rho_A c_A V_A (T_1 - T_2)} \quad (107)$$

It is convenient in solar process system calculations to use effectiveness-NTU (number of transfer units) method of calculations of heat exchanger performance. The overall heat transfer coefficient-area product is “ UA ”. The maximum possible temperature drop of the hot fluid is from T_1 to T_3 ; the heat transfer for this situation would be [314]:

$$Q_{max} = (\dot{m}C_p)_{hot}(T_1 - T_3) \quad (108)$$

The maximum possible temperature rise of the cold fluid would be from T_3 to T_1 . The corresponding maximum heat exchange would be:

$$Q_{max} = (\dot{m}C_p)_{cold}(T_1 - T_3) \quad (109)$$

The maximum heat transfer that could occur in the exchanger is thus fixed by lower of the two capacitance rates, $(\dot{m}C_p)_{min}$, and:

$$Q_{max} = (\dot{m}C_p)_{min}(T_1 - T_3) \quad (110)$$

The actual heat exchange Q is given by:

$$Q = (\dot{m}C_p)_{cold}(T_4 - T_3) = (\dot{m}C_p)_{hot}(T_1 - T_2) \quad (111)$$

Efficiency ε_{he} is defined as the ratio of actual heat exchanger heat occurs to the maximum possible Q/Q_{max} , so:

$$\varepsilon_{he} = \frac{Q}{Q_{max}} = \frac{(\dot{m}C_p)_{hot}(T_1 - T_2)}{(\dot{m}C_p)_{min}(T_1 - T_3)} = \frac{(\dot{m}C_p)_{cold}(T_4 - T_3)}{(\dot{m}C_p)_{min}(T_1 - T_3)} \quad (112)$$

Since either the hot or cold fluid has the minimum capacitance rate, the effectiveness can always be expressed in terms of the temperatures only. The working equation for the heat exchanger is:

$$Q = \varepsilon_{he} (\dot{m}C_p)_{min}(T_1 - T_3) \quad (113)$$

For the count flow exchanger, the efficiency is given:

$$\varepsilon_{he} = \begin{cases} \frac{1 - e^{-NTU(1-C^*)}}{1 - C^*e^{-NTU(1-C^*)}} & \text{if } C^* \neq 1 \\ \frac{NTU}{1+NTU} & \text{if } C^* = 1 \end{cases} \quad (114)$$

Where NTU is the number of transfer units, defined as:

$$NTU = \frac{UA}{(\dot{m}C_p)_{min}} \quad (115)$$

And the dimensionless capacitance rate is given by:

$$C^* = \frac{(\dot{m}C_p)_{min}}{(\dot{m}C_p)_{max}} \quad (116)$$

By transferring heat through heat exchanger, the evaporated water condenses and it would help the basin water raise its temperature. Therefore there is less amount of sun radiation requiring heating up basin to reach evaporation point.

5.4. Laboratory Scale Double Slope Solar Still Unit Construction

After choosing the shape concept of solar still to use with two linear focus Fresnel lenses as top cover (concept 1), the design needed to be adapted to use an extraction ventilation fan to be connected to heat exchanger pipes, in order to increase both evaporation and condensation rates inside the solar still. Therefore, the basic principle in this proposed novel design is to expose a considerably larger amount of water in comparison with conventional solar stills. This solar still was designed using Google Sketch up 2016 software as shown in figure 119.

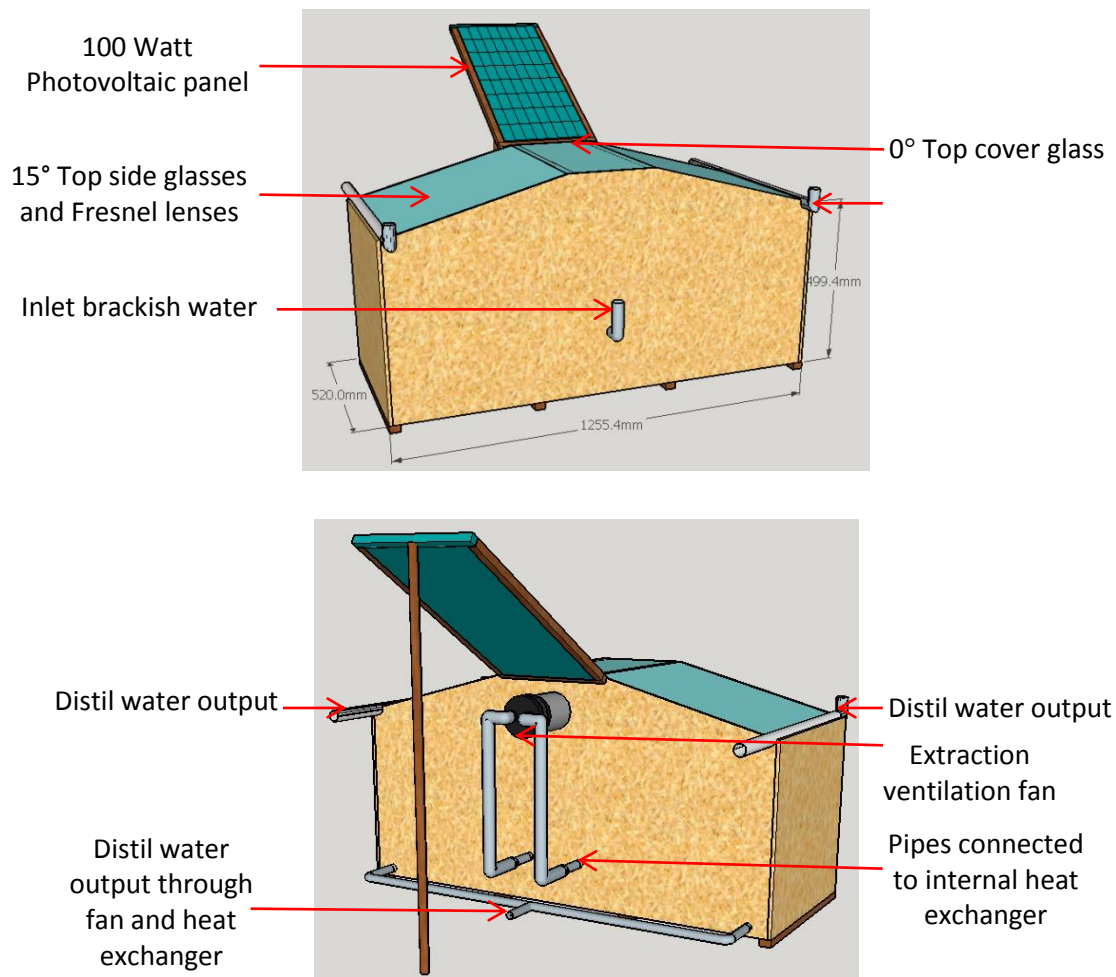


Figure 119: Single basin double slope solar still enhance with ventilation fan and heat exchanger

5.4.1. Concentrated Solar Still Structure

This single basin double slope solar still is packable for ease of shipment as it was planned to test the unit in the field in the remote areas such as Spain and Iran. It was also the intention to use only available market parts in order to keep the cost to a minimum. The shape of the solar still is unique as it was designed to use linear focus Fresnel lens (positive linear focus lenses with size of 500 mm × 500 mm with thickness of 3 mm) that assembled on the top the glazing material (glasses) in order to increase the evaporation rate at the sunrise and sunset periods. The glasses are tilted with the angle of

15° which can be varied based on the location latitude where solar still needed to be commercialized to be use for community scale desalination. This is to ensure maximum transmission of solar radiation into the solar still as well as enabling condensed vapour to trickle down the through built in the still to be collected from distilled output. This angle is adjustable with different design to use the present solar still in areas with different latitude. There is also 0° angle for the top cover (glass) to avoid any radiation losses through when the sun is at its highest point (noon period). The overview of completed single basin double slope solar still unit is shown in figure 120.

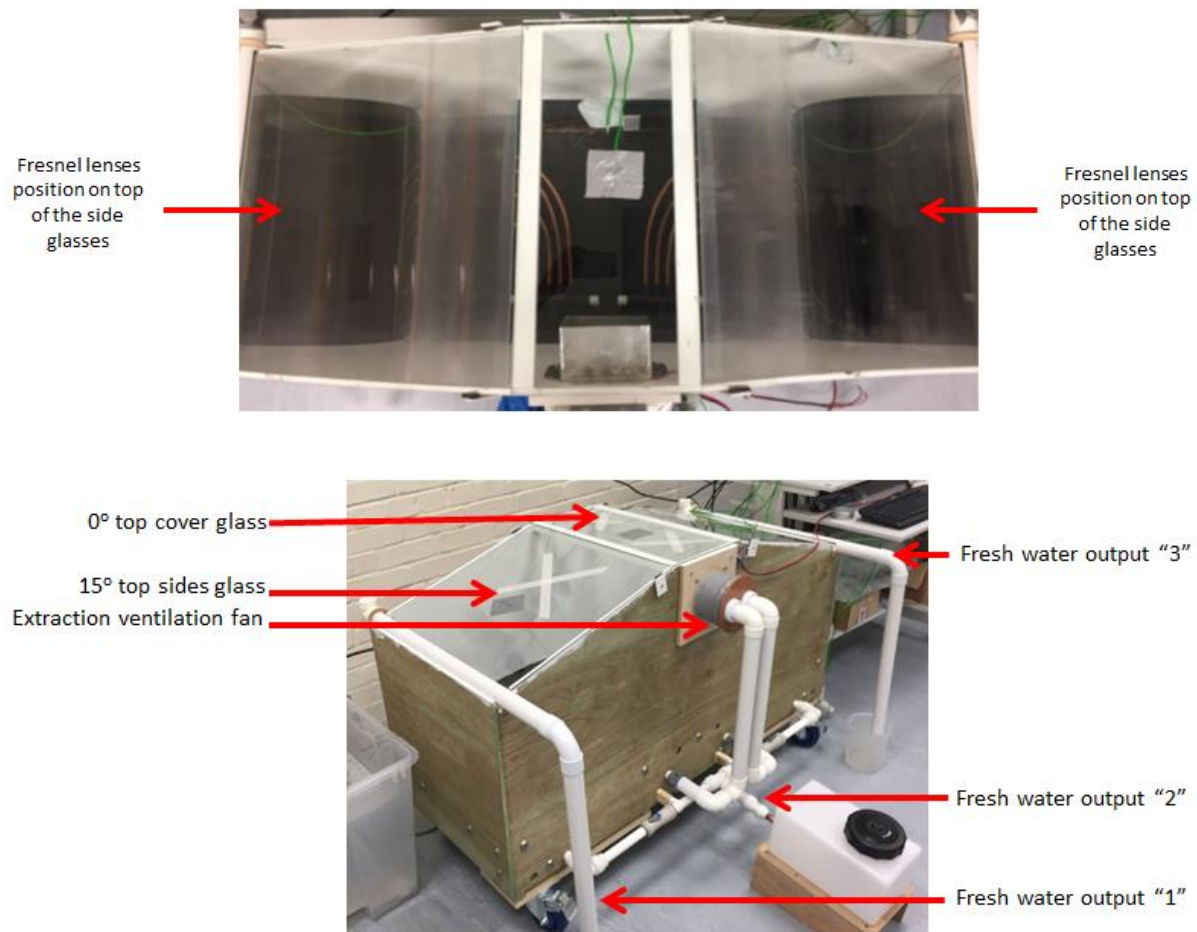


Figure 120: Overview of completed single basin double slope solar still unit

There are also two side mirrors to reflect the solar radiations into the basin area while the sun is not at its highest position in the sky (figure 121). The introduced solar still unit was planned to be tested in the lab, therefore side mirrors were designed in a way to be detached during laboratory experiments as there is no sun.

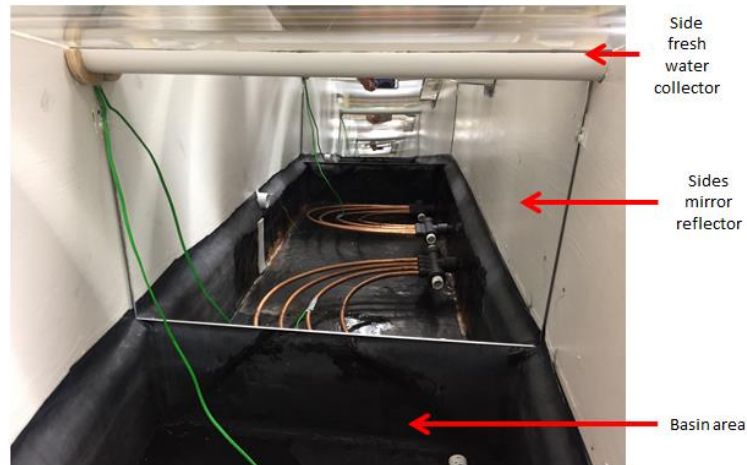


Figure 121: Solar still sides' reflectors

The structure of solar still was made of 9 mm ply-wood in order to minimise the weight. This should enable the unit to be shipped in order to test it under different environmental conditions. The basin was also covered by a 2 mm thick black pond liner in order to absorb maximum solar radiations. It also acts as an insulator for the basin to reduce heat leakages through the basin area (figure 122). The bottom and the sides of the basin are shielded to reduce heat loss through conduction.



Figure 122: Basin area covered by black pond liner

Several thermocouples connected to the PC recorder was placed in the solar still unit to measure the glass cover temperature (inner/outer), basin water temperature, heat exchanger temperature, output water temperature and ambient temperature (figure 123). The top of the solar still area is sheltered with 3 mm thick transparent glass (transitivity of 0.088 [326]) to direct solar radiation into the basin area.

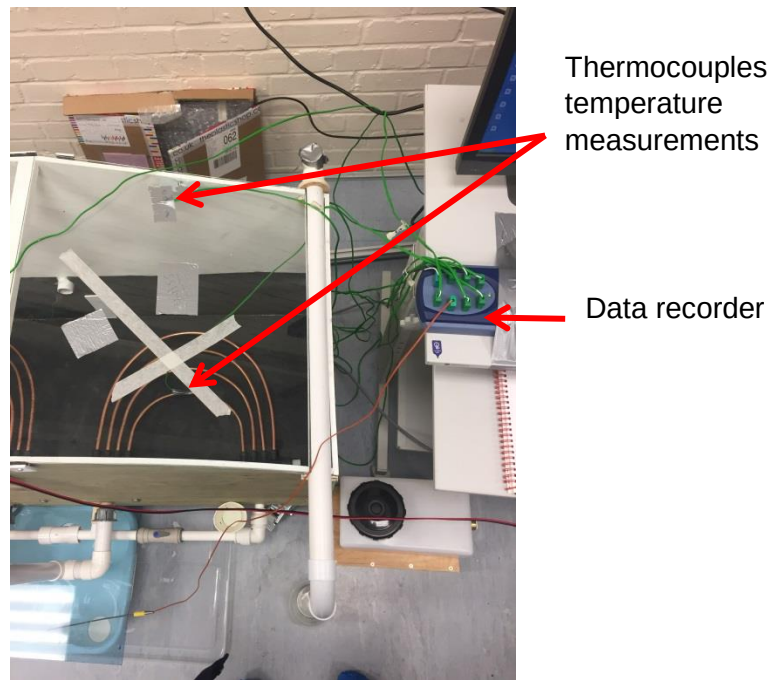


Figure 123: Temperature data recorder

In this design, there are three output pipes that accumulate fresh water. Two 32 mm outer diameter sides' collector plastic pipes were slotted 8 mm in order to hold the glasses and collect fresh water simultaneously (figure 124). One of the main benefits of using this technique is to limit energy requirement as collection is observed using gravitational force.

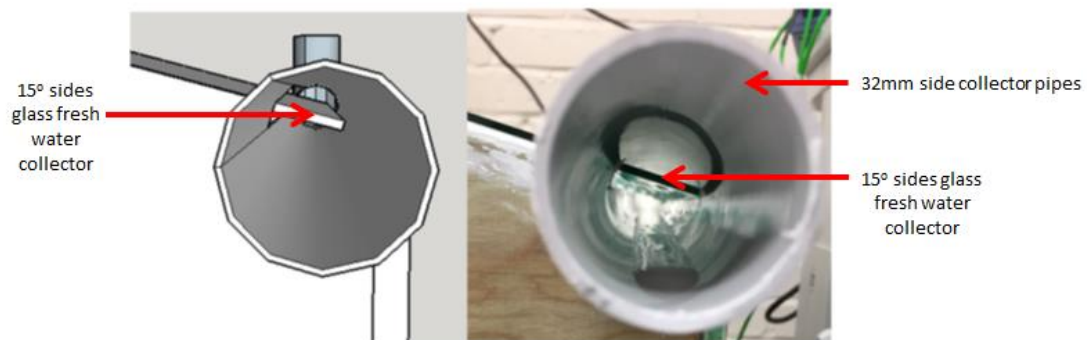


Figure 124: sides output pipes.

5.4.2. Concentrated Solar Still Ventilation Fan Instalment

A 110 mm pipe adaptor was used at the back of ventilation fan to divide the air flow rate into two 32 mm pipe. The 32 mm pipe was then reduced to 22 mm set of in order to connect it to 22 mm port rail on the basin area. These are connected to two 4×10 mm copper pipes on each side (figure 125).

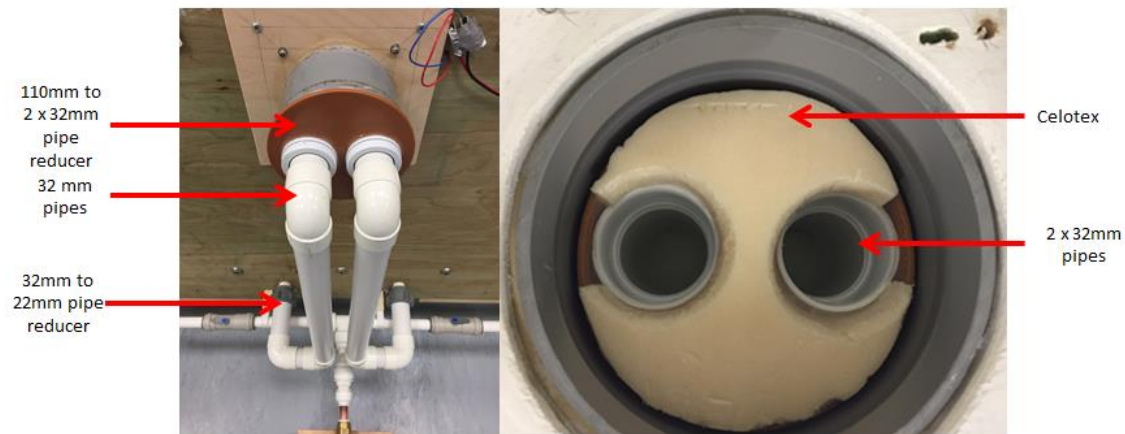


Figure 125: Isolated fan diameter reducer to two 32 mm pipes.

Table 16: Output air flow measurements through pipes.

Voltage	With Fan Shroud		Without Fan Shroud	
	32 mm output airflow (l/s)	22 mm output airflow (l/s)	32 mm output airflow (l/s)	22 mm output airflow (l/s)
15	7.6	1.4	7.1	1.3
12	7.0	1.1	6.6	1.1
9	5.5	0.9	5.4	0.9
6	4.2	0.5	4.0	0.6

Figure 126 and 127 presents the comparison of different air flow versa voltage for both with and without fan shroud (Appendix A).

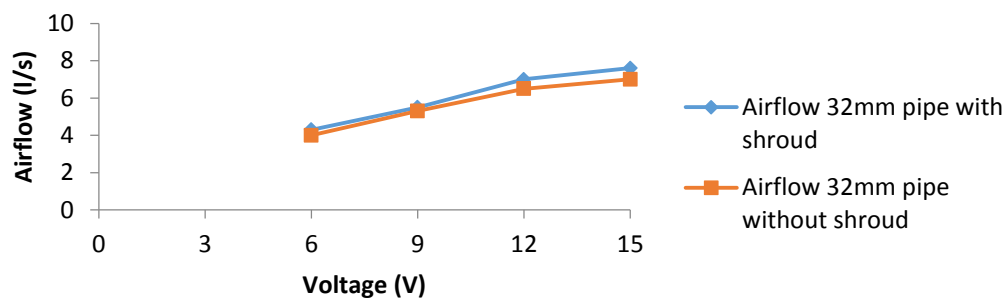


Figure 126: The airflow of fan (with and without shroud) verse fan voltage in 32mm pipes

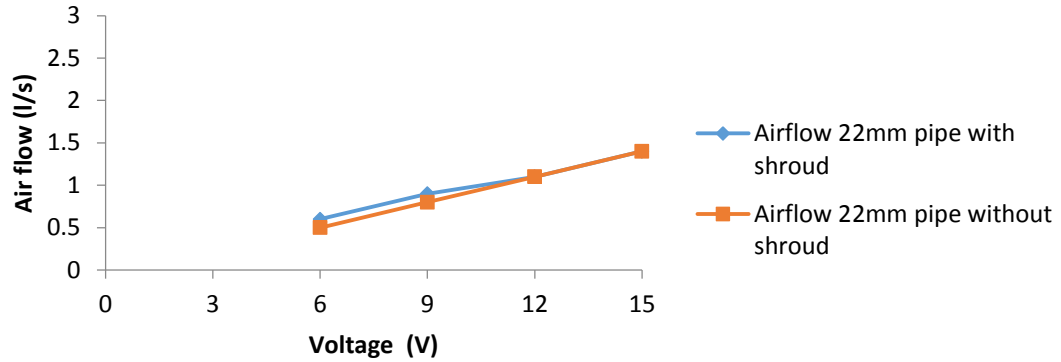


Figure 127: The airflow of fan (with and without shroud) verse fan voltage in 22mm pipes

5.4.3. Concentrated Solar Still Piping

Further, a single ventilation fan was used internally to extract the vapour out of the system. The fan is connected to eight 10 mm copper pipes diameter with a total length of 5,735 mm. These pipes are placed on top of basin area surface below water level. They act as thermal heat exchanger to transfer latent heat from vapour to the basin water while condensing. Copper pipes are placed with 10 degree angle in order to use gravitational force to take the condense water out to the collector tank (figure 128).



Figure 128: Eight 10 mm copper pipes on the basin with the 10 degree angle

6. Experimental Equipment and Procedures

6.1. Experimental Procedures

In this study, experimental tests were carried out to investigate the effect of using a ventilation vapour extraction fan, heat exchanger (new design modifications) and thermal storage material (operational modification) on the performance of a novel shaped solar still (presented in chapter 5.4). The experiments were done in the laboratory with constant metrological parameters. The performance of introduced solar still was compared with a conventional solar still without ventilation fan, heat exchanger, thermal storage material (Figure 129).

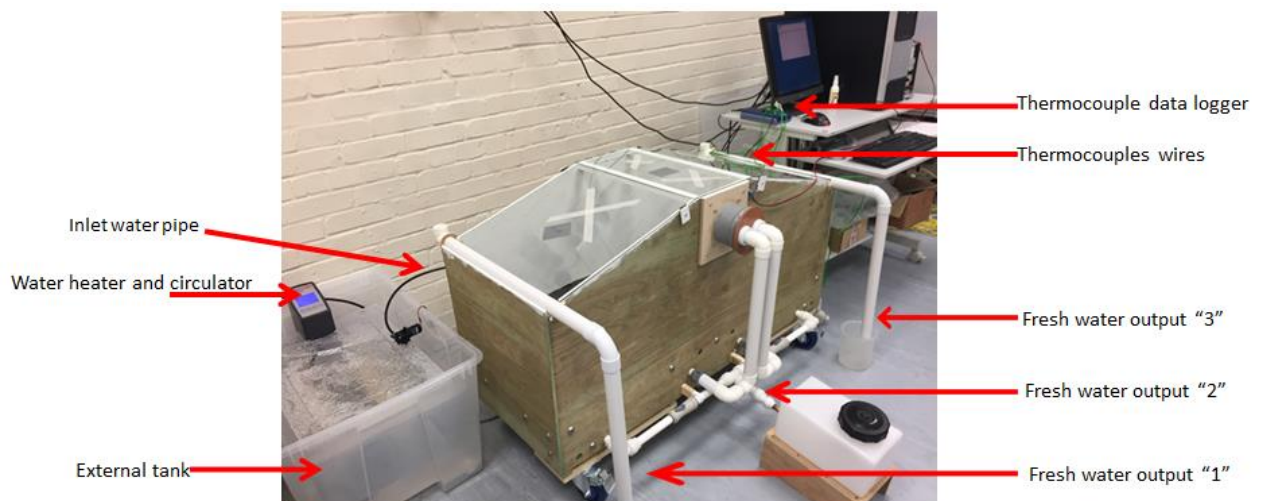


Figure 129: Novel single basin double slope solar still

According to new modifications in design and operational aspects of the novel solar still, two main sets of experiments were carried to measure the outcome of the solar still productivity. These sets of experiments are as follows:

1. Set 1 was stated to measure the HOURLY productivity of solar still (with/without fan) at constant basin water temperatures in order to be compared with a conventional solar still at the same temperature.
2. Set 2 was stated to measure 20 HOURS productivity of solar still with its novel modifications such as different fan air flow ratio with/without shroud and lava stone as heat strong material in order to be compared with a conventional solar still without modifications.

In each set of laboratory experiments, the water was heated to the certain temperatures in an external tank (figure 129) with the heater and circulator. The volume of water which was required to be heated up was approximately 70 litres, thus the time requirement was varied (2-4 hours) depending on the required experimental basin water temperature. The water in the external tank was inked by blue food colour in the external tank to make it visible to separate condense water (no colour) from heated

water. The food colour evaporation process occurs at higher temperature than water, thus the condense water does not have food colour in it. Once the external tank water reached a certain temperature, the water was pumped into the solar still basin area. Pumping the water was reducing its temperature by approximately 20°C, consequently the water needed to be heated up additional 20°C for the required basin water temperature.

The water depth was kept at constant level of 80mm on the basin area all experiments as constant parameter. Copper pipes that act as heat exchanger pipes are constructed with 10° angle in order to use gravitational force to direct the condensed water to the output (3) pipe. Therefore, the basin water depth level needed to be adjusted (at 80mm) to cover up all the copper pipes (figure 128)

The solar still was constructed with three fresh water output pipes (figure 129), where water collector “1” and “2” are condensed water from the top cover (inner surface of glasses) and water collector “3” is the condensed water through the extraction fan through that passes through heat exchanger pipes. The water collector “3” was also connected to an enclosure tank to measure the amount of water collected through the fan and heat exchanger separately.

The experiments were taken to measure the outcome of solar still by installing ventilation fan (with/without shroud) with various airflow (measured in part 5.2) connected to heat exchanger pipes in the solar still unit in compare with conventional unit. The shroud (figure 116) was helping to avoid air turbulence inside the solar still unit and its effect on the productivity of the unit.

In all experiments, thermocouples, which were connected to TC-08 data logger, were placed in basin water, inner and outer surface of glasses and copper pipes (heat exchanger) to measure temperature changes (figure 130). The ambient temperature was measured separately.

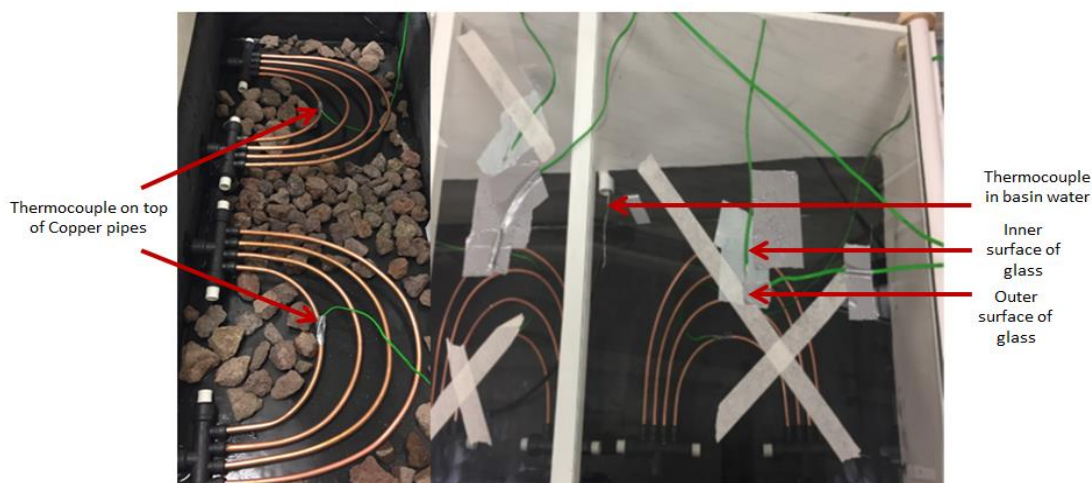


Figure 130: Positions of Thermocouples

The two sets of experiments were divided into four main experimental groups as follows:

- I. The basin water temperatures were kept at constant temperatures (30°C, 40°C, 50°C and 60°C) by circulating the water between the external tank and the solar still unit for a constant period of one-hour time. The hourly productivity of the solar still was then measured (in each output pipe collector) with different experimental factors. In each mentioned constant temperature, the solar still was tested by running the fan with its maximum airflow rate (1.4 l/s at the solar still output pipe) and without operating the fan (4 experiments). *(Note: this group of experimental results contribute the hourly productivity of the novel solar still by the new modifications to compare with both theoretical and experimental results of conventional solar still)*
- II. The basin water temperature was heated up to 90 °C in the external tank, then it was pumped in the basin area. The water was kept for a constant period of 20 hours (it reaches laboratory temperature) by running the ventilation fan without shroud via different airflow rate (1.4, 1.2, 0.9 and 0.6 l/s at the solar still output pipe). Subsequently, same types of experiments were repeated with the fan shroud to measure the productivity of the solar still (8 experiments). *(Note: this group of experimental results contribute the effect of the different fan flow rate with and without the shroud to find the optimise operational condition of ventilation fan)*
- III. The basin water temperature was heated up to 90 °C in the external tank, then it was pumped in the basin area. The water was kept for a constant period of 20 hours (it reaches laboratory temperature) by running the ventilation fan without shroud via different airflow rate (1.4, 1.2, 0.9 and 0.6 l/s at the solar still output pipe). Subsequently, lava stones (thermal conductivity of 1.7 W/m K [324]) were used as thermal storage material to measure the effect of it to the productivity of solar still (4 experiments). *(Note: this group of experimental results contribute the effect of different fan flow rate without shroud in addition with thermal storing material used on the basin area of the solar still to compare with part of group II experimental results)*
- IV. The basin water temperature was heated up to 90 °C in the external tank, then it was pumped in the basin area. The water was kept for a constant period of 20 hours (it reaches laboratory temperature) without running fan as conventional solar still unit. Subsequently, lava stones were used to measure the effect of it to the productivity of conventional solar still (2 experiments). *(Note: this group of experimental results contribute the productivity of the solar still as conventional unit with/without heat storage material to be used in 20 hours experimental results)*

6.2. Experimental Equipment

The novel single basin double slope concentrated solar still was designed and constructed to be used for laboratory experimental work throughout this project (figure 131). The unit was installed with an external tank, a water heater, a pump, temperature measurement equipment, air velocity measurement equipment and a ventilation fan (with and without a shroud) to be assessed and tested under different operational conditions.

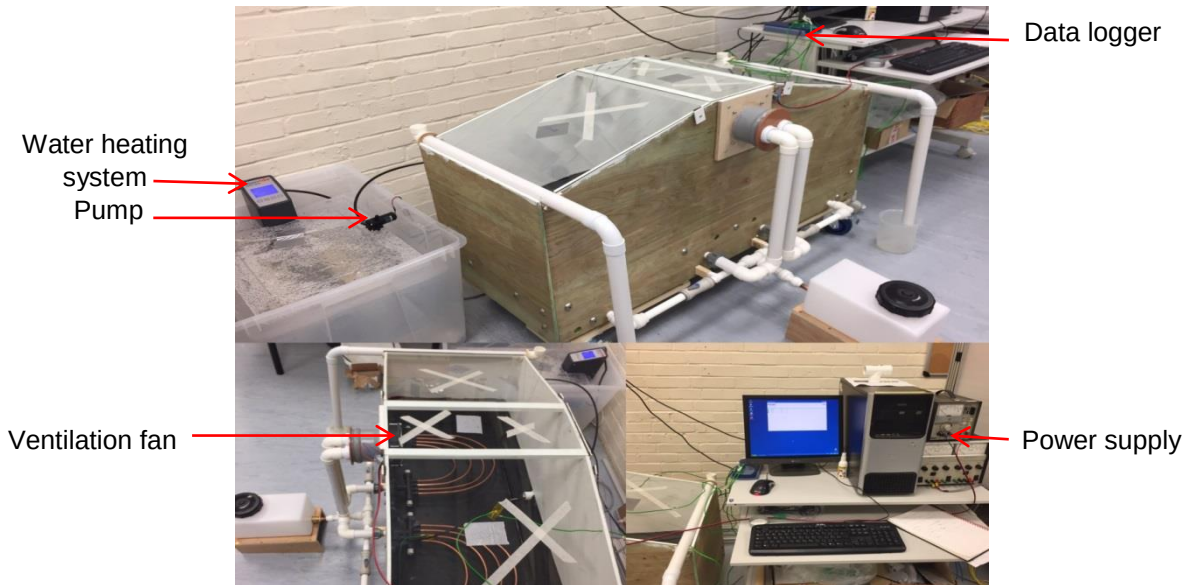


Figure 131: Single basin double slope solar still

Equipment used in this research is as follows:

6.2.1. Water heating system

The water feeding system employed, for laboratory experiments, consists of two tanks, a water heating system and a circulating system. The Sous thermal circulator was used as a thermal circulator to heat up the water to specific temperatures in an external tank as shown in figure 132. The temperature range is between 20-100 °C with an accuracy of 0.01°C and a maximum flow rate of 16 litres per minute. The voltage is 220-240 volts, with an output power of 1300 W.



Figure 132: SousVide Tools Precision thermal circulator [315]

6.2.2. Water circulating system

Two mini plastic gear self-priming water (0-100°C) pumps were used (figure 133). Each of the mentioned pumps has a weight of 138 gram and dimensions of 0.15m × 0.1m × 0.05 m. The maximum flow rate is $2.7 \pm 10\%$ litres per minutes.



Figure 133: Q-Baihe 12 volt mini plastic gear pump ZC-A210 [316]

6.2.3. Temperature measuring

A 8 channel Pico technology thermocouple data logger (TC-08) was used to measure and record the temperature on various parts of the solar still unit (figure 134).



Figure 134: Pico Technology thermocouple data logger [317]

The PicoLog data acquisition software provided with the TC-08, allowed to measure and record temperature during each experiment. The TC-08 specifications are presented in table 17.

Table 17: The Pico thermocouple data logger TC-08

Number of channels	8
Temperature range	-270°C to +1820°C
Temperature accuracy	The sum of $\pm 0.2\%$ and $\pm 0.5\text{ }^{\circ}\text{C}$
Voltage accuracy	The sum of $\pm 0.2\%$ and $\pm 10\text{ }\mu\text{V}$
Overload protection	$\pm 30\text{ V}$
Voltage input	$\pm 70\text{ mV}$
Reading rate	Up to 10 per second
Input connectors	Miniature thermocouple
PC connection	USB
Dimension	$0.022\text{m} \times 0.104\text{m} \times 0.034\text{ m}$

The measuring instrumentations were, experimentally calibrated; for example, the thermocouples were placed in ice water to validate calibration to compare with manufacturing accuracy.

6.2.4. Humidity sensor

The Asscom humidity thermometer monitor sensor (figure 135) was used to measure humidity inside the solar still unit and of the laboratory simultaneously.



Figure 135: Asscom humidity thermometer [318]

Specifications of this these device are highlighted in table 18:

Table 18: Asscom humidity thermometer

Temperature accuracy	0.1°C
Humidity accuracy	0.1 RH
Power supply	1.5V (AAA size) x 1
Storage condition	-20°C~60°C, 20~80%RH
Dimension	0.098m × 0.075m × 0.018 m

6.2.5. Air Velocity sensor

A stainless steel Skywatch Xplorer 1 anemometer (figure 136) was used to measure air flow produced by the ventilation fan in different area of solar still unit.



Figure 136: Skywatch Xplorer 1 [319]

The specifications are presented in table 19.

Table 19: Skywatch Xplorer 1 specification data

Units	km/h, mph, m/s, fps and knots
Resolution	at the 10th up to 99.9, then to the unit
Accuracy	± 3%
Measuring range	from 3 to 150 km/h

6.2.6. Exhaust ventilation fan

A DC axial fan (figure 137) was used to extract the vapour from inside solar still unit.



Figure 137: Ebmpapast DC ventilation fan [320]

The air is conducted to a great extent parallel to the axis of rotation, namely axial direction. Axial fans with free air delivery at zero static pressure have a low power input which increases with back pressure. The compact design allows for space-saving.

Table 20: Series 4300 Ebmpapast DC Axial fan

Air flow	95m³/h
Nominal voltage	12 V
Voltage range	6-15 V
Input power	1-2 Watts
Nominal speed	1550 rpm
Temperature range	-20 to +85 °C

6.2.7. Off-grid power supply

a) Solar panel kit

A 20W 12V Photonic Universe solar panel kit with 5A charge controller and battery cables (figure 138) were purchased in order to run the ventilation fan during outdoor experiments [321].

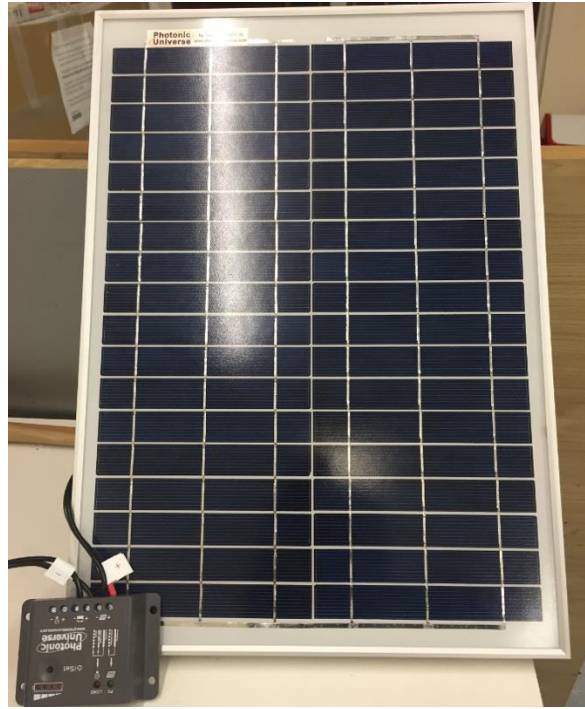


Figure 138: Photovoltaic solar panel kit

Specifications of photovoltaic solar panel kit is presented in table 21.

Table 21: Solar Panel specifications

Peak power	20W
Maximum power voltage	17.5V
Maximum power current	1.14A
Open circuit voltage	21.0v
Short circuit current	1.12A
Power allowance range	± 3%
Dimensions	0.49m × 0.35m × 0.025 m
Weight	2.5kg

b) A charge controller was used with solar photovoltaic panel and its specifications are presented in table 22.

Table 22: Charge controller specifications

Rated charging load current	5A
Rated voltage	12V
Self-consumption	6mA max
Working temperature	-35 t0 +55°C
Dimensions	0.085m × 0.045m × 0.010 m
Weight	0.05kg

c) Battery

A deep cycle discharge battery (HRL 1210W) [322] was selected (figure 139) as a power supplier and connected to the charge controller.



Figure 139: HRL 1210W DC battery

Its characteristics are a high energy density, a small footprint and a high discharge efficiency. It can be used for more than 260 cycles at 100% discharge in cycle service and up to 8 years in standby service. Table 23 shows the specifications of this battery.

Table 23: HRL 1210W battery specifications

Cells per unit	6
Voltage per unit	12V
Capacity	10W
Weight	1.1kg
Maximum discharge current	40A
Internal resistance	35mΩ
Operation temperature range	Discharge: -15 ~50 °C Charge: -15 ~40 °C Storage: -15 ~40 °C
Float charging voltage	13.5 to 13.8 VDC/unit Average at 25°C
Recommended maximum charging current limit	1A
Equalization and cycle service	14.4 to 15.0 VDC/unit Average at 25°C

6.2.8. Scale unit

A Sartorius MP8 scale balance (figure 140) was used to measure the amount of fresh water output. The calibration of the system was carried out after each experiment.

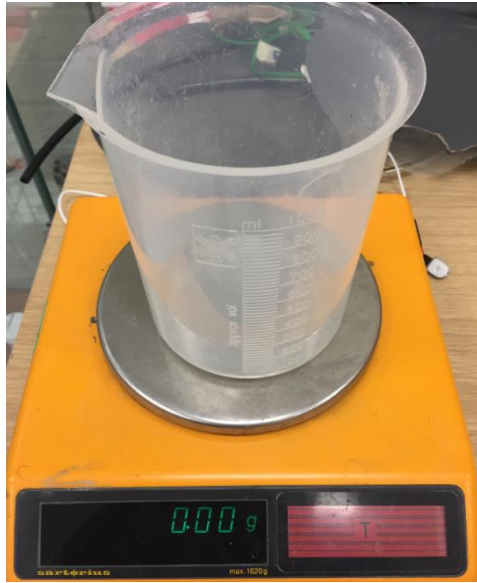


Figure 140: Sartorius scale balance MP8-1 1412

6.2.9. Fresnel lenses

Two LF500-B linear focus Fresnel lenses were purchased (figure 141) from NTKJ manufactures [323].

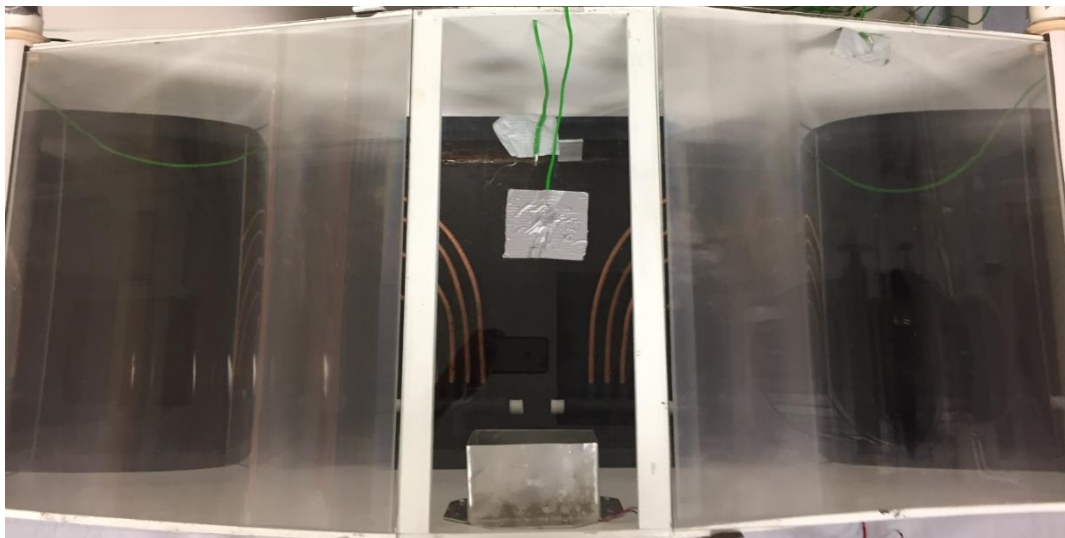


Figure 141: Linear focus Fresnel lens

The Fresnel lens specifications are shown in table 24.

Table 24: Linear focus Fresnel lens specifications

Size	0.5m × 0.5m
Thickness	0.003m
Focal length	0.5m
Pitch	0.0003m
Material	PMMA

7. Results

In this chapter, theoretical and experimental study was directed to investigate the effect of fan flow rate with/without shroud connected to the heat exchanger pipes, which sit on top of basin area to help vapour to change its phase to condense water while heat energy transfers to the basin water in addition with heat storing material (lava stone) on the performance of the solar still. An evaluation analysis between theoretical values of the solar still as conventional unit and new modifications in experimental results indicate the improvement for the novel solar still.

A theoretical model based on different authors (Dunkle and Clark's known as new model) was developed for both internal and external heat transfer (chapter 4). Evaporation, convective and radiative heat transfer coefficients are three types of heat transfer that are placed internally, and top, bottom and sides heat transfer coefficient are placed externally. Each of these terms are calculated separately to discover evaporation and condensation rate of solar still at different temperatures to calculate the theoretical values (predict) of the solar still productivity without considering any modification in the unit. Consequently, these results present the maximum amount of fresh water within constant temperature of the unit.

Next, the experimental results obtained through 14 individual experiments to find the best case operational state of the novel shape solar still. Later, these results will analyse with the theoretical and experimental productivity results values of conventional solar still unit.

7.1. Theoretical Results

7.1.1. Internal Heat Transfer (Evaporation Process)

The heat transfer is accompanied by transport of the vapour formed above the water surface through an air-vapour mixture in the solar still unit. Within this process the convective and evaporation heat transfer occurs in the unit, while the radiative heat transfer occurs inside and outside the solar still unit. Therefore, the heat transfer in the solar still that cause the productivity grouped into two and internal and external heat transfer. The internal heat transfer is responsible for the transportation of pure water in vapour form leaving behind all the impurities in the basin, whereas, the external heat transfer through condensing cover is responsible for the condensation of pure vapour as distillate. Both of the heat transfers are most desired heat transfers in a solar still, but external heat transfer through the sides and bottom of a solar still is very undesirable.

Internal and external transfer are two essential thermodynamic elements, which causes direct influence on both evaporation and condensation rate. Internal heat transfer governed by conduction, convection and radiation processes, which are independent of each other, are causes basin water evaporation, while external heat transfer throughout top cover and the unit body (bottom and sides)

causes condensation of water vapour. Hence, following results have been calculated based on productivity of the novel solar still to calculate the theoretical results of output freshwater.

As it was discussed in the thermal and heat principle of solar still chapter (part 4.2 table 12), a property of vapour depending on the temperature is one of the key points to comprehend the thermodynamic parameters in the solar still unit. The vapour temperature is expected to vary from 30 °C to 90 °C (Note: these values needed to analyse heat transfer in the solar still) .Table 25 presents properties of specific heat, density, thermal conductivity, viscosity, latent heat of water vaporization, partial saturated vapour pressure at condensing cover temperature, partial saturated vapour pressure at water temperature and expansion factor.

Table 25: Temperature dependent physical properties of vapour from 30 °C to 90 °C

Temperature (°C)	30	40	50	60	70	80	90
Specific heat (C_p) <i>J/kg °C</i>	1003.6	1005.1	1006.6	1008.1	1009.8	1011.3	1012.9
Density (ρ) kg/m^3	1.16	1.12	1.09	1.06	1.02	1.00	0.97
Thermal conductivity (k) <i>W/mK</i>	0.026	0.027	0.028	0.029	0.029	0.030	0.031
Viscosity (μ) <i>kg/m – s</i>	1.9186×10^{-5}	1.9264×10^{-5}	1.9324×10^{-5}	1.9472×10^{-5}	1.9527×10^{-5}	1.9619×10^{-5}	1.9738×10^{-5}
Latent heat of vaporization of water <i>(L) J/kg</i>	2.38×10^6	2.39×10^6	2.40×10^6	2.41×10^6	2.41×10^6	2.43×10^6	2.44×10^6
Expansion factor (β) <i>1/k</i>	0.0032	0.0031	0.0030	0.0029	0.0028	0.0028	0.0027

As it was mentioned in part 4.2, transition in a boundary layer depends on the relative magnitude of the buoyancy and viscous forces in natural convection in the fluid. It is correlated in terms of “Ra” number, which is the product of “Gr” and “Pr” numbers, where “Gr” looks after the type of flow and “Pr” the type of fluid. Table 26 presents the Grashof number (Gr), Prandtl number (Pr) and Rayleigh number (Ra) for a water layer of thickness 0.1 m with different value of ΔT (water temperature to the ambient temperature of average 20 °C) from equations 9, 10 and 11.

Table 26: Calculating Grashof number, Prandtl number and Rayleigh number for different temperature with water depth of 0.1 m.

ΔT (°C)	10	20	30	40	50	60	70
Gr	1.15 $\times 10^6$	2.05 $\times 10^6$	2.80 $\times 10^6$	3.36 $\times 10^6$	3.74 $\times 10^6$	4.28 $\times 10^6$	4.47 $\times 10^6$
Pr	0.74	0.71	0.69	0.67	0.67	0.66	0.64
Ra	0.85 $\times 10^6$	1.45 $\times 10^6$	1.93 $\times 10^6$	2.25 $\times 10^6$	2.50 $\times 10^6$	2.82 $\times 10^6$	2.86 $\times 10^6$

In order to calculate the convective heat transfer coefficient, partial saturated vapour pressure at condensing cover temperature (P_{ci}) and partial saturated vapour pressure at water temperature (P_w) calculated as follow (table 27):

Table 27: Partial saturated pressure table for different temperature

T (°C)	30	40	50	60	70	80	90
Partial saturated vapour pressure at condensing cover/ water temperature N/m^2	4188.51	7204.75	11983.71	19332.68	30330.69	46386.42	69399.06

The convective heat transfer coefficient (h_{cw}) calculated for different temperatures by using Dunkle's model from equation 43. The value of partial saturated vapour temperature at condensing cover (T_{ci}) assumed to be as room temperature at 20°C ($P_{ci} = 2346.51$), and partial saturated vapour temperature at water temperature (T_w) are varies from 30 °C to 90 °C. Therefore, by using equation 42, the value of convective heat transfer presented in table 28. The value of h_{ew} can be also found from equation 23.

Table 28: Convective heat transfer coefficient for different temperatures

T (°C)	30	40	50	60	70	80	90
Convective heat transfer coefficient (h_{cw}) W/m^2k	2.02	2.60	3.05	3.46	3.94	4.45	5.07
Evaporative heat transfer coefficient (h_{ew}) W/m^2k	0.026	0.033	0.039	0.044	0.051	0.057	0.065
Convective heat transfer (q_{cw}) W/m^2	20.2	52.0	91.5	138.4	197.0	267.0	354.9

In order to calculate convective heat transfer (h_{cw}) in part 4.2.1, two models were introduced. From equation 37 the value of “C” and “n” are varies depending to Gr number.

$$Nu = \frac{h_{cw} \times d}{k} = C(Gr \times Pr)^n$$

$$h_{cw} = \frac{k}{d} \times C(Gr \times Pr)^n$$

Values of thermal conductivity “ k ” can be presented from table 27 for different values of temperature of vapour. The value of water depth “ d ” is constant for laboratory experiment ($d=0.1$ m). The values of C and n are varies depending to the “Gr” number, which it was explained in a full detail in the methodology part 4.2.1.

Table 29: Dunckl's and Cooper (new) model convective heat transfer (h_{cw})

T (°C)	30	40	50	60	70	80	90
Dunkle's model (h_{cw})	1.84	2.20	2.42	2.55	2.64	2.75	2.76
New model (h_{cw})	2.39	2.99	3.36	3.59	3.75	3.94	3.96

From equation 25 the value of evaporative heat transfer coefficient (h_{ew}) for both Dunkle's and Cooper (new) model can be calculated as table 30.

Table 30: Dunckl's and new model evaporative heat transfer (h_{ew})

T (°C)	30	40	50	60	70	80	90
Dunkle's model (h_{ew})	5.51	8.69	12.65	17.62	24.04	32.84	43.02
New model (h_{ew})	7.16	11.81	17.56	24.80	34.15	47.06	61.72

The convective heat transfer coefficient “ h_3 ” for heat flow from horizontal basin liner to the water mass in the basin was presented in part 4.2.1.3. The present solar still unit has total basin area of 0.6 m² (assumption). Via using the equation 59 the values of convective heat transfer for different water temperature at the basin to the atmosphere (laboratory) at around 20 can be calculated as table 31. (Using appendix B)

Table 31: Convective heat transfer from basin liner to the water h_3

T (°C)	30	40	50	60	70	80	90
Convective heat transfer (h_3) W/m^2k	17.02	19.89	21.60	22.79	23.79	24.82	25.05

The rate of radiative heat transfer “ $\dot{q}_{rw}$ ” from the water surface to glass cover for considered infinite parallel planes (assumption: the water surface is in parallel to the glass cover due to the small inclination of glass cover and large width of solar still unit) is given by equation 60 in part 4.2.1.4.

In order to find the value of radiative heat transfer coefficient from water to the glass cover from equation 62, the value of “ ε_{eff} ” needs to be calculated from equation 63. The value of $\varepsilon_w = \varepsilon_g$ are 0.90 [327]. Therefore:

$$\varepsilon_{eff} = \left[\frac{1}{0.9} + \frac{1}{0.9} - 1 \right]^{-1} = 0.82$$

Consequently, the value of radiative heat transfer coefficient h_{rw} from water surface to the glass cover with atmosphere temperature of 20 °C can be calculated as table 32.

Table 32: Radiative heat transfer coefficient h_{rw}

T (°C)	30	40	50	60	70	80	90
Radiative heat transfer coefficient (h_{rw}) W/m^2k	4.89	5.15	5.41	5.69	5.98	6.28	6.60

The total internal heat transfer coefficient is the combination of convective, evaporative and radiative heat transfer coefficient from water surface to the inner surface of glasses that it can be find from equation 64 (table 33).

Table 33: Total internal heat transfer coefficient

T (°C)	30	40	50	60	70	80	90
Convective heat transfer coefficient $(h_{cw}) \text{ W/m}^2\text{k}$	2.02	2.60	3.05	3.46	3.94	4.45	5.07
Evaporative heat transfer coefficient $(h_{ew}) \text{ W/m}^2\text{k}$	0.026	0.033	0.039	0.044	0.051	0.057	0.065
Radiative heat transfer coefficient (h_{rw}) $\text{W/m}^2\text{k}$	4.89	5.15	5.41	5.69	5.98	6.28	6.60
Total internal heat transfer coefficient $(h_{1w}) \text{ W/m}^2\text{k}$	6.916	7.783	8.499	9.194	9.971	10.787	11.735

The absolute value of the total rate of internal energy transfer from water to the glass can be found by summation of all heat transfer rates between the two. This is obtained by the addition of the resultant values of respective heat transfer obtained by equations 17, 42 and 61 that it can be found in table 34.

$$\dot{Q}_1 = \dot{Q}_{cw} + \dot{Q}_{ew} + \dot{Q}_{rw}$$

$$\dot{Q}_1 = h_{cw}(T_w - T_{ci}) + h_{ew}(P_w - P_{ci}) + h_{rw}F_{12}(T_w + T_{ci})$$

Table 34: Total internal heat transfer

T (°C)	30	40	50	60	70	80	90
Convective heat transfer $(\dot{Q}_{cw})$ W/m^2	20.2	52.0	91.5	138.4	197.0	267.0	354.9
Evaporative heat transfer $(\dot{Q}_{ew})$ W/m^2	47.8	160.3	375.8	747.3	1427.1	2510.2	4358.4
Radiative heat transfer $(\dot{Q}_{rw})$ W/m^2	244.7	309.0	378.7	455.2	538.2	628.0	726.0
Total internal heat transfer $(\dot{Q}_1) \text{ W/m}^2$	312.7	521.3	922.5	1340.9	2162.3	3405.2	5439.3

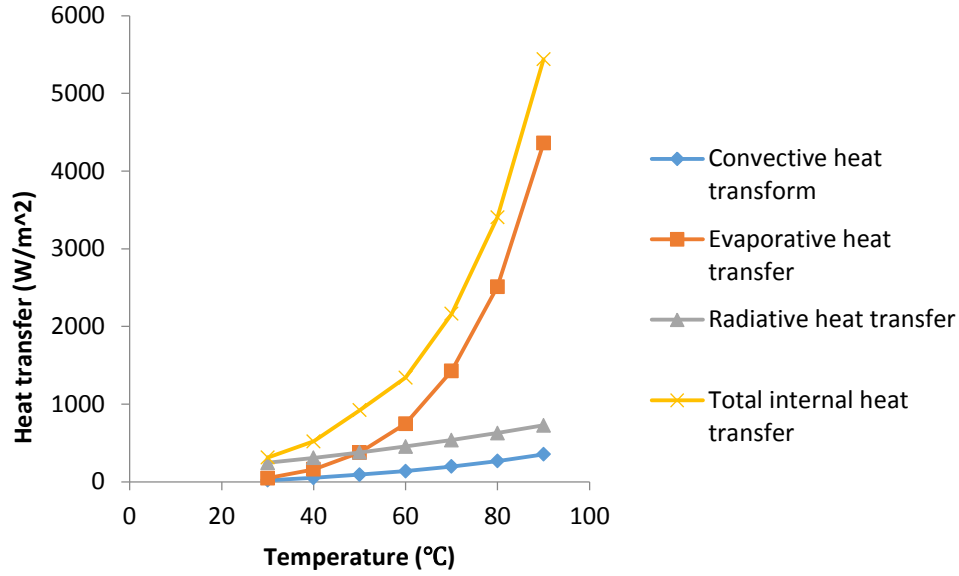


Figure 142: Total internal heat transfer

The relative significance of these three modes of heat transfer can be better understood by energy fractions of each mode. Thus, evaporative, convective and radiative energy fraction can be calculated from equation 66 as table 35 presents.

Table 35: Evaporative, convective and radiative energy fraction

T (°C)	30	40	50	60	70	80	90
Evaporative Energy fraction (F_e)	0.15	0.30	0.40	0.55	0.65	0.73	0.80
Convective Energy fraction (F_c)	0.06	0.09	0.09	0.10	0.09	0.07	0.06
Radiative Energy fraction (F_r)	0.78	0.59	0.41	0.33	0.24	0.18	0.13

The variation of these three energy fractions with respect to water temperature for indoor simulation as carried out for 15° inclinations of condensing cover and 0.1 m water depth.

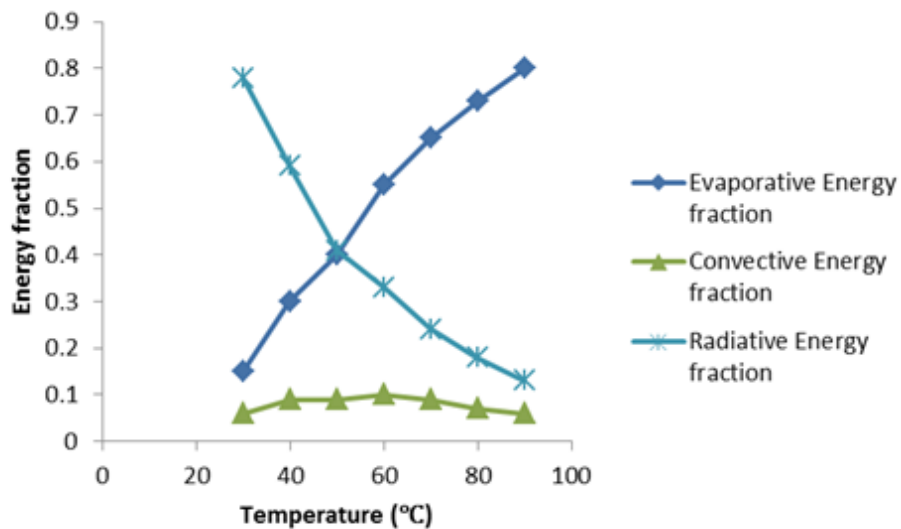


Figure 143: Evaporative, convective and radiative energy fraction

7.1.2. External Heat Transfer (Condensation Process)

Internal heat transfer in solar still was discussed earlier, but there are two type of external heat transfer placed in the solar still unit. One is the heat transfer from condensing cover made of glass to the ambient (former), and two is from body of the solar still to ambient (latter).

In order to calculate the overall top loss coefficient U_t , the value of heat transfer coefficient h_{rg} , h_{lg} and h_{cg} needed to be calculated from equations 72, 74 and 75 ($l_g = 0.003 \text{ m}$, $k_g = 1.01 \text{ W/mK}$). Table 36 presents the value of heat transfer coefficients and total top loss coefficient as follow (the value of h_{cg} is constant with value of $2.8 \text{ W/m}^2\text{k}$ as there is no wind in the laboratory experiment):

Table 36: Top heat loss coefficient

T ($^{\circ}\text{C}$)	30	40	50	60	70	80	90
Radiative heat transfer coefficient from water to glass cover (h_{rg}) $\text{W/m}^2\text{k}$	8.39	7.17	6.97	7.03	7.20	7.43	7.71
convective heat transfer coefficient from water to glass cover (h_{cg}) $\text{W/m}^2\text{k}$	2.80	2.80	2.80	2.80	2.80	2.80	2.80
Radiative heat transfer coefficient from lower basin to glass cover (h_{lg}) $\text{W/m}^2\text{k}$	11.19	9.97	9.77	9.83	10.00	10.23	10.51
Total internal loss coefficient (h_{lw}) $\text{W/m}^2\text{k}$	6.91	7.78	8.49	9.19	9.97	10.78	11.73
Overall top loss coefficient (U_t) $\text{W/m}^2\text{k}$	4.23	4.33	4.50	4.70	4.94	5.19	5.48

The external radiative and convective losses from glass cover to the outside atmosphere $\dot{q}_g$ (W/m^{-2}) was given in equation 73 as it presents in table 37.

Table 37: The external to heat losses

T ($^{\circ}\text{C}$)	30	40	50	60	70	80	90
Total external top heat loss from top cover ($\dot{q}_g$) W/m^{-2}	119.00	199.40	293.10	393.2	500.00	613.80	735.7

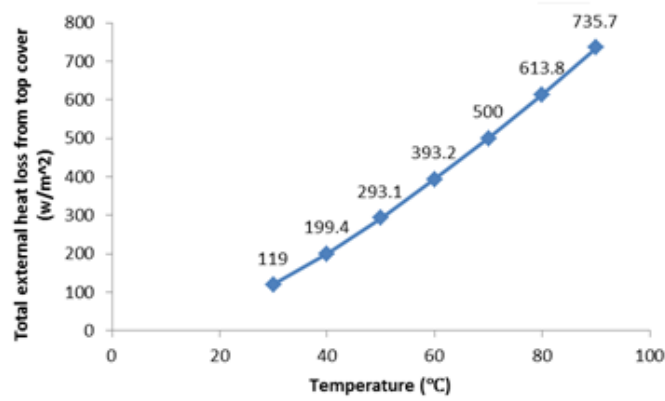


Figure 144: Total external heat loss from top cover vs temperature

The second external heat transfer loss placed from the water mass in basin to the ambient through the insulated wall and from the basin liner to the ambient through the insulated bottom. The introduced solar still was mounted on a stand wheels, therefore the bottom and side heat losses occur in sequence (first convection, then conduction and finally convection) and radiation losses to the ambient.

The structure of solar still was made of 9 mm plywood with thermal conductivity of 0.1154 W/mK . The top layer of basin area was covered by 3mm pond liner with thermal conductivity of 0.19 W/mK . The value of bottom and side loss can be calculated from equations 81 and 82 follow:

$$U_b = \left(\frac{0.1154}{0.009} \right) + \left(\frac{0.19}{0.003} \right) = 76.15$$

$$U_s = \left(\frac{(2 \times 0.01 \times 1.2) + (2 \times 0.01 \times 0.5)}{1.2 \times 0.5} \right) \times \left(\frac{0.1154}{0.009} \right) = 0.72$$

$$U_{bs} = 76.87 \text{ W/m}^2\text{k}$$

Therefore, the overall heat transfer coefficient from water to ambient through top, bottom and sides was given in equation 84 as table 38 shows.

Table 38: The overall heat transfer coefficient of solar still

T (°C)	30	40	50	60	70	80	90
The overall heat transfer coefficient (U_L) $\text{W/m}^2\text{k}$	81.10	81.20	81.37	81.57	81.81	82.06	82.35
Total external top heat loss from solar still unit ($\dot{q}_g$) W/m^{-2}	200.10	280.60	374.47	474.77	581.81	695.86	818.05

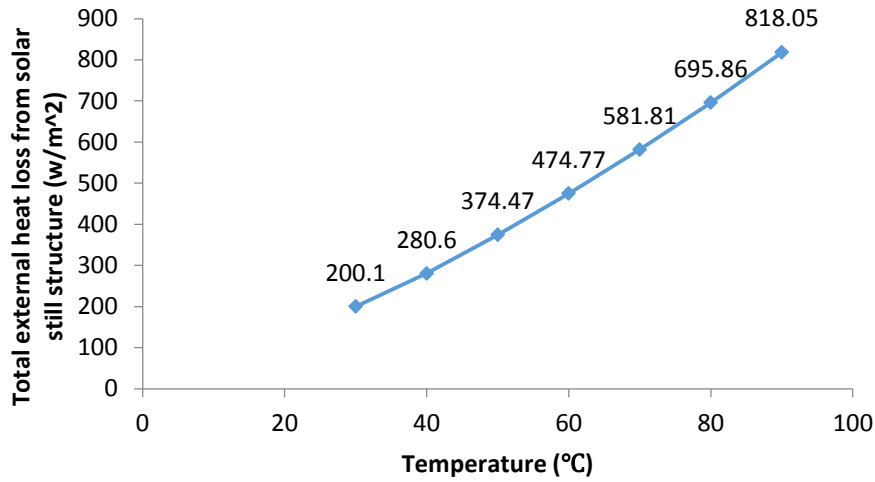


Figure 145: Total external heat loss through the structure of solar still

7.1.4. Hourly Theoretical Solar Still Productivity

The theoretical values of output from the solar still can be calculated using equation 28 after evaluating the internal and external heat transfer. Therefore, the hourly (60 minutes) distillate from distiller unit can be found in table 39.

Table 39: Solar still output (theoretical)

T (°C)	30	40	50	60	70	80	90
The hourly distillate output of solar still unit ($\dot{m}_{ew}$) $kg/m^2 h$	0.08	0.26	0.56	1.05	1.79	2.91	4.43

Figure 146 presents the values of hourly productivity of present solar still with its specifications.

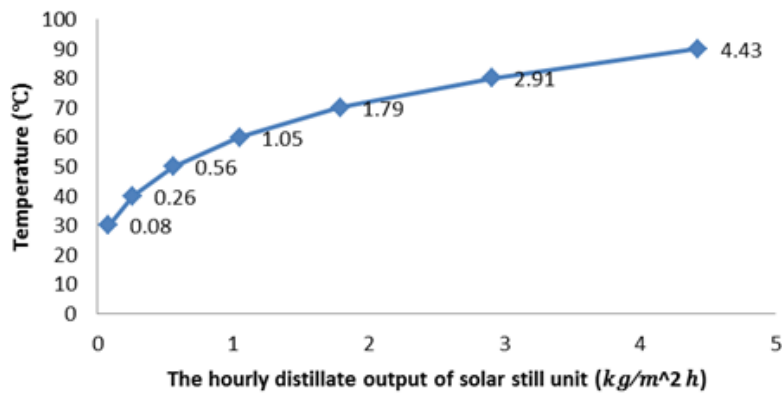


Figure 146: Theoretical results of solar still productivity

These theoretical hourly results obtained to be evaluated with experimental hourly results (set 1 experiments) in order to measure productivity of the conventional solar still with its descriptions in the construction. There are no operational parameters (except basin water depth) considered in these theoretical calculation, thus it is important to measure the effect of new modifications in the solar still productivity.

7.1.5. Heat Exchanger

One of the main key in designing the novel solar still was to calculate the temperature difference of heat exchanger pipes between evaporated water inside pipe and the effect of it to the productivity of solar still. The evaporated water is extracted by ventilation fan; which it is connected to the pipes that passes through the basin water. In this process, the thermal energy (heat) of evaporated water extracted by basin water and it helps the vapour condenses within higher rate which it increases the productivity of solar still unit.

The water vapour concentration rise considerably as the basin water temperature increases, as a result the vapour concentration reaches 100% at 100 °C. However, the density difference between water vapour and air still exist. Therefore, the assumption in calculating the amount of energy transfers by heat exchanger to the solar still basin water taken as the vapour temperature stay at constant temperature of 100 °C at the time. Correspondingly, there is no heat loss of vapour between ventilation fan and to the basin water, so the vapour reaches to the basin at same temperature as it getting out of ventilation fan.

The steam water specific heat on the collector has a value of $C_p = 4216 \text{ J/kg K}$ and flow rates are varies (chapter 5.3). The UA of the copper pipes is estimated to be as maximum 455 W/K ($U = 340\text{--}455 \text{ W/m}^2 \text{ K}$) [328]. The steam water enters the 8x10mm copper pipes with total length of 5.735 m, which it acts as heat exchanger, on the basin area of 0.6 m^2 by the basin water. The temperature of basin water varies between 30 to 90 °C therefore the heat exchanger rate and outlet temperature can be calculated:

The capacitance rates on the high and low temperatures sides of the heat exchanger and the value of “ C^* ” can be calculated by using equation 116 (section 5.3):

$$C_h = 0.0001 \times 4216 = 0.4216 \text{ W/K}$$

$$C_c = 0.0003 \times 4180 = 1.254 \text{ W/K}$$

Then, the cold-side capacitance rate is the minimum of the two, and it can be obtained from equations 115 and 116:

$$C^* = \frac{0.4216}{1.254} = 0.3362$$

$$NTU = \frac{UA}{(\dot{m}C_p)_{\min}} = \frac{0.3141}{0.4216} = 0.75$$

The effectiveness is now can be obtained by equation 114:

$$\varepsilon = \frac{1 - e^{-0.75(1-0.3362)}}{1 - 0.3362 e^{-0.75(1-0.3362)}} \cong 0.50$$

As a result, the average heat transfers with the maximum fan flow rate inside heat exchanger copper pipes are calculated from equation 113 (table 40 and figure 147):

Table 40: Avrage heat transfer trough heat exchanger at diffrent temprature

T (°C)	30	40	50	60	70	80	90
Heat transfer with heat exchanger ($\dot{Q}_{hex}$) W	14.75	12.64	10.54	8.43	6.32	4.21	2.10

It can be notice that the amount of heat transfer from copper pipes, which it transfers to the basin water, is not considerable, but it reduces the rate of decreasing basin water temperature during sun set period.

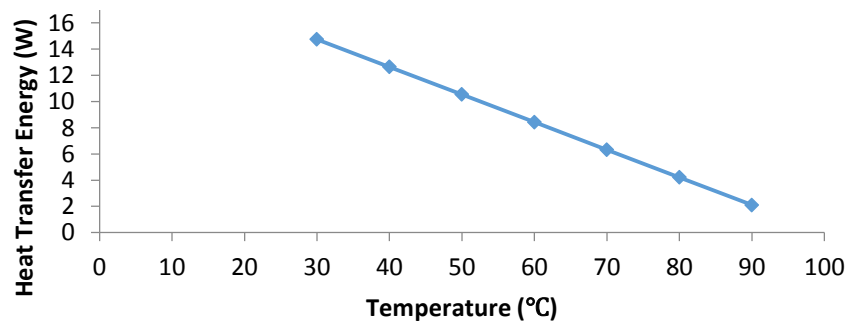


Figure 147: Heat transfer energy by heat exchanger to basin water at different temperature

The rate of energy transfer at lower basin water temperature is higher and it can be determined the effect of using heat exchanger at lower temperature is more beneficial. Accordingly, the relation between the heat transfer by heat exchanger and temperature has reverse relation with the basin water.

7.2. Experimental Results

The experimental results are divided into two sets of experiment:

1. Set 1 was stated to measure the HOURLY productivity of solar still (with/without fan) at constant basin water temperatures to be evaluated with the theoretical values of the conventional solar still (4 experiments).
2. Set 2 was stated to measure 20 HOURS productivity of solar still with its novel modifications such as different fan air flow ratio with/without shroud and lava stone as heat strong material to be evaluated with the conventional solar till experimental results (10 experiments).

7.2.1. Set 1 Experiments (Constant Temperature Productivity)

The first sets of experiments were set at the constant temperatures of 30, 40, 50 and 60 °C to measure the hourly productivity of the solar still in order to find the outcome at different temperature with its maximum fan air flow (1.4 l/s). Further, these results compared with theoretical values to optimise the best operational condition of the solar still unit. Accordingly, the solar still productivity was also measured without using vapour extraction ventilation fan and heat exchanger to measure the productivity as the conventional solar still (without modifications). The comparison results between the amounts of fresh water produced within these experiments with and without fan presents the effect of modify solar still (with fan and heat exchanger) to the conventional solar still.

Experiment 1

The water was heated in the external tank to the temperature of 45°C, and then it was pumped in the basin area of the solar still. By the time it reaches the basin area, the water temperature was reduced to approximately 30°C. Figure 143 present the value of temperature at different part of the unit. The ventilation fan was also set to its maximum fan flow rate (1.4 l/s) without shroud. In addition, the productivity of the solar still without using the fan at same constant basin water temperature (30°C) as the conventional solar still.

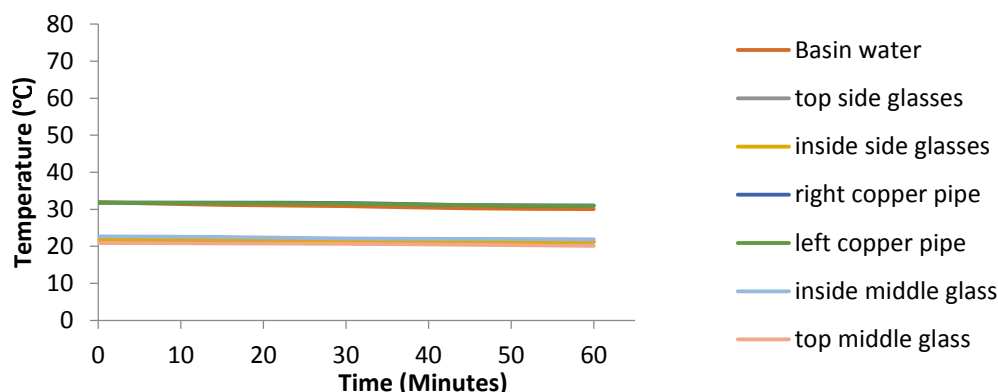


Figure 148: Temperatures at different part of solar still unit (experiment 1)

The total amount of fresh water that was collected after a period of one hour was **0.03 litres** (*Output 1*: 0.014 litres; *Output 2*: 0.0 litres; *Output 3*: 0.016 litres) with fan (without shroud). No water (**0.0 litres**) was collected during the conventional still experiment without running fan.

Experiment 2

The water was heated in the external tank to the temperature of 55°C, and then it was pumped in the basin area of the solar still. By the time it reaches the basin area, the water temperature was reduced to approximately 40°C. Figure 144 present the value of temperature at different part of the unit. The ventilation fan was also set to its maximum fan flow rate (1.4 l/s) without shroud. In addition, the productivity of the solar still without using the fan at same constant basin water temperature (40°C) as the conventional solar still.

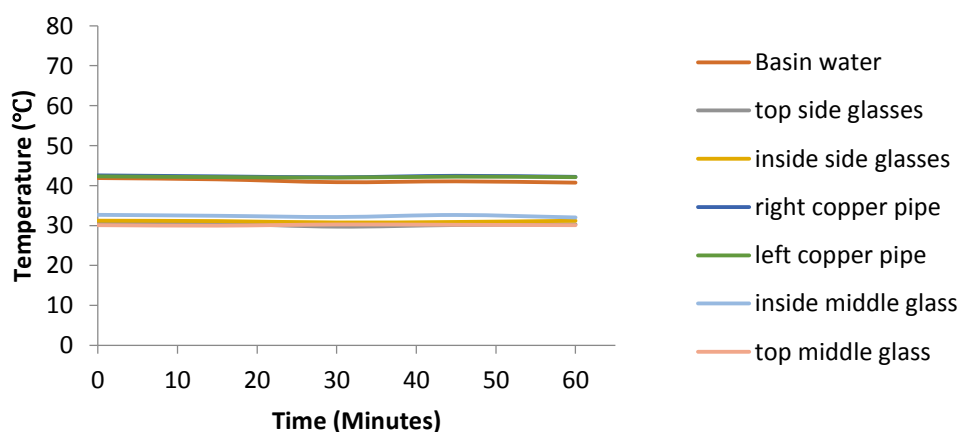


Figure 149: Temperature at different part of solar still unit (experiment 2)

The total amount of fresh water that was collected after a period of one hour was **0.15 litres** (*Output 1*: 0.06 litres; *Output 2*: 0.04 litres; *Output 3*: 0.05 litres) with fan (without shroud). The amount of water was collected as the conventional still (without running fan) was **0.09 litres**.

Experiment 3

The water was heated in the external tank to the temperature of 65°C, and then it was pumped in the basin area of the solar still. By the time it reaches the basin area, the water temperature was reduced to approximately 50°C. Figure 145 present the value of temperature at different part of the unit. The ventilation fan was also set to its maximum fan flow rate (1.4 l/s) without shroud. In addition, the productivity of the solar still without using the fan at same constant basin water temperature (40°C) as the conventional solar still.

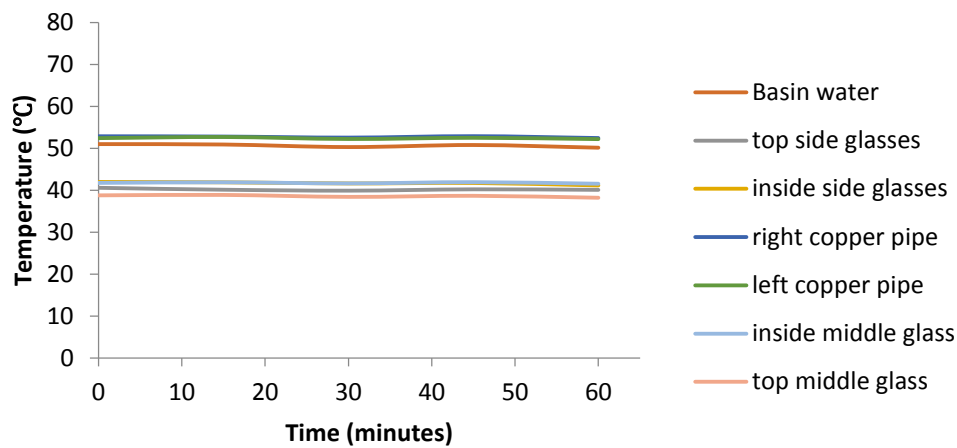


Figure 150: Presents the value of temperature at different part of solar still unit (experiment 3)

The total amount of fresh water that was collected after a period of one hour was **0.36 litres** (*Output 1: 0.14 litres; Output 2: 0.09 litres; Output 3: 0.13 litres*) with fan (without shroud). The amount of water was collected as conventional still (without running fan) was **0.22 litres**.

Experiment 4

The water was heated in the external tank to the temperature of 75°C, and then it was pumped in the basin area of the solar still. By the time it reaches the basin area, the water temperature was reduced to approximately 60°C. Figure 146 present the value of temperature at different part of the unit. The ventilation fan was also set to its maximum fan flow rate (1.4 l/s) without shroud. In addition, the productivity of the solar still without using the fan at same constant basin water temperature (40°C) as the conventional solar still.

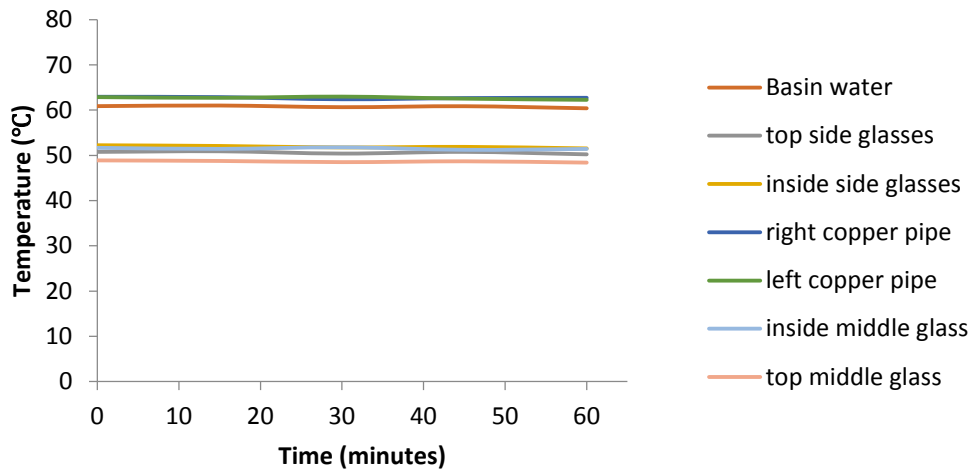


Figure 151: Presents the value of temperature at different part of solar still unit (experiment 4)

The total amount of fresh water that was collected after a period of one hour was **0.73 litres** (*Output 1: 0.26 litres; Output 2: 0.22 litres; Output 3: 0.25 litres*) with fan (without shroud). The amount of water was collected as conventional still (without running fan) was **0.51 litres**.

7.2.2. Set 2 Experiments (Operation Modifications Productivity)

7.2.2.1. Group Two Experiments (Different fan air flow ratio with “a” and without “b” shroud)

The second group of set two experiments were configured with the different fan flow rate with (“a” experiments) and without (“b” experiments) the fan shroud and its impact on productivity of the solar still. In each experiment, the blue coloured water was heated up to 90 °C in the external tank and it was pumped in the solar still basin area. Then, the solar still unit was running for a period of 20 hours till the basin water reaches the laboratory temperature (room temperature). Similar category of experiments also taken place by adding shroud to the ventilation fan inside solar still to determine the effect of air turbulence inside solar still that it was generated by ventilation fan to the solar still productivity.

Experiment 5

The water was heated in the external tank to the temperature of 90°C, and then it was pumped in the basin area of the solar still. By the time it reaches the basin area, the water temperature was reduced to approximately 70°C. The ventilation fan was also set to its maximum fan flow rate (**1.4 l/s**) with “a” and without “b” shroud in this experiments collection.

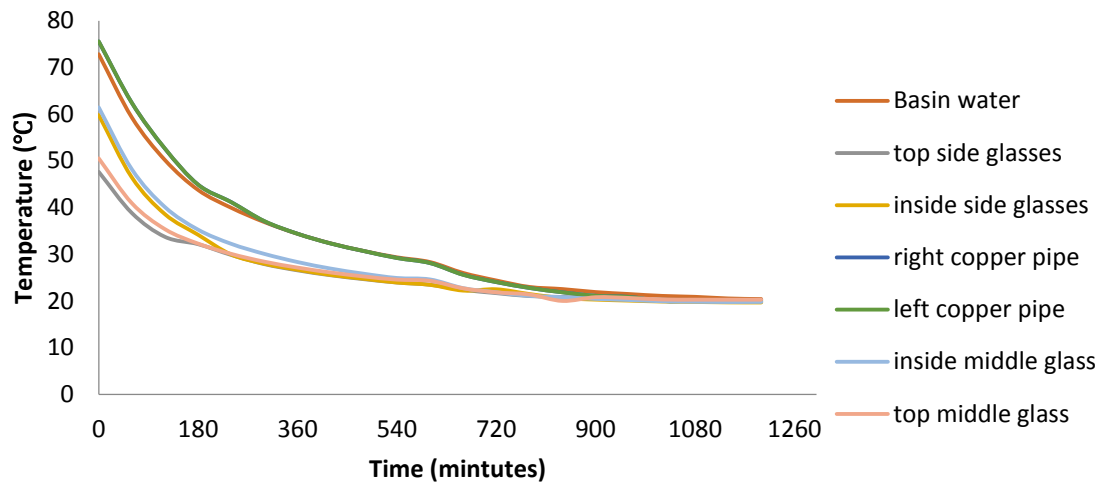


Figure 152: Temperature at different part of solar still unit with fan shroud (experiment 5a)

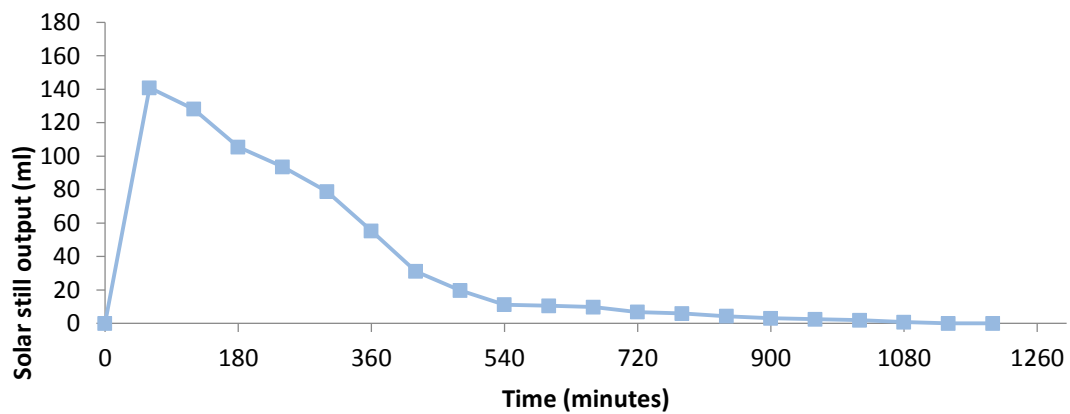


Figure 153: Productivity of solar still with fan shroud (amount of fresh water collected)

Total amount of fresh water collected within 20 hours experiments with fan flow rate of 1.4 l/s and with frame was **0.702 litres** (Output 1: 0.236 litres; Output 2: 0.254 litres; Output 3: 0.212 litres).

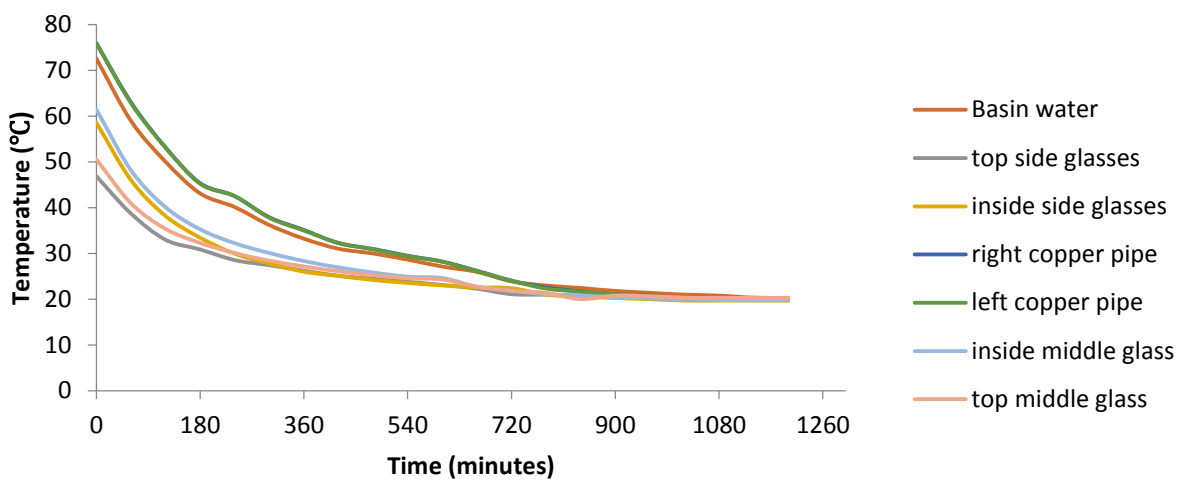


Figure 154: Temperature at different part of solar still unit without fan shroud (experiment 5b)

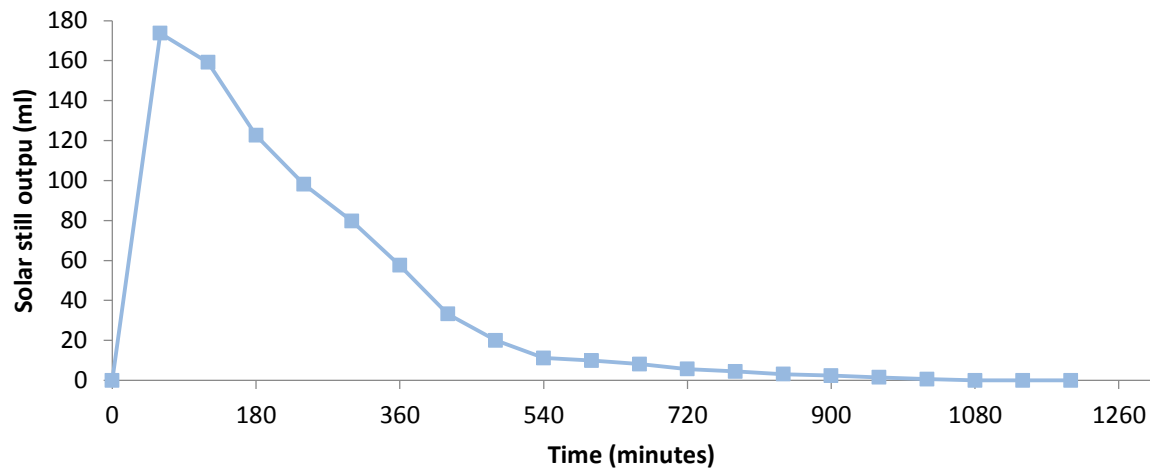


Figure 155: Productivity of solar still without fan shroud (amount of fresh water collected)

Total amount of fresh water collected within 20 hours experiments with fan flow rate of 1.4 l/s and without frame was **0.791 litres** (*Output 1: 0.320 litres; Output 2: 0.238 litres; Output 3: 0.233 litres*).

Experiment 6

The water was heated in the external tank to the temperature of 90°C, and then it was pumped in the basin area of the solar still. By the time it reaches the basin area, the water temperature was reduced to approximately 70°C. The ventilation fan was also set to its maximum fan flow rate (**1.2 l/s**) with “a” and without “b” shroud in this experiments collection.

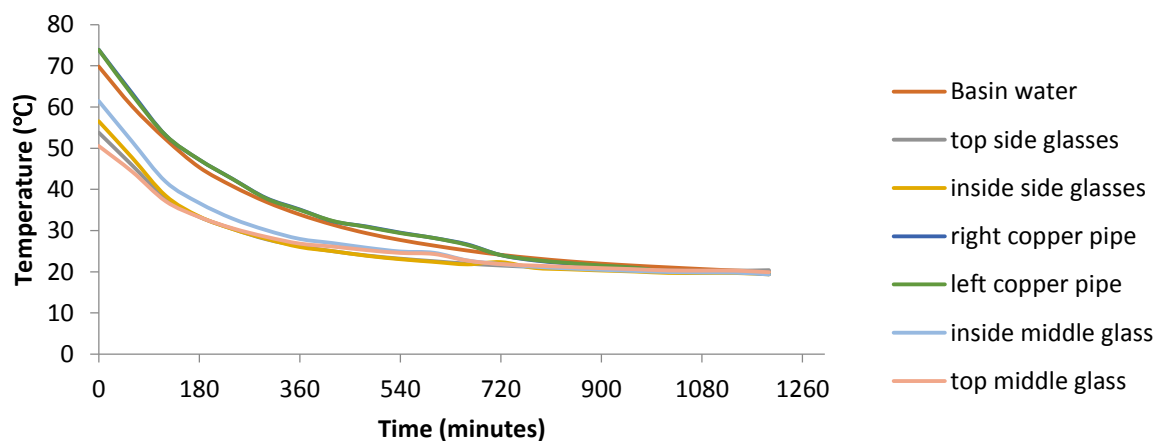


Figure 156: Temperature at different part of solar still unit with fan shroud (experiment 6a)

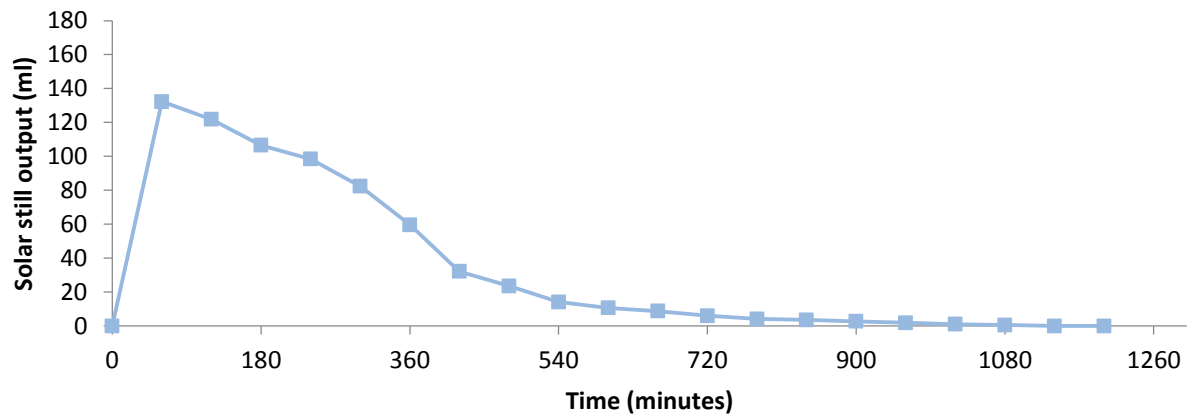


Figure 157: Productivity of solar still with fan shroud (amount of fresh water collected)

Total amount of fresh water collected within 20 hours experiments with fan flow rate of 1.2 l/s and with frame was **0.710 litres** (Output 1: 0.273 litres; Output 2: 0.194 litres; Output 3: 0.243 litres).

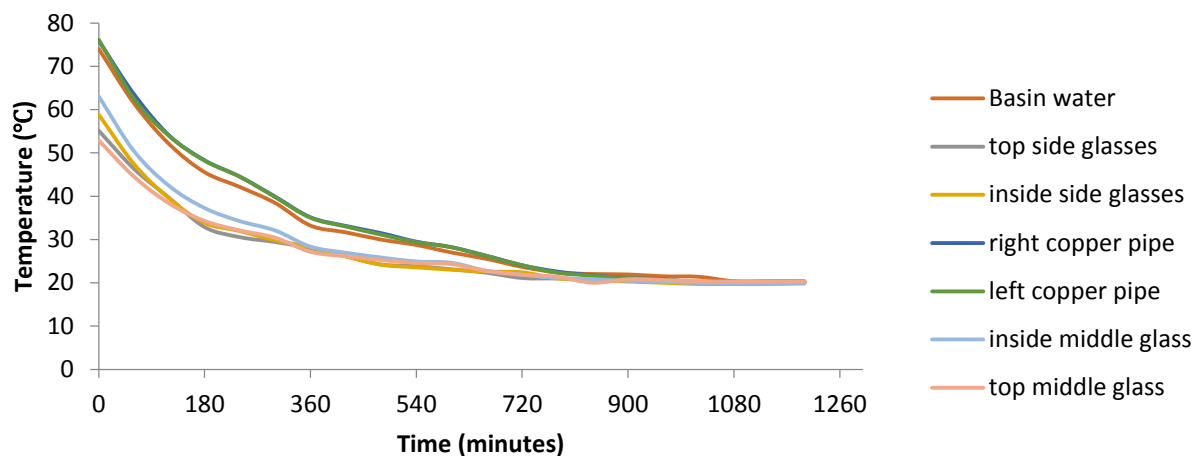


Figure 158: Temperature at different part of solar still unit without fan shroud (experiment 6b)

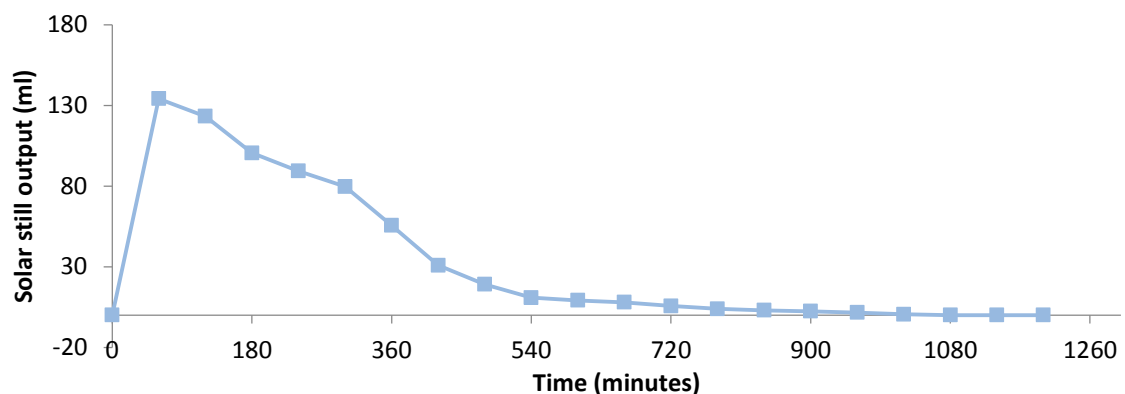


Figure 159: Productivity of solar still without fan shroud (amount of fresh water collected)

Total amount of fresh water collected within 20 hours experiments with fan flow rate of 1.2 l/s and without frame was **0.677 litres** (Output 1: 0.266 litres; Output 2: 0.187 litres; Output 3: 0.224 litres).

Experiment 7

The water was heated in the external tank to the temperature of 90°C, and then it was pumped in the basin area of the solar still. By the time it reaches the basin area, the water temperature was reduced to approximately 70°C. The ventilation fan was also set to its maximum fan flow rate (**0.9 l/s**) with “a” and without “b” shroud in this experiments collection.

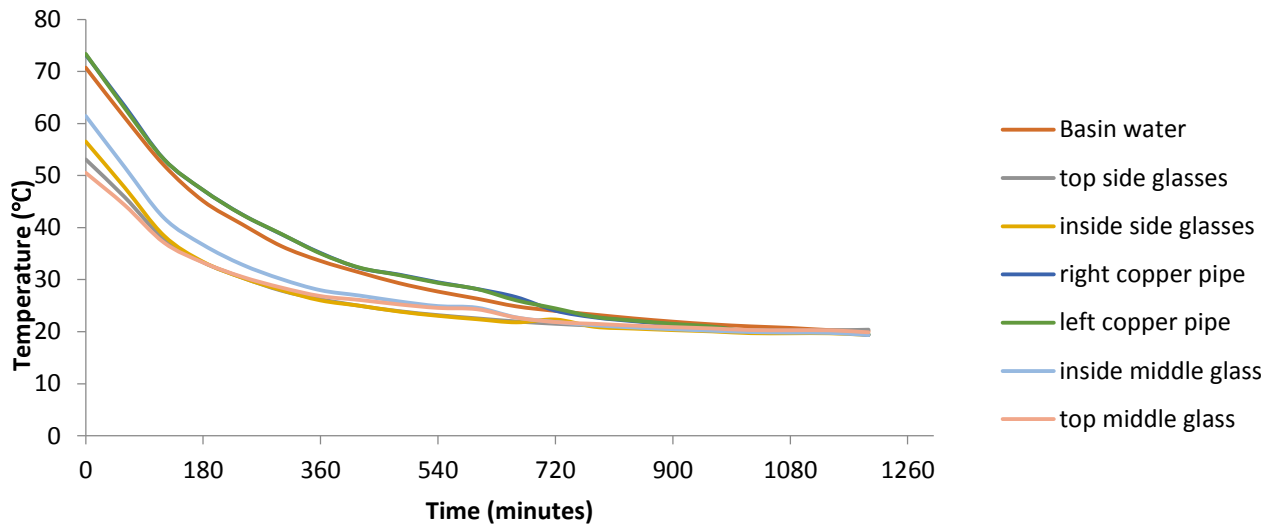


Figure 160: Temperature at different part of solar still unit with fan shroud (experiment 7a)

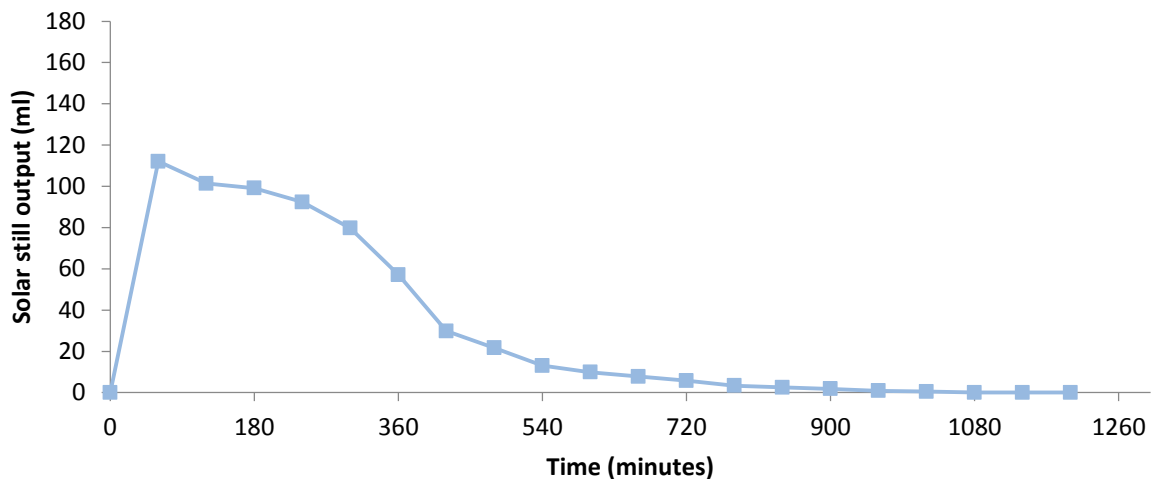


Figure 161: Productivity of solar still with fan shroud (amount of fresh water collected)

Total amount of fresh water collected within 20 hours experiments with fan flow rate of 0.9 l/s and with frame was **0.639 litres** (Output 1: 0.247 litres; Output 2: 0.173 litres; Output 3: 0.219 litres).

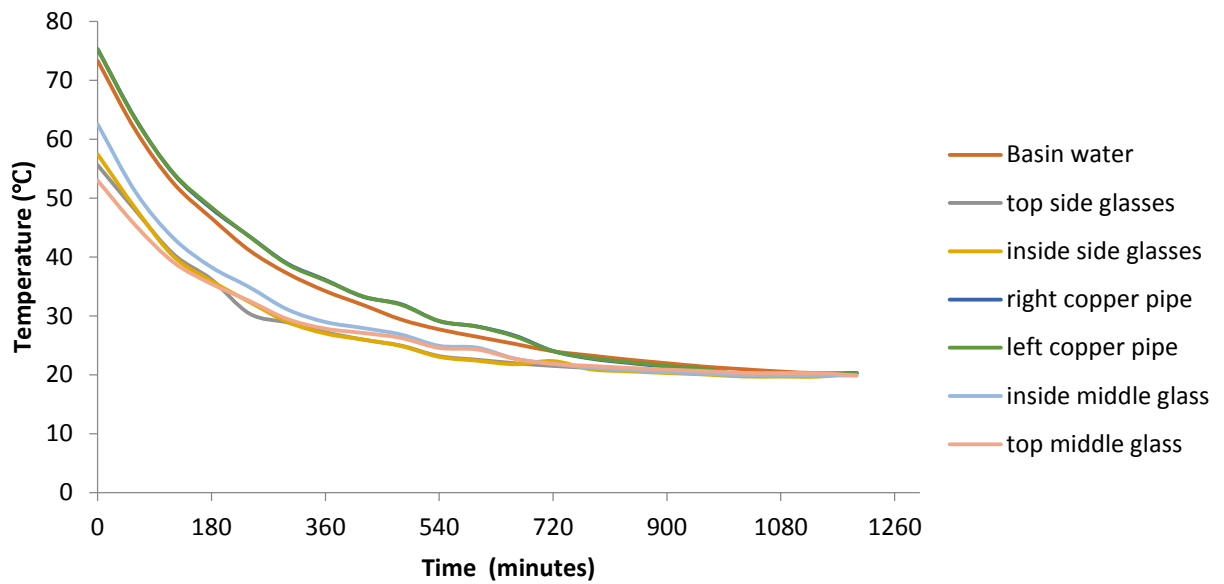


Figure 162: Temperature at different part of solar still unit without fan shroud (experiment 7b)

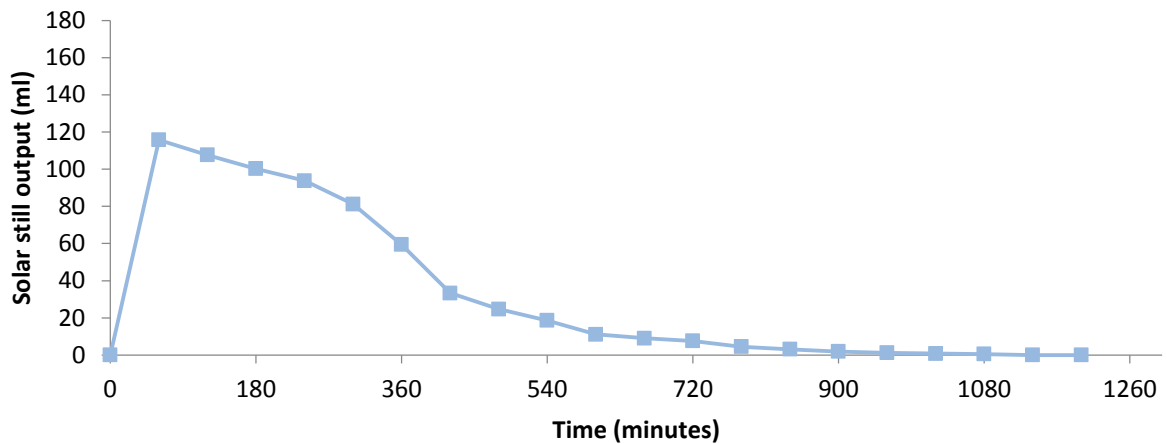


Figure 163: Productivity of solar still without fan shroud (amount of fresh water collected)

Total amount of fresh water collected within 20 hours experiments with fan flow rate of 0.9 l/s and without frame was **0.674 litres** (Output 1: 0.254 litres; Output 2: 0.189 litres; Output 3: 0.231 litres).

Experiment 8

The water was heated in the external tank to the temperature of 90°C, and then it was pumped in the basin area of the solar still. By the time it reaches the basin area, the water temperature was reduced to approximately 70°C. The ventilation fan was also set to its maximum fan flow rate (**0.6 l/s**) with “a” and without “b” shroud in this experiments collection.

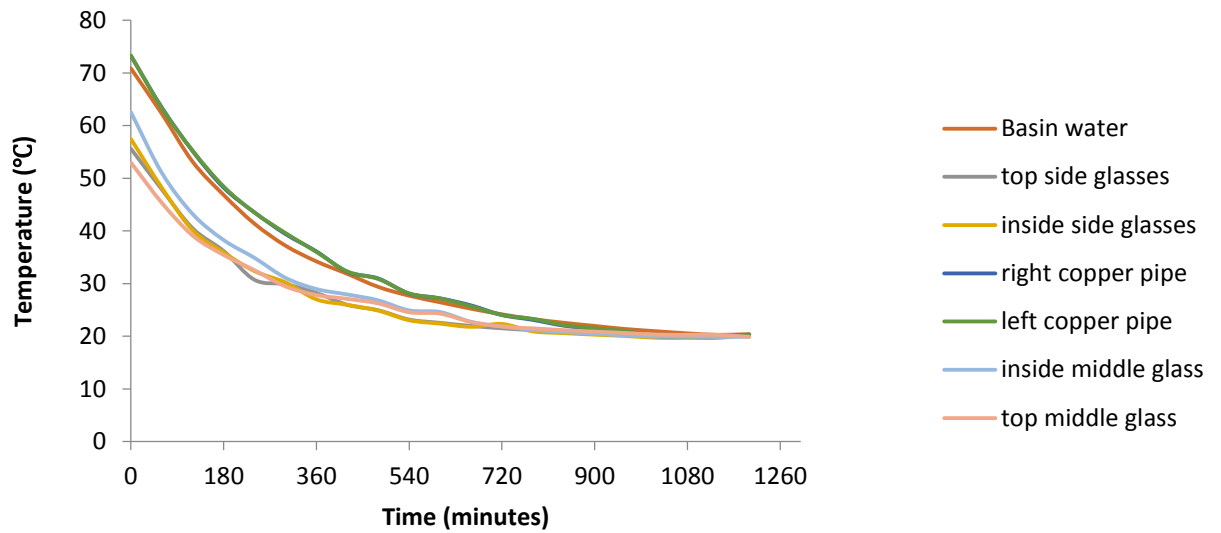


Figure 164: Temperature at different part of solar still unit with fan shroud (experiment 8a)

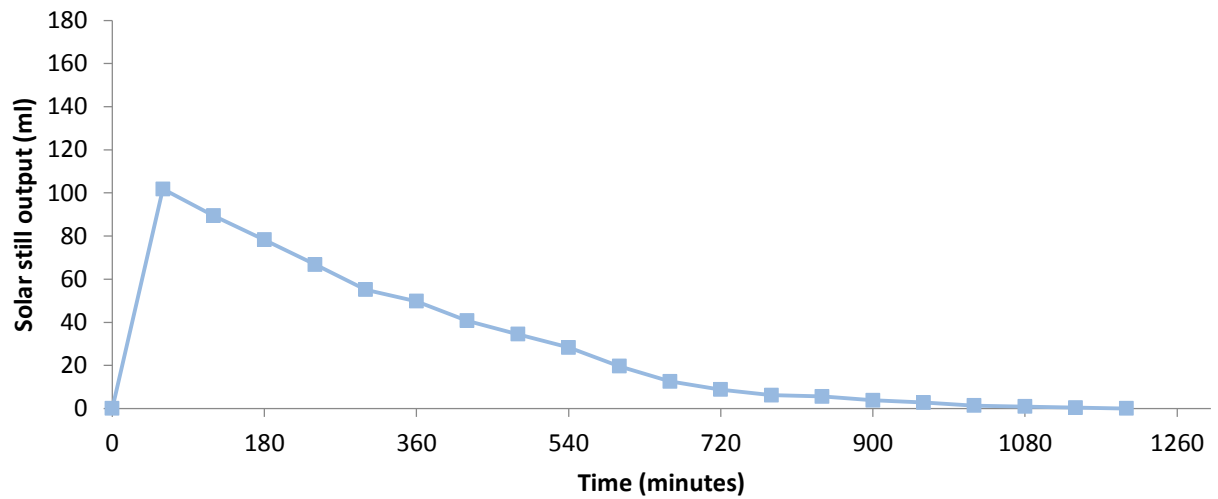


Figure 165: Productivity of solar still with fan shroud (amount of fresh water collected)

Total amount of fresh water collected within 20 hours experiments with fan flow rate of 0.6 l/s and with frame was **0.606 litres** (Output 1: 0.236 litres; Output 2: 0.148 litres; Output 3: 0.222 litres).

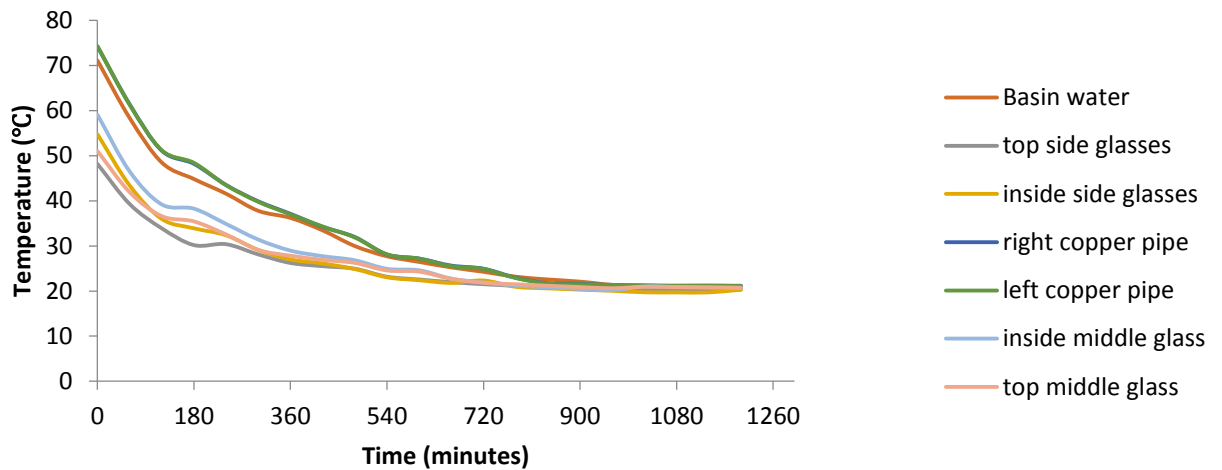


Figure 166: Temperature at different part of solar still without fan shroud (experiment 8b)

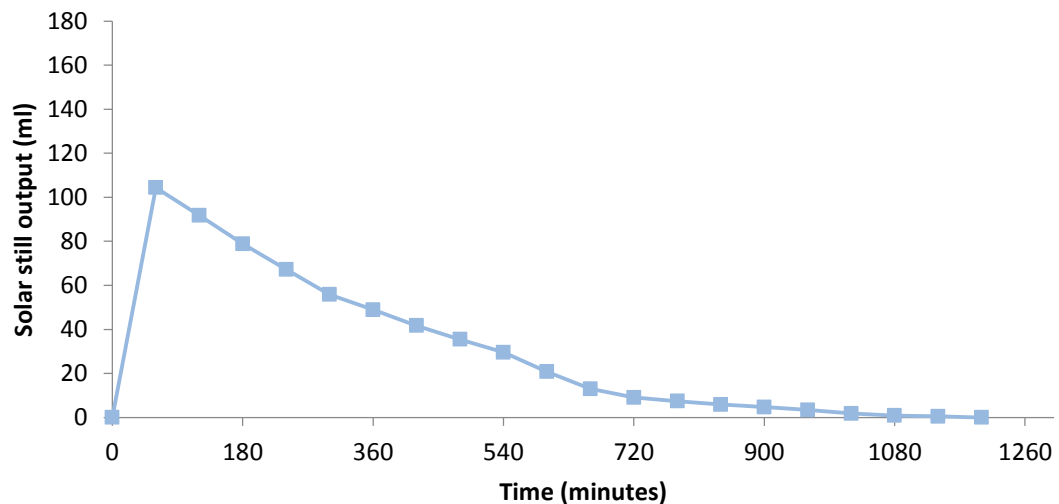


Figure 167: Productivity of solar still without fan shroud (amount of fresh water collected)

Total amount of fresh water collected within 20 hours experiments with fan flow rate of 0.6 l/s and without frame was **0.621 litres** (Output 1: 0.244 litres; Output 2: 0.158 litres; Output 3: 0.219 litres).

7.2.2.2. Group Three Experiments (Thermal storage material)

The third group of set two experiments were configured with the different fan flow rate (1.4, 1.2, 0.9 and 0.6 l/s) without the shroud (as it was found from set two experiments, the solar still productivity is greater without the shroud) with the lava stones as heat storage material (thermal conductivity of 1.7 W/m K [324]) on top of basin area. In each experiment, the blue coloured water was heated up to 90 °C in the external tank and it was pumped in the solar still basin area. Then, the solar still unit was running for a period of 20 hours till the basin water reaches the laboratory temperature (room temperature).

Experiment 9

The water was heated in the external tank to the temperature of 90°C, and then it was pumped in the basin area of the solar still. By the time it reaches the basin area, the water temperature was reduced to approximately 70°C. The ventilation fan was also set to its maximum fan flow rate (**1.4 l/s**) with lava stones in this experiment results collection.

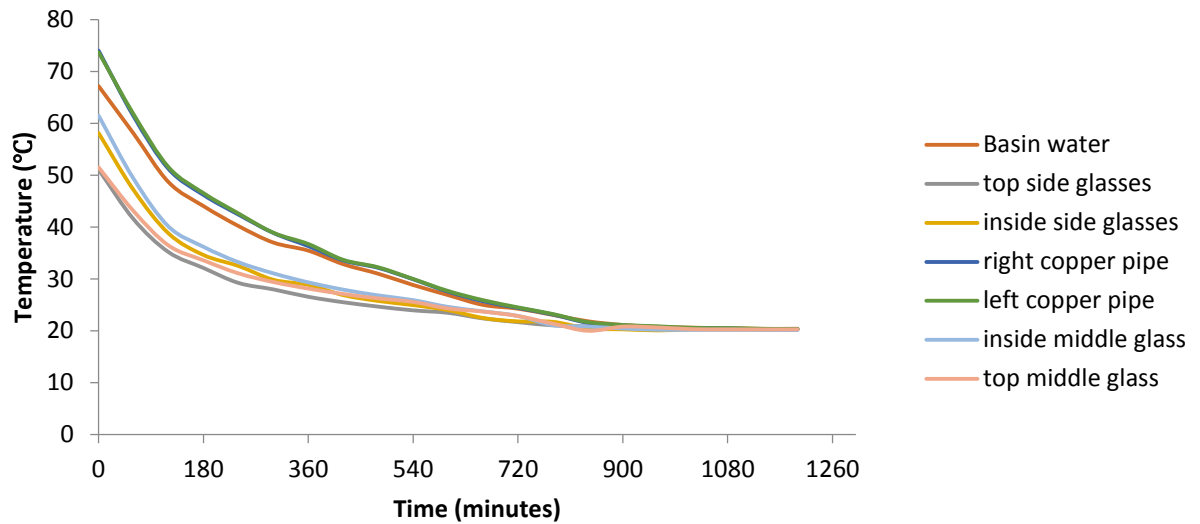


Figure 168: Temperature at different part of solar still unit (experiment 9)

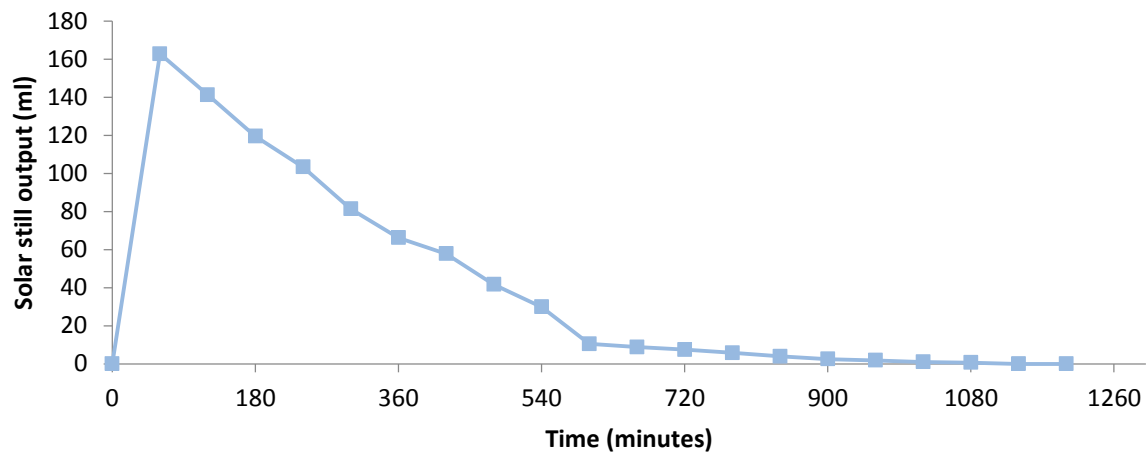


Figure 169: Productivity of solar still without fan shroud with lava stone (amount of fresh water collected)

Total amount of fresh water collected within 20 hours experiments with fan flow rate of 1.4 l/s and without frame with Lava stones on the basin area as heat storage material was **0.846 litres** (*Output 1*: 0.311 litres; *Output 2*: 0.242 litres; *Output 3*: 0.293 litres).

Experiment 10

The water was heated in the external tank to the temperature of 90°C, and then it was pumped in the basin area of the solar still. By the time it reaches the basin area, the water temperature was reduced to

approximately 70°C. The ventilation fan was also set to its maximum fan flow rate (**1.2 l/s**) with lava stones in this experiment results collection.

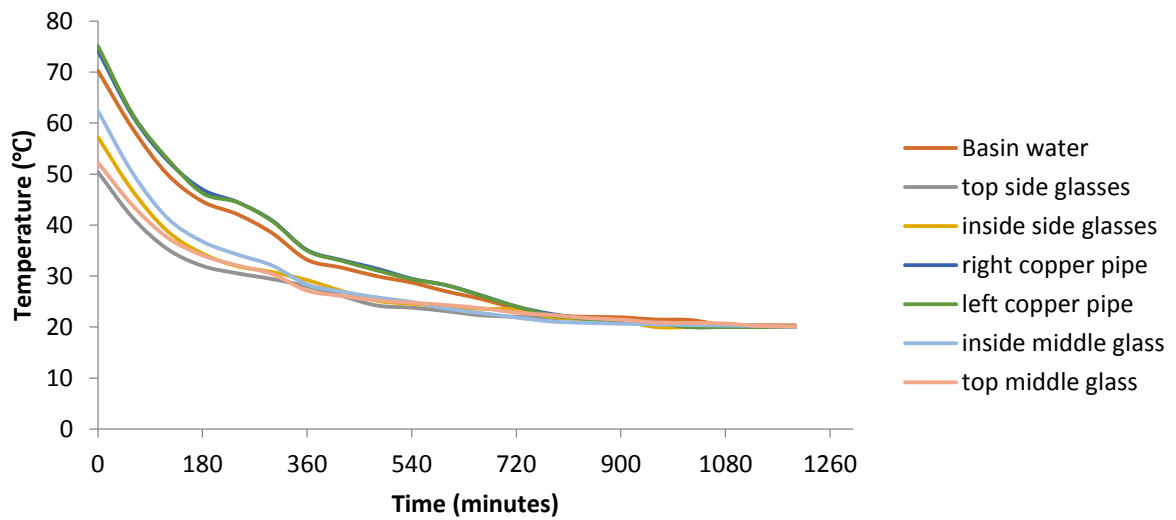


Figure 170: Temperature at different part of solar still unit (experiment 10)

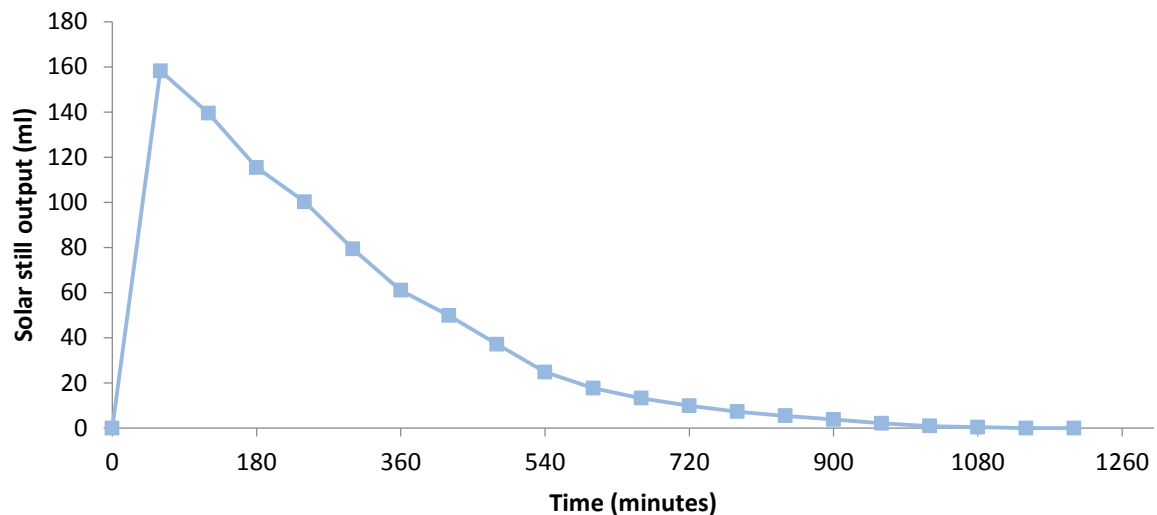


Figure 171: Productivity of solar still without fan shroud with lava stone (amount of fresh water collected)

Total amount of fresh water collected within 20 hours experiments with fan flow rate of 1.2 l/s and without frame with lava stones on the basin area as heat storage material was **0.826 litres** (*Output 1: 0.313 litres; Output 2: 0.219 litres; Output 3: 0.294 litres*).

Experiment 11

The water was heated in the external tank to the temperature of 90°C, and then it was pumped in the basin area of the solar still. By the time it reaches the basin area, the water temperature was reduced to approximately 70°C. The ventilation fan was also set to its maximum fan flow rate (**0.9 l/s**) with lava stones in this experiment results collection.

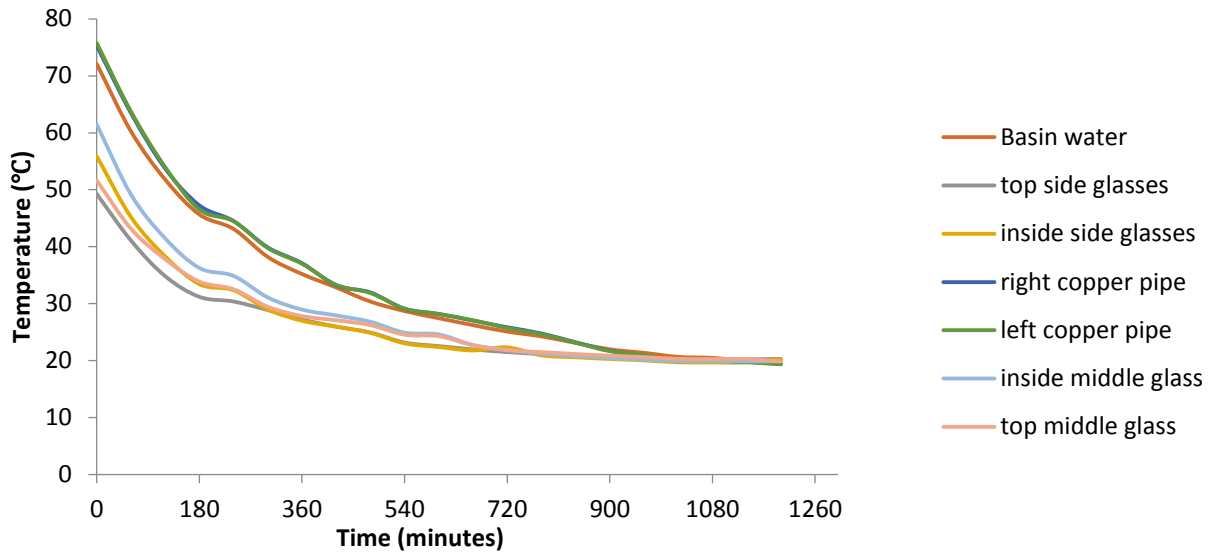


Figure 172: Temperature at different part of solar still unit (experiment 11)

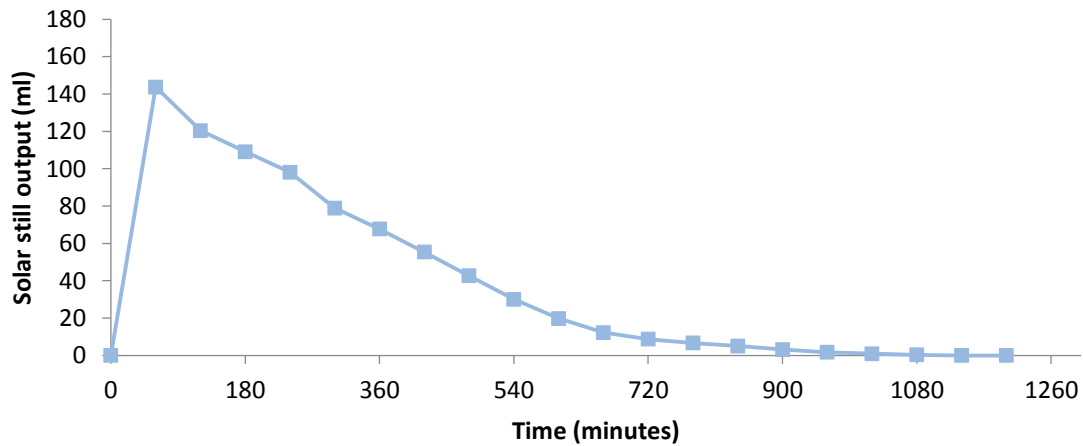


Figure 173: Productivity of solar still without fan shroud with lava stone (amount of fresh water collected)

Total amount of fresh water collected within 20 hours experiments with fan flow rate of 0.9 l/s and without frame with lava stones on the basin area as heat storage material was **0.805 litres** (*Output 1*: 0.316 litres; *Output 2*: 0.199 litres; *Output 3*: 0.290 litres).

Experiment 12

The water was heated in the external tank to the temperature of 90°C, and then it was pumped in the basin area of the solar still. By the time it reaches the basin area, the water temperature was reduced to approximately 70°C. The ventilation fan was also set to its maximum fan flow rate (**0.6 l/s**) with lava stones in this experiment results collection.

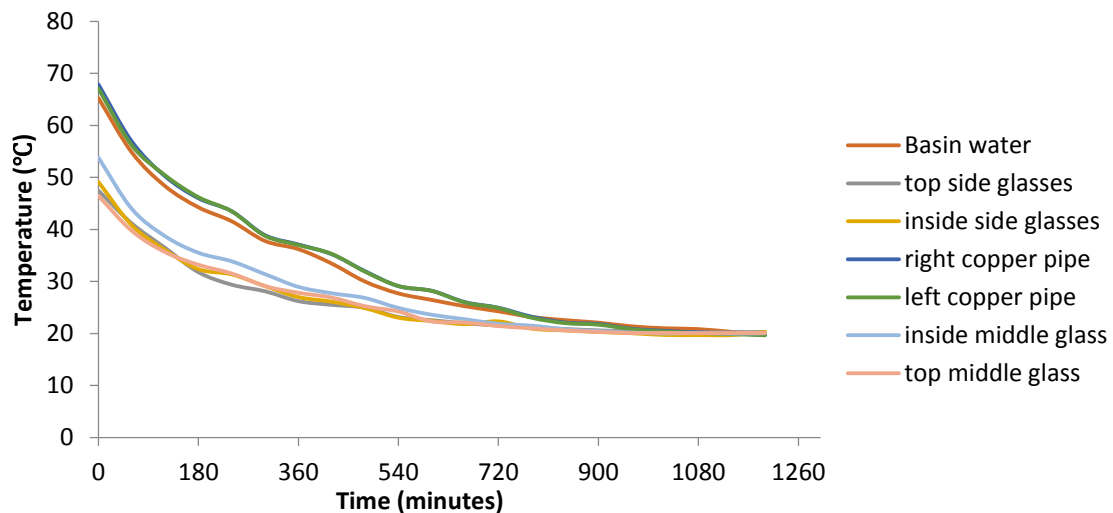


Figure 174: Temperature at different part of solar still unit (experiment 12)

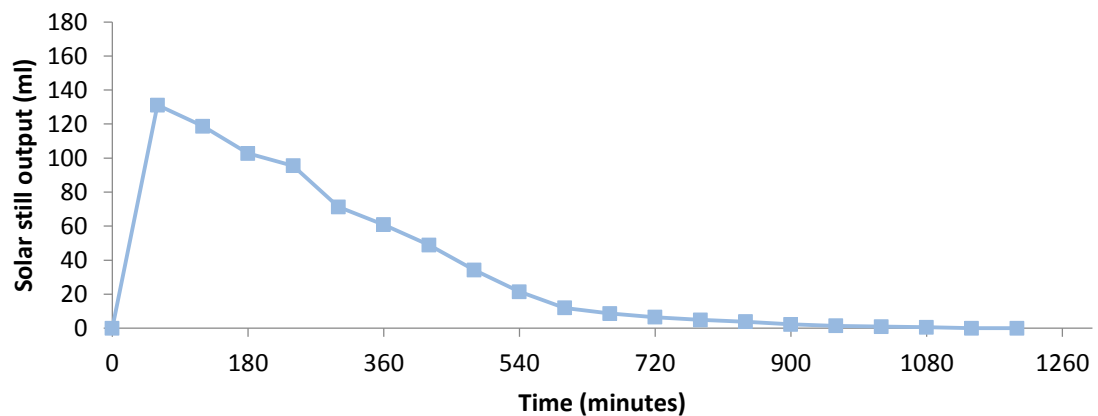


Figure 175: Productivity of solar still without fan shroud with lava stone (amount of fresh water collected)

Total amount of fresh water collected within 20 hours experiments with fan flow rate of 0.6 l/s and without frame with lava stones on the basin area as heat storage material was **0.725 litres** (Output 1: 0.247 litres; Output 2: 0.163 litres; Output 3: 0.315 litres).

7.2.2.3. Group Four Experiments (Conventional solar still without using the fan)

The four group of set two experiments were configured with the different without running the ventilation fan (No heat exchanger) with/without lava stones on top of basin area as conventional solar still. In each experiment, the blue coloured water was heated up to 90 °C in the external tank and it was pumped in the solar still basin area. Then, the solar still unit was running for a period of 20 hours till the basin water reaches the laboratory temperature (room temperature).

Experiment 13

The water was heated in the external tank to the temperature of 90°C, and then it was pumped in the basin area of the solar still. By the time it reaches the basin area, the water temperature was reduced to

approximately 70°C. There are no operational modifications (fan, heat exchanger and lava stones) in this experiment as the results present the solar still as the conventional unit.

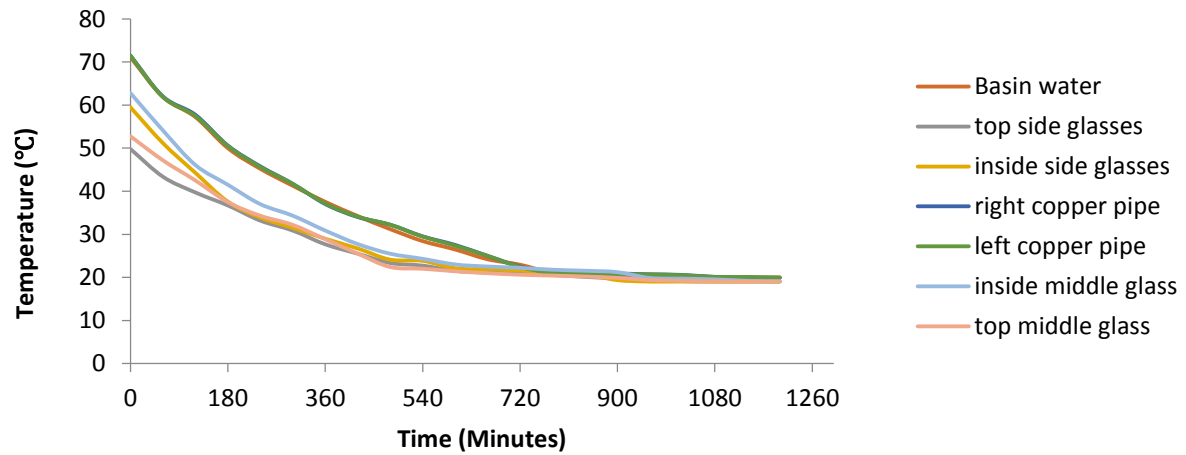


Figure 176: Temperature at different part of solar still unit (experiment 13)

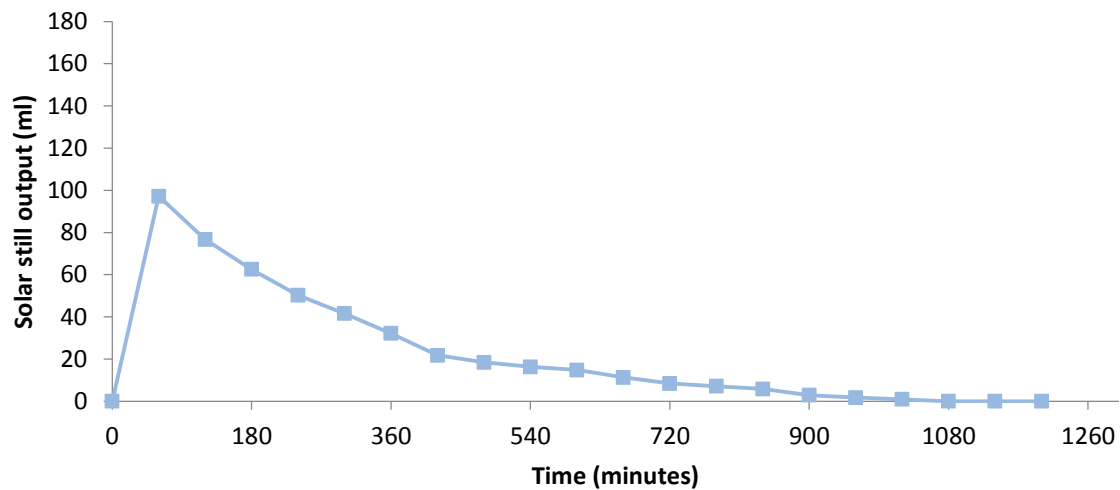


Figure 177: Productivity of solar still without fan without lava stone (amount of fresh water collected)

Total amount of fresh water collected within 20 hours experiments without fan and without lava stones on the basin area was **0.469 litres** (*Output 1*: 0.184 litres; *Output 2*: 0.121 litres; *Output 3*: 0.164 litres).

Experiment 14

The water was heated in the external tank to the temperature of 90°C, and then it was pumped in the basin area of the solar still. By the time it reaches the basin area, the water temperature was reduced to approximately 70°C. There is no fan in this experiment, but lava stones were added on the basin area to measure the solar still productivity in compare with the conventional unit.

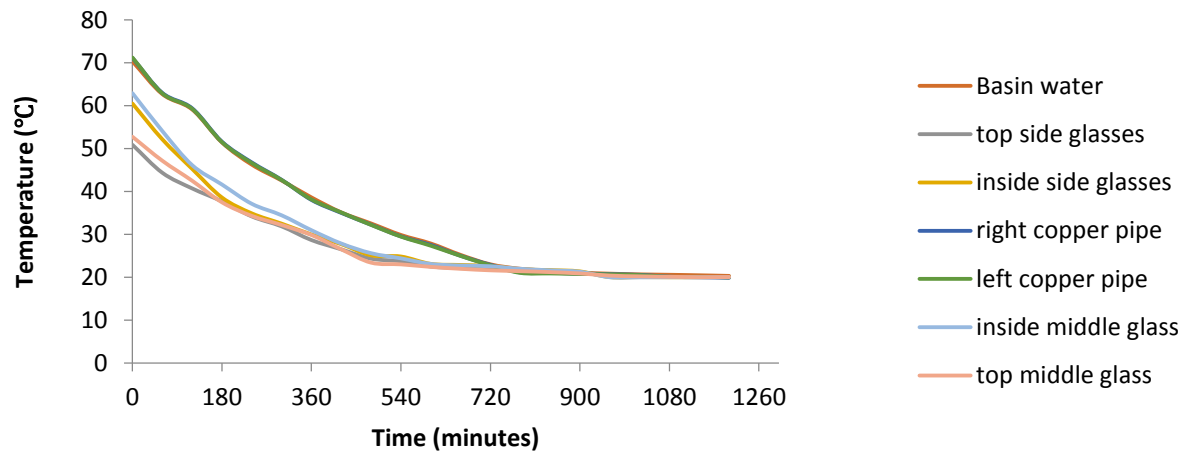


Figure 178: Temperature at different part of solar still unit (experiment 14)

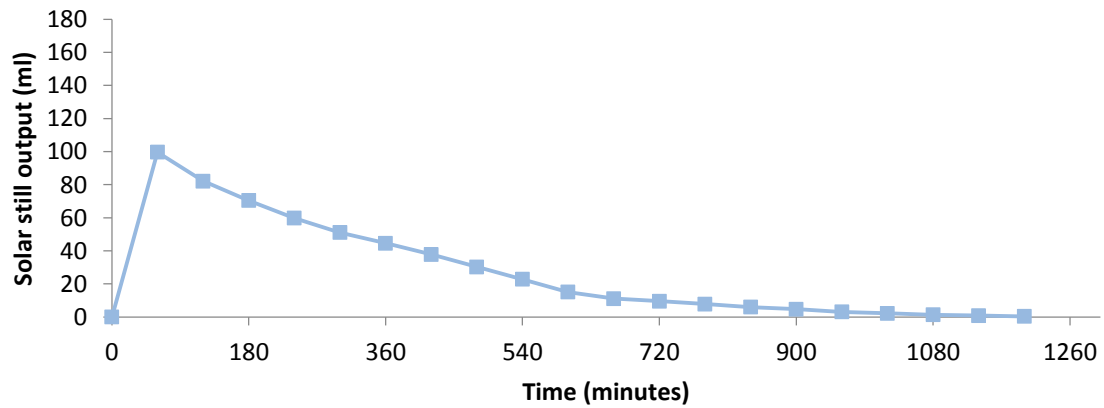


Figure 179: Productivity of solar still without fan with lava stone (amount of fresh water collected)

Total amount of fresh water collected within 20 hours experiments without fan and with lava stones on the basin area was measured **0.561 litres** (*Output 1: 0.220 litres; Output 2: 0.142 litres; Output 3: 0.199 litres*).

8. Discussions

The present study investigate to review and design of the use of the direct solar still in production and treatment of clean water in the form of drinking water, in particular the water sources from brackish water in remote areas.

The aim of this research was to explore new method of direct solar desalination to increase the daily productivity of fresh water per unit of area for small community scale in inaccessible area. The introduce method is to design and fabricate the single basin double slope solar still enhance with internal ventilation fan and the heat exchanger. This study set out to assess the impact of ventilation fan that it connected to the heat exchanger copper pipes to the productivity of solar still and its effects on evaporation and condensation rate. The unit was also designed in a way to be used linear focus Fresnel lens in order to concentrate and direct solar radiations into the solar still basin area.

This study demonstrates that using ventilation fan has a direct influence on both evaporation and condensation rate, thus it is important to discover the best state of ventilation fan air flow ratio for the yield of solar still unit. This study has also shown that using copper pipes as heat exchanger has its direct influence to the yield of solar still.

As the core set of activities within this project, three designs were presented namely structure of single basin double slope solar still unit, ventilation fan and heat exchanger. This gave an overall view of available systems and design options for the equipment used in the process which would result in efficient desalination operation.

After undertaking a set of calculations in order to translate the vapour volume into the ventilation fan capacity indicators, a universal unit for evaluation of fan capacity was obtained. The process involved considerations in terms of geographical location of the site, weather information and evaporation tank volume in terms of forecasted seawater volume capacity. A common parameter that measures the capacity of the ventilation fans is air flow rate, which in the experiment of the design for this particular project had a variable values.

In contrast to some reports in the literature, there were differences between the present solar still unit and some other work in geometry plus the structure. The structure of solar still was designed to use two Fresnel lenses as solar radiation concentrator. The other differences are using ventilation fan and internal heat exchanger in order to escalate the productivity.

In order to examine the outcome of solar still with new modifications, numbers of experiments in compare with theoretical analysis has been completed. The results are broadly consistent with constant climatic parameters as the tests were placed in the laboratory.

As it was discussed earlier, there was two sets of experiments were carried out to measure the hourly productivity in order to compare the experimental results with the theoretical conventional solar still, while a second set of experiments were used to examine the best operational parameters to accomplish the maximum fresh water productivity of the unit. Accordingly, this chapter explains the theoretical and experimental results to evaluate the unit productivity under different condition. Future, the water production and the effect of using the fan, thermal storage material and heat exchanger pipis will be discussed to assess results.

8.1. Theoretical Results Heat Transfer Evaluation

The efficiency of a solar still can be described as the amount of thermal energy ratio operated to get an amount of distilled water within a certain time. Therefore, there are two main heat transfers placed in the solar still. These two heat transfers can be classified as internal and external. Calculating physical properties of vapour such as specific heat, density, thermal conductivity, viscosity, latent heat of water vaporization, expansion factor and partial saturated vapour pressure (table 27) at its constant temperature are key elements to calculate internal and external heat transfer in solar still.

The internal heat transfer is responsible for transportation of fresh water in vapour from saline water in the basin area, while, the external heat transfer through condensing cover is in control for condensation of pure vapour as distillate water. Both of the heat transfers are most desired heat transfers in the solar still.

The total internal heat transfer process ($\dot{Q}_1$) can be divided into convective heat transfer ($\dot{Q}_{cw}$), evaporative heat transfer ($\dot{Q}_{ew}$) and radiative heat transfer ($\dot{Q}_{rw}$). Figure 142 presents the total internal heat transfer with its modes through the solar still. The most internal heat transfer in the present solar still is evaporative heat as it is one of the key elements to increase the productivity still. The importance of these three heat transfer modes can be better understood by the energy fraction of each mode (figure 143). Therefore, these three energy fractions with respect to water temperature showed that the evaporative energy rises as the temperature rises, while radiative fraction decreases. It can be also noted that the convective energy fraction reduces slightly within different values of temperature and it does not have impact in compare to two other heat transfer elements as internal heat transfer in presented solar still. Therefore, the best temperature that the solar still productivity start to produce considerable amount of fresh water is above 50 °C. Although by using better insolation material in order to reduce heat loss through the structure and top cover the productivity of solar still increases and it starts from lower temperatures. The results from experimental work also proved that the water production below the temperature 30 °C is almost zero.

External heat transfer mode ($\dot{q}_g$) is mainly directed by conduction ($\dot{Q}_{dg}$), convection ($\dot{Q}_{cg}$) and radiation ($\dot{Q}_{rg}$) procedure, which are independent of each other. These heat transfers exist outside solar still, from glass cover and the bottom and side protection. The total external heat loss for both top cover and structure of present solar still presented in figure 144 and 145. Figure 180 indicates the comparison of total internal and external heat transfer.

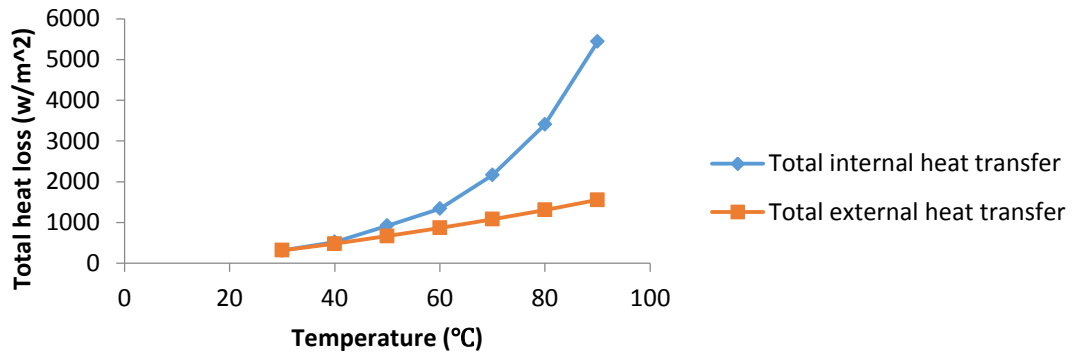


Figure 180: Total internal and external heat transfer vs temperature

From figure 180, it can be found the difference between the total amount of internal and external heat transfer. It can be noted that the external heat transfer raises steady while the internal heat transfer escalate exponentially as the temperature of basin water increases.

The developed energy balance equations are solved iteratively to estimate the temperatures, mass balance and energy rate stream in the solar still unit as function of time over constant period of time. The hourly values of improvement potential rate calculated for the different experiment studies to explore the opportunities of system improvement. Ultimately, the possible performance improvements are identified.

8.2. Experimental Result Evaluation

8.2.1. Productivity of Solar Still

The parametric study of the desalination system is carried out on the hourly and daily average basis for different experiment studies. In this part, figure 181 shows the *hourly* fresh water production with maximum the fan air flow (1.4 l/s) and without running the fan to be compared with the theoretical results achieved as conventional solar still without any operational adjustments.

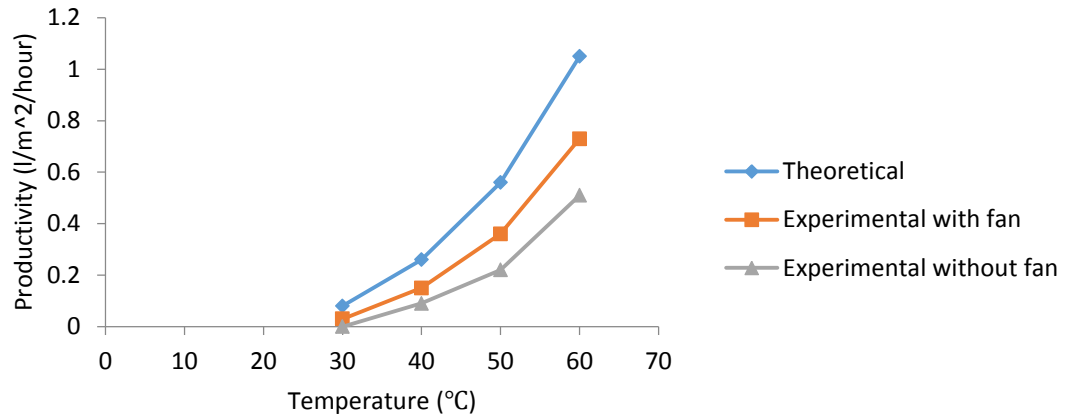


Figure 181: Hourly fresh water production at constant period temperatures

As figure 181 presents, the maximum productivity achieved during the one hour experiments was 0.73 litre at the constant temperature of 60 °C with the maximum fan flow rate (1.4 l/s) without using its shroud, while the maximum productivity of present solar still without running the fan was obtained 0.51 litre/m² hour. It can be observed that the use of the ventilation fan causes water production to increase, which it has positive impact on the performance of solar still. An average gain of 20% increase was recorded for fresh water collection by using ventilation fan in compare with the same unit of solar still without running the fan.

8.2.2. Water Production

The set two experiments were convened in three groups of experiments to measure different operational conditions on productivity of the solar still. The experimental results from this set of experiments were assistances to compare the solar still productivity with different ventilation fan flow rate, ventilation fan aluminium shroud and thermal storage material on the basin. Comparison between the accumulative of fresh water productivity of 20 hours experiments (set 2) are shown in figure 182,183 and 184.

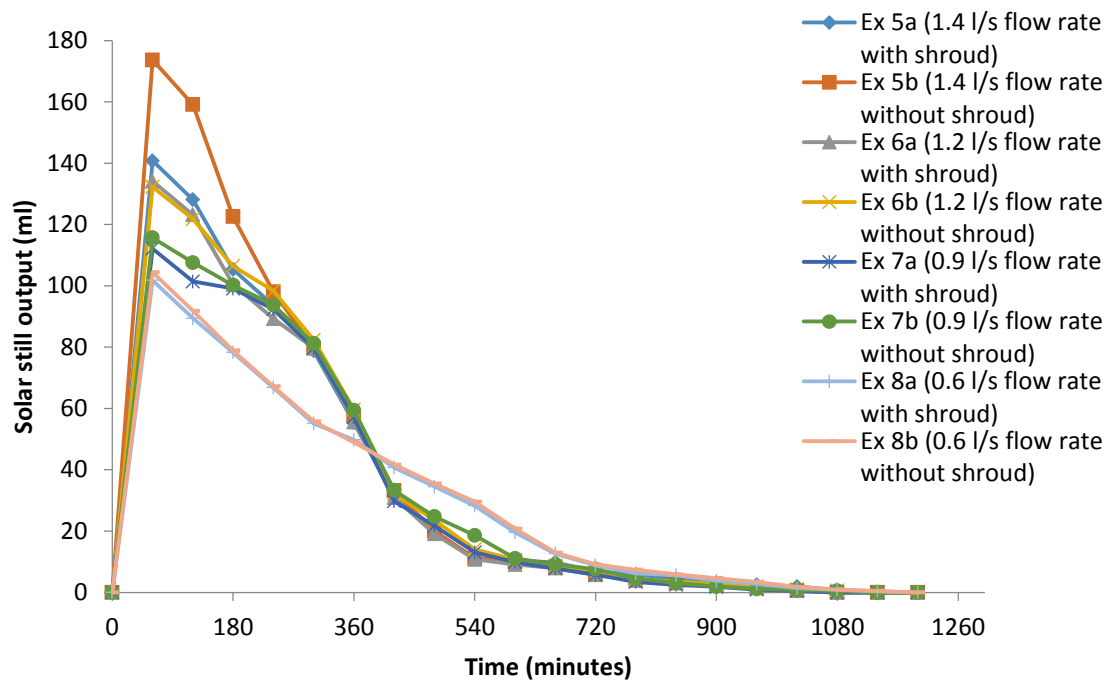


Figure 182: Set 2 group 2 experimental measurements of solar still fresh water productivity within 12 hours period.

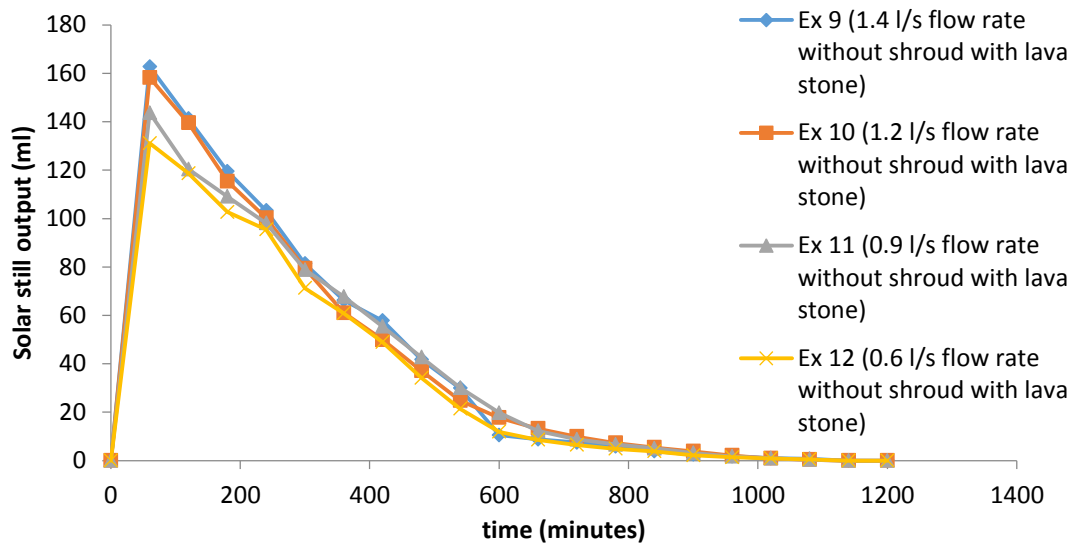


Figure 183: Set 2 group 3 experimental measurements of solar still fresh water productivity with lava stone as heat storing material within 12 hours

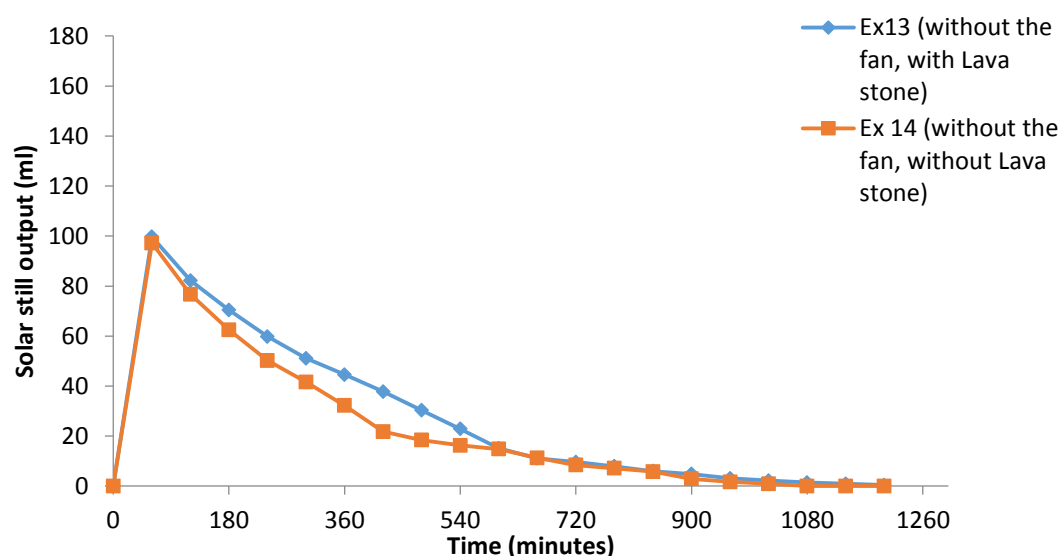


Figure 184: Set 2 group 4 experimental measurements of solar still fresh water productivity without the fan within 12 hours

Figure 182 presents comparison results of productivity of solar still with varies airflow ratios of 1.4, 1.2, 0.9 and 0.6 l/s with (“a” experiments) and without (“b” experiments) the aluminium fan shroud. The maximum fresh water productivity was obtained during experiment 5b (*0.791 litre*), while, the fan was at its maximum airflow ratio (1.4 l/s) without shroud. However, the minimum productivity of present solar still reached to *0.606 litres* during experiment “8a” despite the fact that the fan air flow ratio was 0.6 l/s with the Aluminium fan shroud. Therefore, in the entire group 2 experiments the productivity of solar still without the shroud was higher than using the fan shroud. The shroud was used in order to avoid air turbulence inside unit, despite the fact that it was producing a force in addition to gravitational force to push the condense water to the side pipes fresh water collector.

Figure 183 shows fresh water productivity of solar still with different fan airflow ratios without using the shroud in addition with the lava stone on the basin area as an acting thermal storage material. The total amount of fresh water collected in these sets of experiments was compared with the group two “b” experiments (different fan flow rate without shroud). It was found that the effect of using lava stone shows a 17% increase in productivity between 5b and 9 experiments, 15% increase between 6b and 10experiments, 12% increase between 7b and 11experiments and 15% increase between 8b and 12 experiments. Therefore, an average of 14.75% increases was achieved by using lava stone on the basin area.

The productivity of solar still without using ventilation fan with/without using lava stone was presented in figure 184. The total productivity of present solar still (without lava stone) without using the fan was reached to 0.469 litre of fresh water within 20 hours as conventional solar still. The outcome of using Lave stone without using the fan was shown an increase in total productivity by 12%. It can be also found that the rate of reducing temperature in proportion to time decreases by using lava stone on the basin area of solar still.

Figure 185 presents the total fresh water production of the present solar still with different modifications (set 2 experiments).

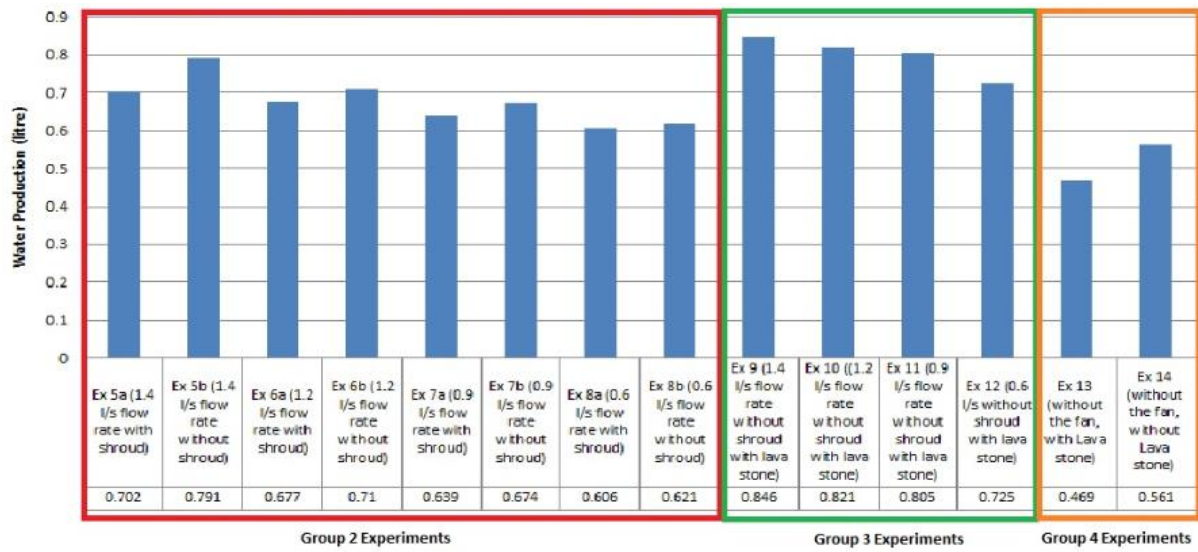


Figure 185: Total fresh water productivity of different experiments (Set 2, 3, 4)

It can be noted, the most productivity were retained while the lava stone were used on top of the basin area as thermal storage material (Ex 9, 10, 11 and 12), whereas the minimum productivity was placed for experiment 13 without fan and without lava stone as conventional solar still.

8.2.3. Effect of Using Fan

Finding the effect of using extraction fan with different air flow ratio proves that this method is beneficial to reduce the temperature of inner surface of glasses (condense cover). Therefore, the temperature difference between basin water and inner glass temperature was measured for both sets of experiment. The hourly four experiments on figure 186 (set1) and 20 hours experiments on figure 187 (set 2).

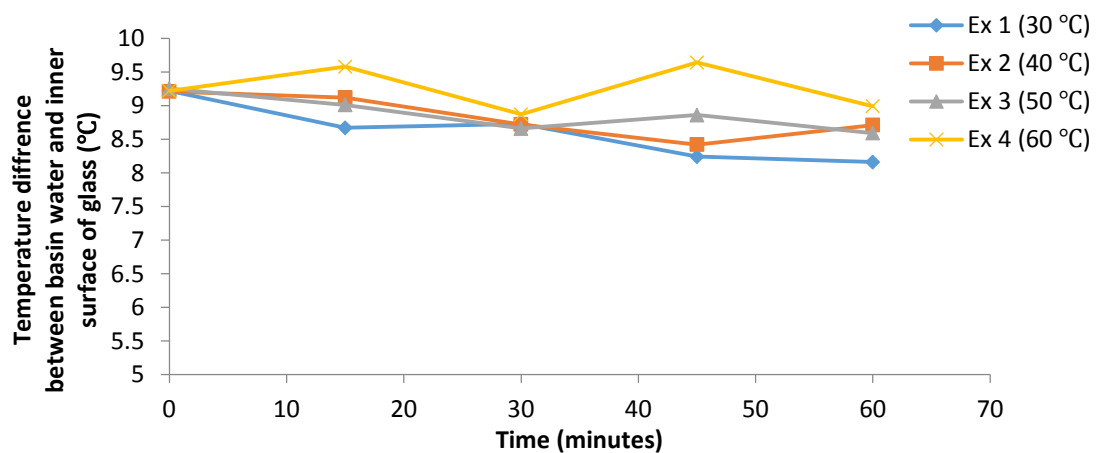


Figure 186: Temperature difference between basin water and inner surface of glass for set 1 experiment

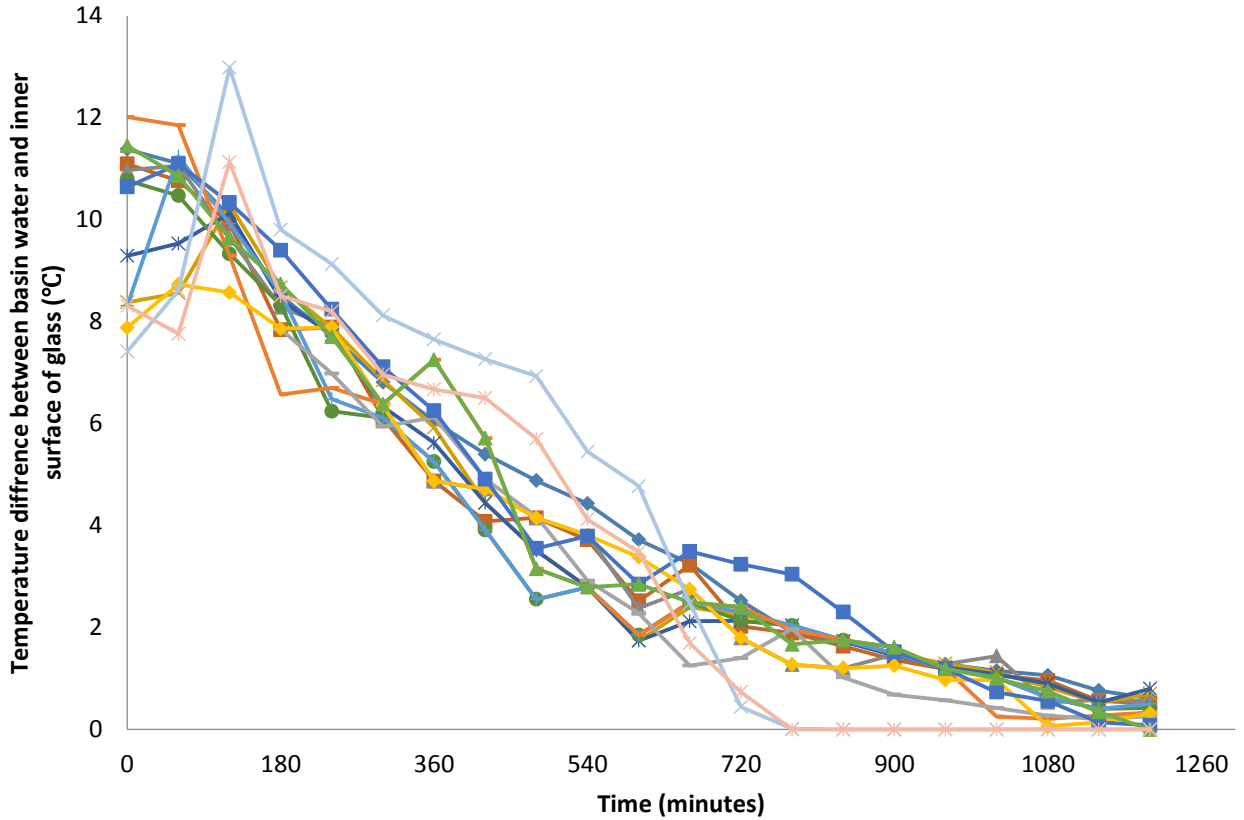


Figure 187: Temperature difference between basin water and inner surface of glass for set 2 experiments

Based on figures 186 and 187, it can be comprehend that, as the temperature of basin water increases, the temperature differences between the inner surface of the glasses and basin water increases instantaneously. Temperature difference between the basin water and inner surface of glasses plays an important role in productivity of solar still as it acts as condenser; therefore the ratio of fan airflow is directly in proportion to temperature difference between basin water and glasses.

A comparison of using fan shroud and its affect correspondingly can be discussed in order to measure temperature difference between basin water and inner surface of top roof glasses. Figure 181 presents the effect of various fan air flow ratio and the influence of blocking the air turbulence by fan shroud to the temperature difference between basin water and inner surface of glasses. The evaluation of temperature difference in set two experiments (5a and 5b, 6a and 6b, 7a and 7b, 8a and 8b) indicates that the range of temperature difference in experiments without fan frame is more sophisticated than using the frame in order to shield the air turbulence in solar still unit.

Figure 188 presents the total productivity of the solar still with different fan flow rate with and without using shroud.

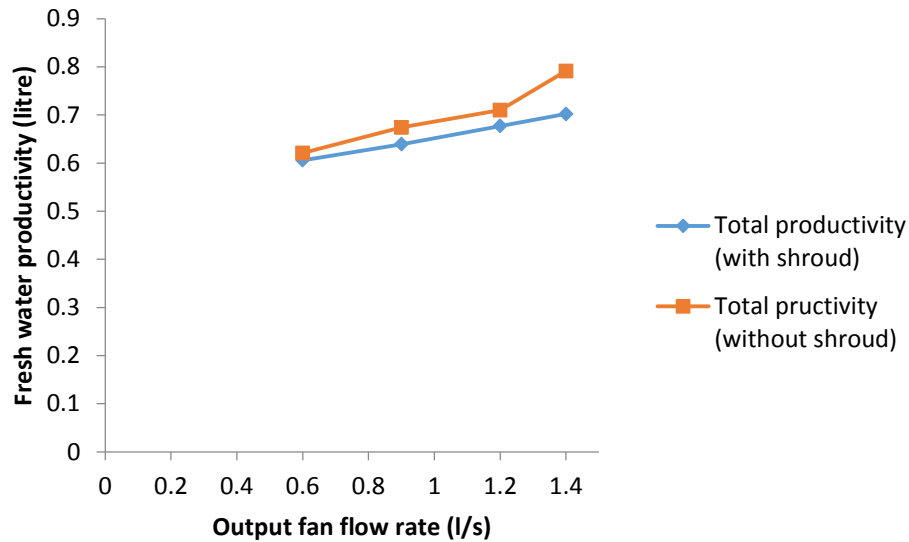


Figure 188: Solar still productivity with different fan flow rate with and without frame

Figure 188 proves the positive effect of using ventilation fan without the shroud on the final productivity of the solar still. An average increase of 6.15% in total productivity were obtained by using the fan without its shroud in comparison with shroud as it's reduces the inner surface top cover temperature (condensing cover).

8.2.4. Effect of Thermal Storage Material

Thermal storage material can be used on the basin area of the solar still in order to store latent heat while the basin water at its maximum temperature, then it releases the store latent heat when the basin water reduces its temperature during the period of time. Figure 189 illustrates the basin water temperature for different groups of experiments in order to see the difference of basin water temperature reduction ratio with and without using lava stone as thermal storage material on the basin area.

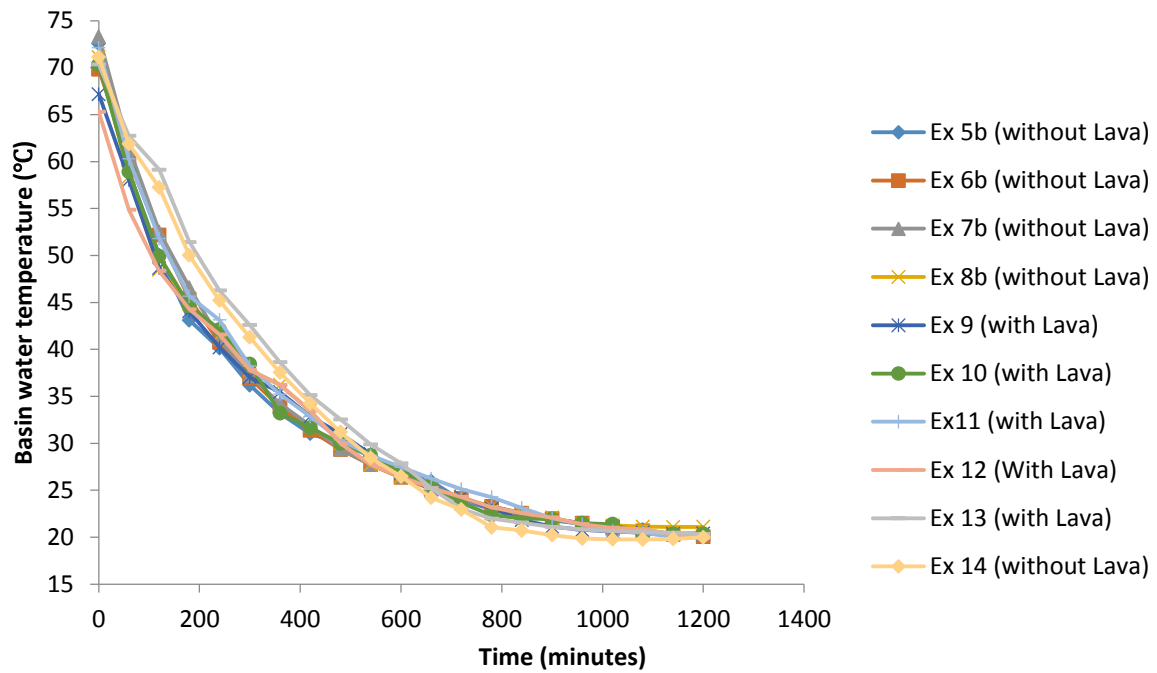


Figure 189: Basin water temperature for experiments with and without lava stone as thermal storage material

The comparison between the experiments results with similar fan air flow ratio, with and heat storing material presents the rate of decreasing temperature are slightly subordinate ratio by using lava stones on the basin area. The total weight of lava stone were used in experiments were 7.4 kilograms as it absorb latent heat of sun radiation and the basin water heat, then it releases its latent heat while the basin water losses its temperature. An average increase of 33.1% in productivity of solar still was achieved by using lava stone with different air flow ratio in compare with experiments without using lava stones. In addition, experiments 13 and 14 (without using fan) confirm the positive impact of using lava stone on the basin as the productivity of solar still increases by 16.3%.

8.2.5. Effect of Using Heat Exchanger

The extraction ventilation fan was connected to copper pipes by plastic pipes, which they act as heat exchanger division to transfer latent heat from water vapour to the basin water in order to condense. Figure 190 presents the average temperature difference between the copper pipes and basin water for hourly set 1 experiment.

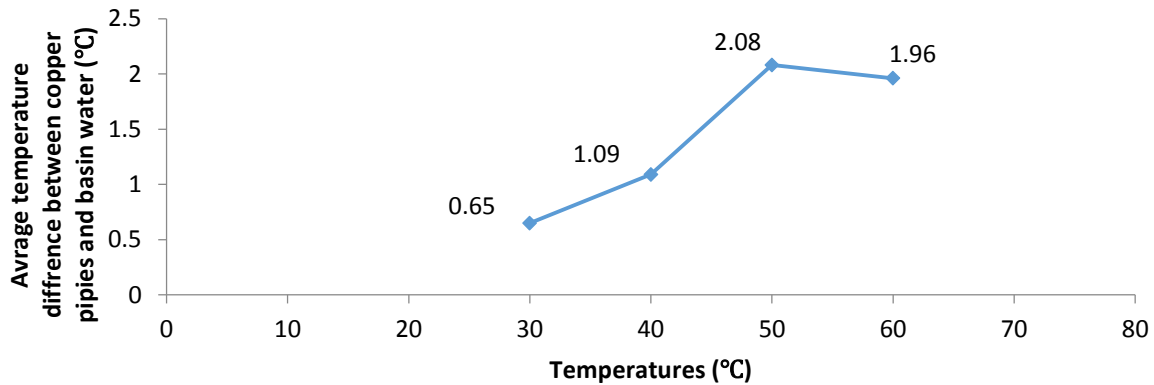


Figure 190: Average temperature difference between basin water and copper pipes for set 1 experiment

It can be noted, the temperature difference between the copper pipes and basin water increases with the raise of temperature of basin water from 30 to 50 °C then it reduces slightly while the temperature of basin water rises. Hence, the best time for copper pipes to act as heat exchanger is within the period that the basin water is at 50s °C.

8.3. Case Study and Comparison of Present Solar Still with Others

Many types of solar stills with different modifications and shapes were presented in the literature review (chapter 2.4 and 2.5). Comparisons of these units are difficult job to do as solar stills were tested under different conditions and parameters. As it has been discussed earlier the productivity of solar still is dependent on climatic, design and operational parameters. In this present work, the climatic parameters are constant in all experiments as they all placed in laboratory. Therefore, design and operational parameters needed to be evaluated with others in order to interpret the influence of present solar still.

Based on the present solar still productivity results obtained during experimental work, two case studies were evaluated to calculate to assume the final values of water production. Almeria (Spain) and Qeshm Island (Iran) are the two locations that are chosen to measure the productivity of the solar still unit (these two locations were chosen as it was planned to take the unit to the mentioned sites and it would be useful to calculate the expected values of the solar still productivity). The values of air temperature, daily solar radiation, day hours, atmospheric pressure and wind speed were taken from NASA [329] data sheet in order to evaluate the final output of the unit. Base on the calculations (Appendix C) the present solar still output in Almeria would be expected to be 4.26 litre/m² per day by with fan at its maximum airflow ratio without the frame and with lava stone, and 2.66 litre/m² per day without fan/lava stone, while in Qeshm Island a productivity of 6.32 litre/m² per day with fan/lava stone and 4.21 litre/m² per day without fan/lava stone.

Various designs and shapes were introduced in part 2.4 of literature review, which can be divided into five main divisions, such as single slope solar still, double slope solar still, pyramidal solar still,

hemispherical solar still and miscellaneous solar still. Table 41 presents the difference between demonstrated solar still units with others that was presented in part 2.4.2 (double slope solar still).

Table 41: Comparison of similar design (double slope) solar still (double slope)

Author(s)	Size	Productivity	Modifications	Location
<i>Bahrami</i>	<i>0.600 ×</i>	<i>4.26 litre/m²/day</i>	<i>Internal ventilation fan+ heat</i>	<i>Cranfield</i>
	<i>1.255 ×</i>	<i>(Almeria)*</i>	<i>exchanger (25.73%)</i>	<i>University</i>
	<i>0.633 m</i>	<i>6.32 litre/m²/day</i>	<i>Lava stone (16.3%)</i>	<i>(England)</i>
		<i>(Qeshm)*</i>		
Tabrizi et al.	0.610 ×	1.7 litre/m ² /day	Sand (44%)	Zahedan
[225]	0.680 ×			(Iran)
	0.750 m			
Kalidasa	2.30 × 1.00	2.1 litre/m ² /day	Jute, coir mate, sponge sheet,	Ovilpatti
Murugavel et al. [81]	× 0.10 m		aluminium fin	(India)
Zeroual et al.	0.90 × 0.70	5.8 litre/m ² /day	Cooling glass with water	Ouargla
[82]	× 0.03 m		(11.82%)	(Algeria)
Rajamanickam et al. [171]	1.00 × 1.00	2.7 litre/m ² /day	Different water depth 0.01,	Tamilnadu
	× 0.15 m		0.025, 0.05 and 0.075 m	(India)
			(11%)	
Suneesh et al.	2 × 0.75 ×	3.3 litre/m ² /day	Cotton gauze top cover	Tamilnadu
[270]	0.05 m		cooling (24%)	(India)
			Air flow (29%)	
Selva Kumar et al. [87]	0.5 × 0.5 ×	2.15 litre/m ² /day	Charcoal (30%), Mirror	Bihar
	0.15 m		(11.9%), Charcoal and mirror	(India)
			(14%)	
Morad [90]	1.7 × 0.7 ×	6.3 litre/m ² /day	Applying cover cooling flash	Zagazig
	0.15 m		tactic (19%)	University
				(Egypt)
Aburideh et al.	0.7 × 0.5 ×	4.0 litre/m ² /day	N/A	Tipaza
[84]	0.15 m			(Algeria)

“*” expected productivity values in specific location.

Operational parameters are adjustments in use of the solar still in order to either increase evaporation or condensation rate of water (or both). A full literature review was presented with different modifications to solar still such as basin material and solar radiation absorption, inlet water temperature, transparent material angle, basin water depth, reflector, transparent material cooling and

etc. There are mainly three operational changes placed in presented solar still functioning as concentrator (Fresnel lenses), exhaust ventilation fan, heat exchanger and thermal storage material (Lava stone). A comparison of some of the related operational tests with the present solar still has shown in table 42.

Table 42: Comparison of related operational parameters to the present solar still

Author(s)	Size	Productivity	Modifications	Location
<i>Bahrami</i>	<i>0.600 × 1.255 × 0.633 m</i>	<i>4.26 litre/m²/day (Almeria)* 6.32 litre/m²/day (Qeshm)*</i>	<i>Internal ventilation fan+ heat exchanger (25.73%) Lava stone (16.3%)</i>	<i>Cranfield University (England)</i>
<u>Transparent Cover Cooling</u>				
Abu-Arabi [261]	1.0 × 1.0 × 0.5 m	2.4 litre/m ² /day	Double glass covers cooling (32%)	Sultan Qaboos University (Oman)
T. Arunkumar [268]	1.10 × 1.10 × 0.25 m	4.2 litre/m ² /day	Top cover cooling (8%)	Tamilnadu (India)
S. A. Lawrence [246]	N/A	3.1 litre/m ² /day	Water flow over glass covers (10%)	Papua (Guinea)
<u>Condenser</u>				
S. H. Elsherbiny [264]	0.5 × 0.5 × 0.4 m	3.8 litre/m ² /day	External Condenser (- 30%)	Alexandria (Egypt)
Y. Zurigat et al. [266]	N/A	3.5 litre/m ² /day	Cooling top glass by wind (20%)	Amman (Jordan)
P. U. Suneesh [270]	2 × 0.75 × 0.05 m	3.3 litre/m ² /day	Cotton gauze top cover cooling (24%) Air flow (29%)	Tamilnadu (India)
El-Bahi [206]	1 × 1 × 0.05 m	6.5 litre/m ² /day	Outside condenser (8%)	Ankara

				(Turkey)
S. T. Ahmed [253]	$1 \times 0.4 \times 0.2$ m	5.5 litre/m ² /day	Internal condenser (7%)	Baghdad (Iraq)
<u>Thermal Storage Material</u>				
K. K. Murugavel [81]	$2.08 \times 0.84 \times$ 0.075 m	3.4 litre/m ² /day	Light black cotton cloth (11%)	Tamilandu (India)
Nafey [217]	$0.5 \times 0.5 \times$ 0.05 m	4.0 litre/m ² /day	Black rubber (20%), black gravel (21%)	Suez (Egypt)
S. Abdallah [122]	$0.69 \times 0.69 \times$ 0.06 m	3.1 litre/m ² /day	Sponges (28%), Volcanic rocks (43%)	Amman (Jordan)

“*” expected productivity values in particular location.

The expected productivity of the solar still was presented in table 41 and 42 in place of Almeria and Qeshm as two case studies via available data from NASA. It can be noted that within the novel design and modifications, the unit productivity increased considerably. Thus, the present solar still unit is sustainable to scale up to be used for small community in compare with other units (presented in literature review).

8.4. Economic Analysis

The payback time of the experimental set-up mainly depends on the overall cost of fabrication, maintenance and operational cost. Fabrication costs of present unit can be divided into four main categories such as structure, electrical, piping and optic categories. Table 43 presents the total cost of each category (full price list is available at appendix D).

Table 43: Fabrication parts categories prices

Structure	Electrical	Piping	Optical	Total
£90.56	£146.98	£143.46	£81.50	£462.50

The total fabrication cost of present solar still is $F = £462.50$. In order to determine the average value of the cost of distillate water, it is important to assume that “M” is the maintenance cost and “C” is the total cost, where, $C = F + M$ (there are no operational cost as both seawater and sun radiations are freely available). Assume maintenance cost equals $0.1F$ per year [95], [31], and the expected still life time is 5 years, then $C = £462.50 + £46.25 = £508.75$ where the average daily productivity can be

estimated from the analysis of different experimental data, and it is taken as 4.26 (Almeria) and 6.32 (Qeshm) litre/m²/day. To determine the annual cost for one litre assuming that the still operates 340 days in year. The total productivity during the still life time is $4.26 \times 8 \times 340 = 11587$ litre in a year (Almeria) and $6.32 \times 10 \times 340 = 21488$ litre in a year. Then the cost of one litre from present solar still are $\text{£}508.75/11587 = \text{£}0.043$ per litre (Almeria) and $\text{£}508.75/21488 = 0.023$ per litre (Qeshm Island) of distillate water.

This unit was designed to be suitable for a community scale of 1,000 people, thus 20,000 litres per day of fresh water needed. Therefore, the land requirement to provide the amount of water needed are 2,857 m² (Almeria) and 1,904 m² for Qeshm Island. The total average price of land obligation in Almeria [330] is £120.00 per m² and Qeshm Island is £100.00, therefore the overall land cost needed to come across require amount of water are £342,840 (Almeria) and £190,400 (Qeshm Island). An average cost of present solar still would reduce to scale up the size, as parts and components will be purchased in different quantities. Therefore, approximate costs of present solar still for the community scale of 1,000 people are shown in table 44.

Table 44: Community scale cost of the present solar still

	Construction Cost approx.	Maintenance and Cleaning Cost approx. (5 years)	Land Cost approx.	Total Cost approx.
Almeria (Spain)	£2,199,890	£21,998	£342,840	£2,564,728
Qeshm Island (Iran)	£1,466,080	£146,608	£190,400	£1,803,088

(Assumption: There is no labour cost in this table as they are fluctuate)

9. Conclusions

There are various methods available to produce clean water. However, it is crucial to understand the efficiency and sustainability of the available methods. Using inefficient and unsustainable methods can have a negative impact on the environment and the planet, which would, cause more harm to what is initially thought to be a process that helps to save the planet and the environment. Such methods have been practiced during the past couple of decades and resulted in adverse effects to what was meant to be achieved.

One of the most popular methods that are currently being used and it is attracting significant attention in terms of research and strategy development is the direct solar still distillation system. A full literature review in the area of desalination and its method, solar still and its kinds and parameters affecting the productivity was presented in this work (Objective 1).

The aim of this research was to explore new method of direct solar distillation to increase the daily productivity of fresh water per unit of area to generate fresh water from brackish water for a small community in an inaccessible area. Within the solar desalination systems, direct solar distillation techniques were subjected to significant amount of interest for its practicality and efficiency to produce substantial amounts of water with maximum efficiency using the most sustainable methods to asses systems in the process of production, which it can be used for community scale purposes in inaccessible area.

As direct solar still systems are subject to substantial consumption in energy it is important to consider simple and economical form of the energy that allow for maximum performance and quality without compromising production volume. Thus, the new transportable double slope solar still was designed, fabricated and experimentally tested in the laboratory to improve the solar still productivity. It is important in enhancing the system performance to maintain its basic advantages of ease of construction, maintenance and operation, simplicity and adaptability to low-tech regions.

The introduced solar still unit was designed to operate with solar radiations, which absorbed by the evaporation tank (basin) filled with coloured water, covered the by glass. The solar radiations increase basin water temperature that causes the evaporation process. The vapour particles as a result of the evaporation process are then raised to top glasses, where it reduces temperature and change its phase to condensed water, collected by from the sides' by a water collector. The novel object of extraction ventilation fan was installed to extract vapour to avoid vapour saturation. The extracted vapour is then directed and passed via copper pipes through the basin area filled with water. Thus, the temperatures of vapour decrease and change its phase to condensed fresh water (Objective 2).

The novelty of the present solar still unit divided in two main parts. First, the shape concept was designed and constructed to use two linear focuses Fresnel lenses in order to direct solar radiations into the basin area when the sun is not at its highest position (Noon period). Secondly, the unit operational modifications were applied to increase both evaporation and condensation rate of water as follows:

- *Air Exhaust:* The internal DC ventilation fan was installed to extract the vapour out of the solar still in order avoid vapour saturation. It also causes a reduction on the inner surface glasses temperature which would cause an increase in the condensation process through top covers. The Aluminium fan shroud was correspondingly made to prevent air turbulence, which was harvested by the fan, in order to measure the productivity of the unit. The fan was tested with different flow rates (1.4, 1.2, 0.9 and 0.6 l/s) to find the best operational constraint with the amount of vapour in the unit.
- *Heat exchanger:* The fan was attached to eight copper pipes that are acting as a thermal heat exchanger to transfer latent heat from vapour to the basin area, which cause condensation of vapour, while it transfers the latent heat to the basin water. Copper pipes were installed in a way to use gravitational force (constructed with 10° angle) to direct the condensed water to the output pipe to be collected.
- *Thermal storage material:* There are materials that could store the latent heat when the sun is available to release its energy when the basin water starts reducing its temperature. The lava stone is the type of volcanic rock with a suitable thermal conductivity that was used in the basin area of the solar still. The new packable shape single basin double slope solar still was designed and fabricated using plywood material with dimensions of L1.2 m × W0.5 m × h 0.5 m. Productivity of solar still was measured in the laboratory by heating the water in the external tank to certain temperatures and importing it to the basin area. Experiments were taken under different operational conditions such as different fan flow rate (with/without shroud), with and without heat exchanger and heat storing material in order to find established state of the solar still unit (Objective 3).

A theoretical and experimental study was directed to investigate the productivity of the modified solar still in comparison with a conventional unit. Results were compared between theoretical and experimental achievements present the amount of output water with a variety of operational conditions in order to find expected productivity values at different locations with data available (such as solar radiations, wind speed.).

The theoretical model based on different authors (Coopers and Dunkle) were developed for both internal and external heat transfer. Evaporation, convective and radiative heat transfer coefficients are three types of heat transfer that are placed internally, and top, bottom and sides heat transfer

coefficient are placed externally. Each of these terms were calculated separately to discover evaporation and condensation rate of the solar still at certain temperatures (30, 40, 50, 60, 70, 80 and 90 °C). The theoretical results of solar still yield were then calculated in order to be comparable to experimental results.

The laboratory experiments were carried with novel solar still. In addition to the theoretical values of the unit, there were two main sets of experiments to measure the outcome of the solar still productivity. Theses sets of experiments are as follows:

Set 1 measured the HOURLY productivity of the solar still (with/without fan) at constant basin water temperatures in order to be compared with conventional solar still at same temperature and theoretical values.

Set 2 measured 20 HOURS productivity of the solar still with its novel modifications, such as different fan air flow ratio, with/without shroud and use of lava stone as heat storage material in order to be compared with a conventional solar till without modifications.

Base on theoretical and laboratory experimental studies for the existing solar still the following key conclusions were drawn from this study (Objective 4):

1. The theoretical results conducted to estimate both internal and external heat transfer in the present unit to find the theoretical output values of the present solar still productivity. These two-heat transfer that act as evaporation and condensation appliance to produce fresh water throughout the unit. Thus, it was found that the internal heat transfer (evaporation) increased exponentially while external heat transfer (condensation) increased steadily with respect to its temperature (figure 191 duplicated from figure 180). Accordingly, new modifications could be classified to increase both evaporation and condensation process simultaneously, which increases both internal and external heat transfer of the unit. The internal heat transfer is responsible for the transportation of pure water in vapour form leaving behind all the impurities in the basin, whereas, the external heat transfer through condensing cover is responsible for the condensation of pure vapour as distillate (determined from part 8.1).

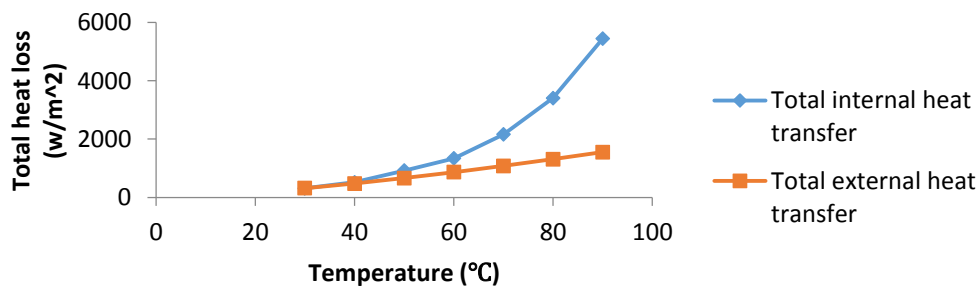


Figure 191: Total internal and external heat transfer vs temperature

2. Convective, evaporation and radiation are the mode of internal heat transfer from the water surface to the condensing cover that causes evaporation process. The performance of the solar still depends on the values of convective and evaporative heat transfer coefficients. Hence, it is essential to know the variation of these coefficients accurately. A number of scientists have developed empirical relations for convective and evaporative heat transfer coefficients. The most important and oldest relationship for convective and evaporative heat transfer coefficients for an air–water system in solar stills was developed by Dunkle and Cooper (Known as the New model). It is also observed that the values of convective and radiative heat transfer coefficient are much lesser than the value of the evaporative heat transfer coefficient (figure 192 duplicated from figure 142).

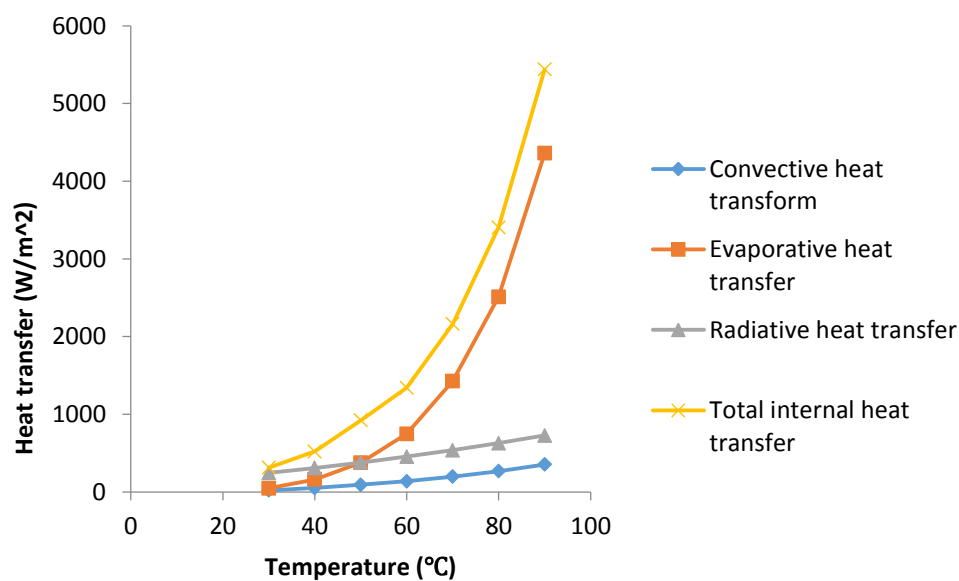


Figure 192: Total internal heat transfer

3. The external heat transfer in solar still is mainly governed by conduction, convection and radiation processes, which are independent of each other. There are two type of external heat transfer placed in the solar still unit. One is the heat transfer from condensing cover made of glass to the ambient (former), and two is from body of the solar still to ambient (latter). The heat is lost from outer surface of the glass to atmosphere through convection and radiation modes. The glass and atmospheric temperatures are directly related to the performance of the solar still. Thus, top loss is to be considered for the performance analysis (figure 193 duplicated from figure 144). The temperatures of the glass cover are assumed to be uniform because of small thickness. The second external heat transfer loss placed from the water mass in the basin to the ambient through the insulated wall and from the basin liner to the ambient through the insulated bottom (figure 194 duplicated from figure 145). It can be noted that both types of external heat transfer increases, while the temperature of the basin increases.

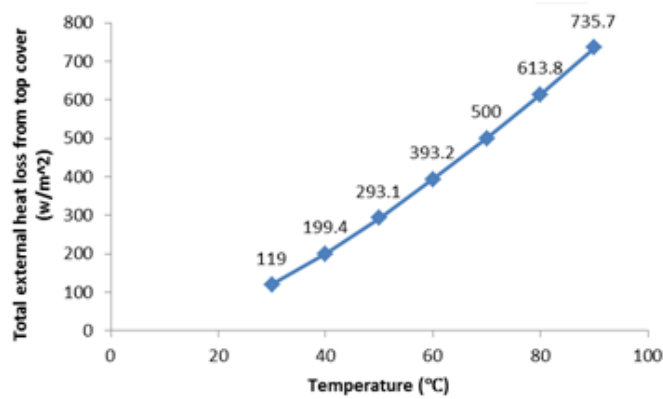


Figure 193: Total external heat loss from top cover vs temperature

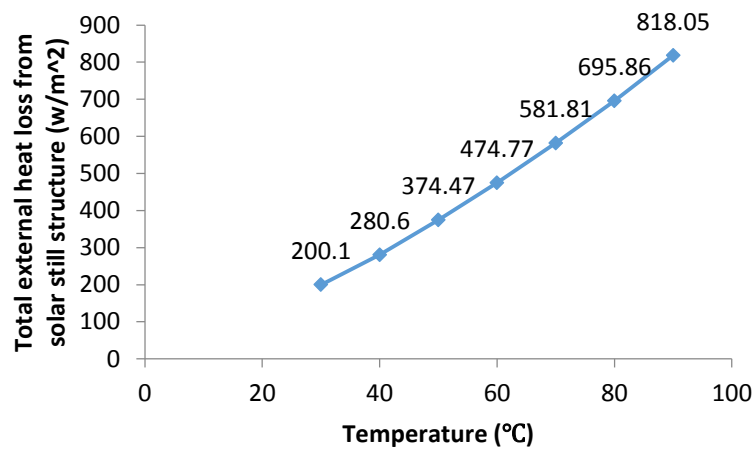


Figure 194: Total external heat loss through the structure of solar still

- The solar still unit was experimentally tested in the laboratory by heating the water in the external tank and pumping it into the basin area (Note: due to absence of the sun in United Kingdom, experimental test was taken inversely). There were two main sets of experiments to evaluate the unit productivity with theoretical expectation results and best operational condition of the conventional solar still. The first sets of experiments were conducted to measure the hourly (one hour) distillate productivities of the present solar still at constant basin water temperature (30, 40, 50, 60 and 70°C). The output of the solar still was then compared with theoretical expectation of a conventional solar still with its specifications. The hourly experiments were taken with and without running the ventilation fan to be able to measure the novel modifications on the productivity (figure 181). Base on the laboratory experimental results achievements, it can be noted that the productivity of solar still with the fan (without shroud) is 56.73% and without the fan is 31.00% respectively in compare with the hourly theoretical expectation values. Hence, the productivity has increase by 25.73% by using the ventilation fan (without fan shroud) with its maximum flow rate of 1.4 l/s, which it connected to heat exchanger pipes to transfer vapour heat back to the basin water (determined from part 8.2.1).

5. The second sets of experiments were taken to the best operational condition of the presented solar still. Each experiment taken within the period of 20 hours by importing the heated water to the basin area. It can be noted that metrological parameters are constant as all experimental test were taken in the laboratory. The set 2 group 2 experiments were taken by using different the ventilation fan air flow ratios (1.4, 1.2, 0.9 and 0.6 l/s) with and without shroud to measure the unit fresh water productivity within the mentioned operational parameters. The laboratory experimental results presented the maximum productivity of the unit was achieved through the fan flow rate was at its maximum rate (1.4 l/s) without using its shroud as 0.791 litre of fresh water, while the productivity with similar fan flow rate with shroud was 0.702 litres. However, the least productivity was obtained with the fan flow rate was at its low rate (0.6 l/s) with the shroud as 0.606 litres. Therefore, the most appropriate operational condition of the present solar still was taken place by using the ventilation fan at its top air flow rate without applying the shroud (determined from part 8.2.2).
6. The set 2 group 3 experiments were taken by using different the ventilation fan air flow ratios (1.4, 1.2, 0.9 and 0.6 l/s) without using the fan shroud and enhanced with lava stone in the basin area, which acted as a thermal storage material, to measure the unit fresh water productivity within the mentioned operational parameters. The average productivity of the unit without using heat storing material on the basin was measured as 0.699 litres, whereas with heat storing material 0.799 litres. Thus, it can be noted an average increase of 16.3% in productivity of the solar still was achieved by using lava stone on the basin area. Figure 195 duplicated from figure 189 presented that the rate of reducing basin water temperature turn out to be slighter by using heat storing material, which means the basin water evaporation placed even when there is no sun (determined from part 8.2.3).

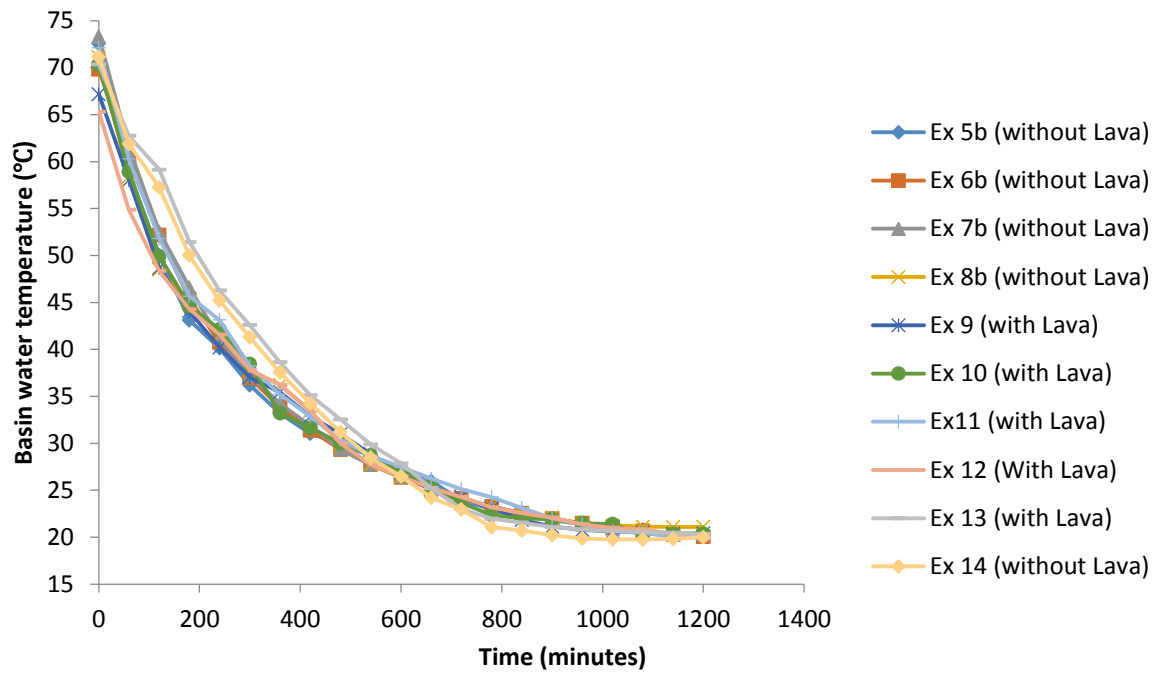


Figure 195: Basin water temperature for experiments with and without lava stone as thermal storage material

7. The set 2 group 4 experiments presented the solar still productivity without running the fan in order to get laboratory experimental results of the conventional unit. The same type of experiments then repeated with lava stones on the basin area. The experimental results then compared with the theoretical expectation. The conventional solar still without the fan and lava stone was measured 0.469 litres in 20 hours, while the conventional solar still productivity increased 0.561 litres by adding lava stone. These results then compared with similar experiments by running the fan at its maximum flow rate with and without shroud. The productivity of solar still (with thermal storage material) was increased by 33.1% with making the maximum fan flow rate in assessment to the productivity of solar still. It can also be found that the productivity of solar still (without thermal storage material) was increased up to 33.4% by maximum flow rate of fan with shroud and it has also increase up to 40.6% without the fan shroud. Thus it can be noted that applying both (fan and lava stones) design and operational modifications obligate positive effects on the solar still productivity (determined from part 8.2.4).
8. The temperature difference between the basin water and inner surface of glass cover plays an important role in productivity of solar still as result of increasing the rate of condensation (external heat transfer). Base on figure 187, the temperature difference between top glass cover and basin water were measured to evaluate different operational parameters to these results. Consequently, it was found the temperature difference is greater while the fan is running without its shroud in the unit. The fan was producing air turbulence in the unit which was pointed to

reduce inner surface of top cover temperature, and it also generating force to assist the condense water directed to sides water collector (determined from part 8.2.3).

9. The extraction ventilation fan was installed in the solar still to direct the vapour to copper heat exchanger pipes, which was mounted to pass through the basin water. The amount of heat transfer from vapour through the copper pipes was varied depending on the basin water temperature. The values of temperature difference between the basin water and copper pipes are not enormous ($\pm 1^\circ\text{C}$), but it played an important role to decrease the rate of temperature reduction during the time that basin water reduces its temperature (sunset). The maximum heat transfer occurred while the basin water was at temperature range of 50°C . (determined from part 8.2.5)
10. According to both theoretical and experimental results achievements of the solar still unit with different operational conditions, there were two locations (Spain and Iran) that was chosen to evaluate the unit fresh water productivity. These locations were selected as potential experimental outdoor locations to compare with the results achieved in the laboratory. The required data (such as air temperature, daily solar radiation, day hours, atmospheric pressure, wind speed and etc.) were taken from NASA to calculate the expected values of productivity. The results then compared with different authors (table 41 and 42) for the unit novel shape and operational conditions, which was pointed considerable increase in the productivity in compare with others. The solar still fresh water output was expected to be $4.26 \text{ litre/m}^2 \text{ per day}$ by the fan at its maximum airflow ratio (without the shroud) plus lava stone as heat storage material, and $2.66 \text{ litre/m}^2 \text{ per day}$ without fan and lava stone in Almeria (Spain), while the unit in Qeshm Island produce $6.32 \text{ litre/m}^2 \text{ per day}$ of fresh water with fan/lava stone and $4.21 \text{ litre/m}^2 \text{ per day}$ without fan/lava stone (determined from part 8.3).
11. Besides the advantages of the present solar still simplicity, the cost analysis clearly indicates that freshwater cost is competitive with conventional desalination system for rural developments areas. The payback time of the experimental set-up was mainly depending on the overall cost of fabrication, maintenance and operational cost. Fabrication costs of the present unit were divided into four main categories such as structure, electrical, piping and optic categories. (determined from part 8.4)

The purpose of this project was to design a portable concentrated solar still that it could be used for community scale purposes (scaling up) to provide fresh water from saline water. A new design was presented and tested in the laboratory with different modifications in order to find the best conditions to operate the present solar still. There have been a few limitations, such as the lack of sun radiation in

the United Kingdom to do experimental tests of present solar still unit in the actual environmental field to measure the effect of metrological parameters on solar still productivity. Cost consideration was the second most important parameter in this unit. This unit was designed for countries with water scarcity problems; therefore, the construction parts were all market available in order to keep the total cost as low as possible.

10. Future work

A list of future work and modifications can be stated as follows:

- The present solar still unit was design and fabricated to use two linear focuser Fresnel lenses as solar radiation concentrator to direct radiations into the basin area. Thus, testing the outcome of using Fresnel lenses in real environmental field to investigate solar still productivity with this modification.
- The solar still was also designed to use mirrors at inner aspect of walls inside solar still to measure the reflectivity and its influence on productivity of solar still.
- The solar still unit can be used for community scale by expanding the propose model by extending the size of it and constructing multiple unit of identical unit.
- The effect of climatic parameters such as wind speed, relative humidity and atmospheric pressure to productivity of solar still.
- Physical and chemical analysis of brackish and distillate water such as turbidity, total dissolved solids, PH and alkalinity.

In order to scale up (community scale) the present solar still (enhanced with internal extraction ventilation fan and connected to the acting heat exchanger pipes),with the addition of linear focused Fresnel lenses as part of the top cover, the suggested strategies are as follows:

- The structure material including the basin area needed to be change in the most optimise condition in both financial and the unit operational productivity, such as applying concrete (Heat Storing) and asphalt (solar radiation absorption) on the basin area.
- The laboratory solar still concept unit could scale up depending on the land availability and fresh water requirement. Constructing parallel units in a way to avoid shadows is also implement to expand the solar still field as it necessary.
- Cleaning and maintenance are required for regular filling of brackish water, distil water collection, to cover (glasses) cleaning, salt deposited removal, pipes leakage checking and pumps checking. As the system life passes om, the maintenance on it also increases. Therefore, it is important key to consider approximately 10% of net cost to be considered as maintenance cost.
- Operational parameters, which may affect the performance of the solar still such as water depth, feed water preheating, colouring the water, cleaning, flushing and etc., are necessary keys to improve the conventional solar still without applying enormous cost.

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12. Appendices

10.1. Appendix A

Table A1. A2, A3, A4, A5, A6, A7 and A8 are present the ventilation fan air flow at different part of present solar still.

Appendix table A1: The right 32mm pipe (without frame)

Voltage	Air speed (km/h)	Air speed (m/s)	Air flow (l/s)
15	32.0	8.8	7.0
12	29.4	8.1	6.5
9	24.0	6.6	5.3
6	18.0	5.0	4.0

Appendix table A2: The left 32 mm pipe (with fan frame)

Voltage	Air speed (km/h)	Air speed (m/s)	Air flow (l/s)
15	33.8	9.3	7.4
12	31.0	8.6	6.9
9	24.0	6.6	5.3
6	17.9	4.9	3.9

Appendix A3: The right 32 mm pipe (without fan frame)

Voltage	Air speed (km/h)	Air speed (m/s)	Air flow (l/s)
15	32.2	8.9	7.1
12	30.1	8.3	6.6
9	24.8	6.8	5.4
6	18.6	5.1	4.1

Appendix table A4: The right 32 mm pipe (with fan frame)

Voltage	Air speed (km/h)	Air speed (m/s)	Air flow (l/s)
15	35.8	9.9	7.9
12	32.3	8.9	7.1
9	26.5	7.3	5.8
6	20.2	5.6	4.5

Appendix table A5: The left 22 mm pipe (without fan frame)

Voltage	Air speed (km/h)	Air speed (m/s)	Air flow (l/s)
15	13.0	3.6	1.3
12	11.5	3.1	1.1
9	9.3	2.5	0.9
6	6.3	1.7	0.6

Appendix table A6: The left 22 mm pipe (with fan frame)

Voltage	Air speed (km/h)	Air speed (m/s)	Air flow (l/s)
15	13.6	3.7	1.4

12	11.0	3.0	1.1
9	8.7	2.4	0.9
6	5.6	1.5	0.5

Appendix table A7: The right 22 mm pipe (without fan frame)

Voltage	Air speed (km/h)	Air speed (m/s)	Air flow (l/s)
15	13.6	3.7	1.4
12	11.8	3.2	1.2
9	9.5	2.6	0.9
6	6.5	1.8	0.6

Appendix table A8: The right 22 mm pipe (with fan frame)

Voltage	Air speed (km/h)	Air speed (m/s)	Air flow (l/s)
15	14.1	3.9	1.4
12	11.8	3.2	1.2
9	9.2	2.5	0.9
6	6.6	1.8	0.6

10.2. Appendix B

Table B1 presents properties of air at atmospheric pressure (the values of μ , K , C_p and Pr are not strongly pressure-dependent and may be used over fairly wide range of pressure).

Appendix table B1: Physical properties of Air

T (k)	ρ (kg/m³)	C_p (kJ/kgK)	μ (kg/ms $\times 10^{-5}$)	ν (m²s $\times$ 10^{-6})	K(W/mK$\times$ 10^{-3})	A (m²s $\times$ 10^{-5})	Pr
100	3.6010	1.0259	0.6924	1.923	9.239	0.2501	0.770
150	2.3675	1.0092	1.0283	4.343	4.343	0.5745	0.753
200	1.7684	1.0054	1.3289	7.490	7.490	1.017	0.739
250	1.4128	1.0046	1.488	9.490	9.49	1.3161	0.722
300	1.1774	1.0050	1.983	15.680	15.68	2.216	0.708
350	0.9980	1.0083	2.075	20.780	20.76	2.983	0.697
400	0.8826	1.0134	2.286	25.900	25.90	3.760	0.689

Table B2 presents properties of water (saturated liquid).

Appendix table B2: Physical properties of water

T (°C)	C_p (kJ/kg°C)	ρ (kg/m³)	μ (kg/ms)	K(W/m°C)	Pr	$\nu = \mu / \rho$ (m²s)
0	4.225	999.8	1.79×10^{-3}	0.566	13.25	1.79×10^{-6}
4.44	4.208	999.8	1.55×10^{-3}	0.575	11.35	1.55×10^{-6}
10	4.195	999.2	1.31×10^{-3}	0.585	9.40	1.31×10^{-6}
15.56	4.186	999.6	1.12×10^{-3}	0.595	7.88	1.12×10^{-6}
21.11	4.179	998.6	9.8×10^{-3}	0.604	6.78	9.82×10^{-6}
26.67	4.179	997.4	8.6×10^{-3}	0.614	5.85	8.63×10^{-6}

32.22	4.174	995.8	7.65×10^{-3}	0.630	5.12	7.69×10^{-6}
37.78	4.174	994.9	6.82×10^{-3}	0.637	4.53	6.87×10^{-6}
43.33	4.174	993.0	6.16×10^{-3}	0.644	4.04	6.22×10^{-6}
48.89	4.174	990.0	5.62×10^{-3}	0.654	3.64	5.68×10^{-6}
54.44	4.179	988.7	5.13×10^{-3}	0.659	3.30	5.20×10^{-6}
60	4.179	985.4	4.71×10^{-3}	0.665	3.01	4.63×10^{-6}
65.55	4.183	983.6	4.3×10^{-3}	0.668	2.73	4.39×10^{-6}
71.11	4.186	980.3	4.01×10^{-3}	0.673	5.53	410×10^{-6}
76.67	4.191	977.3	3.72×10^{-3}	0.675	2.33	3.82×10^{-6}
82.22	4.195	972.7	3.47×10^{-3}	0.678	2.16	3.58×10^{-6}
87.78	4.199	970.2	3.27×10^{-3}	0.679	2.03	3.38×10^{-6}
93.33	4.204	966.7	3.06×10^{-3}	0.680	1.90	3.18×10^{-6}
104.4	4.216	963.2	2.67×10^{-3}	0.684	1.66	2.79×10^{-6}

10.3. Appendix C

Table C1 and C2 present the hourly productivity values for case study of Almeria (Spain) and Qeshm Island (Iran).

Appendix table C1: Almeria (Spain)

Time in mid- August	I(t) (w/m²)	Tempera ture of ambient	Tempera ture of basin water	Tempera ture of top cover	h_{cw}	h_{ew}	m_{ew} with fan	m_{ew} without fan	Theoreti cal producti vity
7.00	455.0	21	27.2	21.8	1.90412	0.02342	0	0	0.081
8.00	596.6	21.8	28	22.5	1.9434	0.0239	0	0	0.0871
9.00	803.3	23.8	32.7	23.7	2.17417	0.02672	0.3337	0.00082	0.1381
10.00	1020	25.8	47.6	38.5	2.90576	0.03566	0.37756	0.24816	0.5335
11.00	1133.3	28.7	58.3	48.8	3.43113	0.04208	0.6247	0.42578	1.0367

12.00	1268.3	32.5	64.2	55.2	3.72082	0.04562	0.76102	0.52372	1.3924
13.00	1275	35.1	66.7	57.2	3.84357	0.04712	0.81877	0.56522	1.56
14.00	1135	35.6	63.1	53.6	3.66681	0.04496	0.73561	0.50546	1.3219
15.00	900	32.8	50.1	41.4	3.02851	0.03716	0.43531	0.28966	0.6347
16.00	651.6	29	38.9	31.3	2.47859	0.03044	0.17659	0.10374	0.2595
17.00	475	25	26.5	25.1	1.86975	0.023	0	0	0.07825
18.00	396.6	22.2	23.8	23.1	1.73718	0.02138	0	0	0.07139

Appendix table C2: Qeshm Island (Iran)

Time in mid- August	I(t) (w/m ²)	Tempera ture of ambient	Tempera ture of basin water	Tempera ture of top cover	h_{cw}	h_{ew}	m_{ew} with fan	m_{ew} without fan	Theoreti cal producti vity
7	638	34.4	37.2	28.3	2.3951	0.0294	0.1373	0.0755	0.2201
						2			
8	776.6	33.9	37.6	28.5	2.4147	0.0296	0.1465	0.0821	0.2289
						6			
9	926.6	33.7	38.2	29.7	2.4442	0.0300	0.1604	0.0921	0.2427
						2			
10	1048.3	34.1	51.1	43.5	3.0776	0.0377	0.4584	0.3062	0.6779
						6			
11	1135	34.1	62.2	54.7	3.6226	0.0444	0.7148	0.4905	1.2656
						2			
12	1235	36.6	67.4	58.8	3.8779	0.0475	0.8349	0.5768	1.6087
						4			
13	1271.6	37.6	71.1	63.2	4.0596	0.0497	0.9204	0.6382	1.8791
						6			
14	1163.3	37.9	68.3	59.7	3.9221	0.0480	0.8557	0.5917	1.6725
						8			
15	988.3	38	63	54.3	3.6619	0.0449	0.7333	0.5038	1.3156
16	808.3	37.7	54.5	46.1	3.2445	0.0398	0.5369	0.3627	0.837

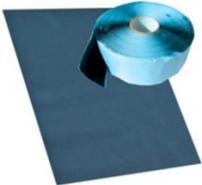
17	666.6	36.5	47.8	38.4	2.9155	0.0357 8	0.3821	0.2514	0.5413
18	623.3	35.4	40.1	36.5	2.5375	0.0311 6	0.2043	0.1236	0.2901
19	606.6	34.9	36.6	35.8	2.3263	0.0290 6	0.1234	0.0655	0.2073
20	566.6	34.5	35.7	35.1	2.292	0.0285 2	0.1026	0.0506	0.1892

10.3. Appendix D

Table D1, D2, D3 and D4 are present the parts prices with its number of quantity, which was used in constructing the present solar still. F

Appendix table D1: Structure parts prices

Structure				
Part Name and Specification	Picture	Quantity	Price per Single Part	Total Cost
WICKES WHITEWOOD PSE 18X144X1800MM SINGLE		2	£6.15	£12.30
WICKES NON STRUCTURAL HARDWOOD PLYWOOD 9 X 1220 X 2440MM		2	£20.99	£41.98
WICKES WHITEWOOD PSE 18X28X1800MM SINGLE		1	£1.85	£1.85
M8 X 60mm Socket Countersunk Screws (DIN 7991) - A2 Stainless Steel		20	£0.35	£7.00
Forgefix Screw Cup Sockets Solid Brass 8x100 FORSCS8BM		1	£6.00	£6.00

2.44 metre x 2.44 metre Firestone Pond Liners		1	£10.00	£10.00
Medium Greenseal / EPDM Pond Liner Repair Kit - 50x50cm pond Liner & 3m Cold Glue		1	£3.99	£3.99
NO NONSENSE WOOD FLOORING SEALANT OAK 310ML		1	£2.49	£2.49
NO NONSENSE 11764502 SANITARY SILICONE BLACK 310ML		1	£1.99	£1.99
GEOCEL 4024907 791 WEATHERPROOFING SILICONE SEALANT 310ML BLACK		1	£2.96	£2.96

Appendix table D2: Electrical parts prices

Electrical				
Part Name and Specification	Picture	Quantity	Price per Single Part	Total Cost
DC Axial Fan		1	£41.19	£41.19
20W Solar Panel Kit		1	£67.99	£67.99
CSB HRL1210W F2-FR Battery		1	£15.00	£15.00
Q-BAIHE 12V Mini Plastic Gear Pump Self-Sucking Water Pump (0-100?) ZC-A210		2	£11.40	£22.80

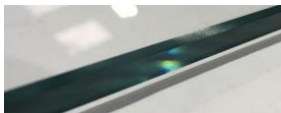
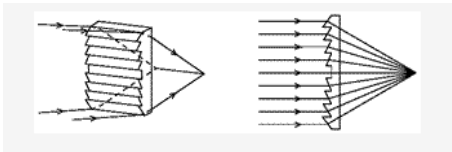
Appendix table D3: piping parts prices

Piping				
Part Name and Specification	Picture	Quantity	Price per Single Part	Total Cost
CIRCULAR ADAPTER 110MM TO 100MM		1	£2.49	£2.49
Solvent Waste Connection 110mm Waste Adaptor with 32mm x 32mm MuPVC		1	£10.22	£10.22
MANROSE METAL HOSE CLIP 100MM		1	£1.99	£1.98
Waste Pipe Push Fit 3m Compression Pipe 32mm - Black		1	£2.99	£2.99
Waste Pipe Solvent Weld 92.5dg Swept Bend 32mm - White		4	£1.01	£4.04
WICKES HOSE CLIPS 20/32MM (PACK OF 2)		2	£1.99	£3.98

MDPE Coupling 32mm x 22mm Conversion Reducer		2	£5.98	£5.98
WICKES WHITE OVERFLOW PIPE 22MM X 2000MM		1	0.99	0.99
22mm SPEEDFIT Plastic Lever Valve - 22SV-H		2	£8.06	£16.12
JG SPEEDFIT CM0722SP TANK CONNECTORS 22MM		4	£3.34	£3.34
22mm x 10mm Speedfit 4 Port Rail Manifold - SFM522210E		4	£13.43	£53.72
22mm Speedfit Plug - PL22		8	£0.72	£5.76
Copper Coil Microbore Soft 10mm x 25m		1	£8.54	£8.54
SPEEDFIT PEM0222WP EQUAL TEES 22MM		1	£4.14	£4.14

5 litre water tank collector		1	£19.17	£19.17
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Appendix table D4: Optical parts prices

Optical				
Part Name and Specification	Picture	Quantity	Price per Single Part	Total Cost
3mm x 518mm x 505mm glass		2	£10.00	£20.00
Linear focus Fresnel lenses 500×500 Focus (mm) 500		2	\$39.60 (≈ £30.5)	\$79.30 (≈ £61.5)