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Experimental Evaluation of a Novel Absorption Refrigeration system with Integrated Thermal Energy Storage and Smart Performance Monitoring

Faculty of Engineering and Applied Sciences
MSc. in Advanced Mechanical Engineering

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Supervisor: Dr. Peter King
September 2025

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This thesis is submitted in partial fulfilment of the requirements for the degree of MSc

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Abstract

In Sub-Saharan Africa, unreliable electricity and inadequate cold storage infrastructure causes high post-harvest losses and vaccine storage problems. Therefore, sustainable off-grid cooling solutions are needed with solar-powered absorption refrigeration offering a promising approach, as it provides cooling driven solely by heat without reliance on grid electricity.

This study evaluates a diffusion absorption refrigeration (DAR) system integrating thermal energy storage and smart monitoring. The study employs a combination of laboratory experiments and simulation modelling using TRNSYS 18 software under controlled conditions quantifying how operating inputs affect performance, focusing on COP, the impact of PCM-based storage, and acoustic diagnostics.

The key finding indicate that the DAR system demonstrated a low steady-state coefficient of performance (COP) of 0.27 which is typical for small absorption systems. Despite the low COP, PCM integration significantly improved cooling signify that the system maintained cooling for extended periods of low or no solar input, preventing rapid warming. Acoustic monitoring confirmed stable operation, as consistent sound signatures indicated no cycle interruptions or anomalies.

This study demonstrates the feasibility of a solar-driven DAR system with integrated thermal storage and smart monitoring for off-grid rural cooling. Despite limited efficiency, its off-grid operation and cooling retention during low-sun periods provide a valuable means to reduce uncertainty of refrigeration in remote communities. Future work should focus on improving the system's efficiency (via design optimization or alternative working fluids) and scaling up cooling capacity. In addition. higher-performance PCMs and intelligent control strategies is also recommended to enhance system performance and reliability.

Keywords:

Off-grid Cooling, Diffusion Absorption Refrigeration, Coefficient of Performance, Thermal Energy Storage, Acoustic Monitoring, TRNSYS 18 Simulation

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List of Abbreviations

DAR	Diffusion absorption refrigeration
DC	Direct Current
DNI	Direct Normal Irradiance
dBFS	decibels relative to full scale
FAO	Food and Agriculture Organization
IEA	International Energy Agency
PCM	Phase Change Material
PV	Photovoltaic
TRNSYS	Transient System Simulation Tool
WHO	World Health Organization
W	Watt
hh:mm	24-hour time format notation
°C	Degrees Celsius
kWh	Kilowatt-hour

1 Introduction

1.1 Context

Reliable access to electricity remains critically limited across Sub-Saharan Africa, with around 600 million people lacking grid connectivity, primarily in rural areas (IEA, 2024). Kenya, reflecting broader regional challenges, continues to face notable impacts in key sectors such as agriculture and healthcare due to the existing energy shortfall. In the agricultural industry, significant post-harvest losses occur, ranging from 20% to over 50%, mainly due to inadequate cold storage infrastructure (FAO, 2021). These losses not only diminish the economic gains of farmers but also worsen food insecurity, weakening economic stability. Concurrently, healthcare facilities struggle with maintaining essential cold chains for vaccine preservation. Notably, roughly one in five health facilities in Kenya lacked any cold-chain equipment that provides consistent refrigeration for vaccines, making them more likely to provide limited immunisation services as they cannot maintain vaccine stocks on-site (Stammer et al., 2022).

To mitigate these challenges, sustainable off-grid refrigeration technologies, particularly standalone solar-powered cooling solutions, have gained prominence in Sub-Saharan African countries. The landscape of solar cooling technologies in sub-Saharan Africa is such that the abundance of solar irradiance offers a major opportunity to meet cooling demands sustainably. Two main approaches are highlighted: (1) Solar electric cooling, typically solar photovoltaic (PV) panels powering conventional vapour-compression refrigerators, and (2) Solar thermal cooling, which includes absorption/adsorption chillers driven by heat. Solar PV–driven fridges are already promoted by organizations and social enterprises in remote areas. However, PV fridges effectively convert sunlight to electricity to mechanical cooling with an overall efficiency around 0.3–0.45 (given PV panel efficiency ~15% and fridge COP ~3). In contrast, solar thermal refrigerators bypass the electrical step by using heat directly, potentially simplifying systems and avoiding reliance on batteries or HFC refrigerants. This makes solar thermal absorption systems attractive for rural Africa, if their performance and cost can be brought to acceptable levels.

Solar thermal refrigeration, particularly diffusion absorption refrigeration (DAR) technology, represents a compelling alternative. Unlike conventional refrigeration that relies on electrical compressors, DAR systems utilise thermal energy to achieve cooling. These systems operate entirely without moving mechanical components, harnessing heat from solar collectors and employing natural refrigerants such as ammonia and water, significantly reducing environmental impact (Freeman & Markides, 2024). Recent initiatives, including a UK-developed solar thermal DAR system implemented in Kenya, demonstrate practical viability, offering cooling for healthcare and agricultural applications without emissions, battery storage, or fuel dependencies (Energy Catalyst, n.d.).

Nevertheless, solar DAR systems are currently constrained by several technical and operational limitations. These systems often display lower COP, particularly under fluctuating solar availability or nighttime conditions. Maintaining consistent and stable cooling performance during periods of low solar irradiation remains challenging (Freeman & Markides, 2024). Addressing this intermittent availability of solar energy and enhancing operational efficiency is vital for DAR technology to become a reliable cooling solution for off-grid communities (Bisulandu et al., 2023).

Integrating thermal energy storage through phase change materials (PCM) is a promising strategy to overcome these limitations. PCMs act as thermal batteries, storing excess thermal energy during periods of high solar irradiation and releasing it during periods of low or absent solar conditions. Recent advancements have suggested that PCM integration can effectively stabilise cooling outputs and maintain consistent operational temperatures, significantly enhancing system reliability (Oubourhim et al., 2025). Despite this potential, there remains a notable research gap regarding optimal PCM configurations, material selection, and performance evaluation, specifically in small-scale solar DAR applications (Guo et al., 2025).

Moreover, another emerging area is the monitoring regime for performance improvement, typically employed in large-scale refrigeration applications. Simplified, low-cost monitoring systems and basic Internet of Things (IoT)

solutions can act as an automated operational control, optimise system efficiency, and prevent operational issues (Atzori et al., 2010). However, literature remains sparse on the feasibility and effectiveness of implementing these smart controls within small-scale, rural-oriented solar absorption refrigeration systems.

1.2 Aim and Objectives of the Study

Given the above context, this research aims to evaluate and enhance a solar-powered diffusion absorption refrigeration system for off-grid cooling, with a focus on integrating thermal energy storage and simple intelligent monitoring to analyse its performance. To fulfil this aim, the study pursues the following specific objectives:

- **Re-commissioning of solar DAR rig:** An existing solar thermal diffusion absorption refrigeration rig will be refurbished and re-commissioned to check its functional integrity by conducting preliminary test runs.
- **Plan and conduct experimental runs:** Performance of the system will be tested under various operating conditions representative of a rural Kenyan environment. This establishes a baseline and ensures the system is functioning as designed before further modifications.
- **Development and validation with TRNSYS simulation model:** A detailed comparison of the experimental runs with a computer model of the solar DAR system built using TRNSYS, capturing the transient interactions of the refrigeration cycle. The model will be validated against the experimental data from the re-commissioned system.
- **Integration of phase change material (PCM) thermal storage:** A suitable phase change material will be incorporated into the system to store energy. The modified setup will be evaluated through simulation using TRNSYS model software to find how the PCM improves temperature stability and cooling duration overnight or during cloudy periods.
- **Implementation of a low-cost monitoring strategy:** To evaluate the feasibility of integrating a cost-effective monitoring system into the DAR rig

by identifying operational diagnostics correlated with bubbling phenomena, deploying vibration/acoustic sensors to detect these patterns, and visualizing/logging data to correlate with performance trends for proactive system control.

Ultimately, by providing empirical performance data, validated simulation tools, and insights into practical monitoring strategies, this study aims to contribute significantly to the existing knowledge on sustainable refrigeration solutions. The results are expected to offer valuable guidance for researchers, engineers, and policymakers involved in developing affordable, reliable, and sustainable cooling systems designed to meet the urgent needs of off-grid communities in Sub-Saharan Africa and similar regions worldwide.

2 Literature Review

This section reviews the existing body of knowledge relevant to diffusion absorption refrigeration (DAR) systems, with emphasis on their thermal behaviour, performance characteristics, and integration with renewable energy sources. It examines prior studies on heat input influences, coefficient of performance (COP), and cooling capacity, while also exploring advancements such as phase change material (PCM) storage and alternative monitoring approaches. The review establishes the research context and identifies knowledge gaps addressed in this study.

2.1 Solar Refrigeration Technologies in Africa

Solar photovoltaic (PV) systems are increasingly being adopted in cold storage initiatives in Kenya, with electricity generation in 2022 nearly doubling compared to previous years due to numerous newly commissioned projects (IEA, 2025). Solar PV systems generate electricity directly without additional mechanical components, allowing users to scale modules based on their specific energy needs (Ngure et al., 2023). However, while solar PV refrigeration addresses immediate cooling needs, it introduces critical limitations. A battery-based solar PV systems incur significant upfront capital expenditure, with batteries often accounting for over 60–80% of total system cost in off-grid contexts and requiring frequent replacements, raising sustainability concerns related to improper disposal and environmental contamination (Arif et al., 2023). Sidney and Mohan Lal (2016) conducted an experiment analysing the exergy performance of a solar PV-driven DC refrigerator, which was found to utilise only about 13.77% of the available energy, with the remainder unused as exergy due to thermal and electrical losses in the PV panel. Additionally, another well-established and efficient cooling technology is the conventional solar-powered vapour compression system, which generates DC electricity and reduces battery dependence. This approach minimises energy losses while improving the coefficient of performance (COP) and overall system efficiency (Saha & Azad, 2024). However, a significant challenge with this system is the high energy demand required to operate compressors, leading to greenhouse gas emissions

and adverse environmental impacts. Additionally, the use of conventional refrigerants such as hydrocarbons (HCs) and hydrochlorofluorocarbons (HCFCs) contributes to HFC emissions, intensifying global warming (Nikbakhti et al., 2020).

2.2 DAR System – An Overview

Diffusion absorption refrigeration (DAR) system was first developed in the early 20^{th} century by Von Platen and Munters (1928) as a heat-powered, pump-free cooling cycle. A standard DAR system includes the main components of Generator, Bubble pump, Rectifier, Condenser, Evaporator and Absorber as depicted in Figure1. Unlike traditional refrigeration system, DAR technology provides distinguished features comprising of a tertiary working fluid; a refrigerant, an absorbent and an auxiliary gas. The main role of the auxiliary gas is to ensure constant pressure level across the entire system. This enables pump-less operation and eliminates the requirement of compressor leading to a substantial cut-off in noise and vibration by its absence of moving parts, and its capability to operate without electrical power (Von Platen & Munters, 1928).

The DAR cycle working principle (Chen et al., 1996) is such that the generator-bubble pump receives a weak ammonia-rich solution from the absorber. Heat input drives ammonia (NH_3) out of the solution, forming bubbles that lift liquid through the pump tube and circulate it through the system. The strong solution remains, while the NH_3 vapour flows to the rectifier for purification before entering the air-cooled condenser, where it liquefies. The liquid ammonia then passes to the evaporator, evaporates into hydrogen, and the resulting ammonia-rich gas moves to the absorber. Here, ammonia is reabsorbed, while the hydrogen which is largely non-absorbable, returns to the evaporator.

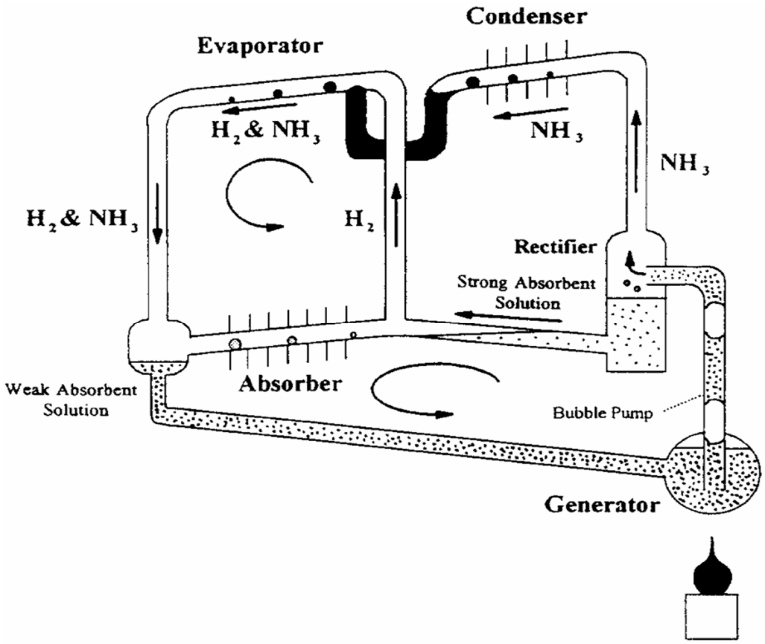


Figure 2-1: Simple DAR System Configuration (Chen et al., 1996)

Early commercial DAR units, such as propane-fuelled refrigerators for off-grid use, proved the concept's feasibility, although their coefficient of performance (COP) was relatively low (Srikhirin et al., 2002). In the late 20th and early 21st centuries, researchers launched experimental efforts to better understand and enhance DAR performance. For example, Mazouz et al. (2014) conducted an experimental thermodynamic analysis of a small ammonia–water–hydrogen refrigerator and found COP values around 0.07–0.12 under steady conditions. Similarly, Ben Jemaa et al. (2016) performed dynamic testing and modelling on a household-scale DAR, powered by electric heaters emphasising how ambient temperature and heat-input stability significantly impact cooling output. These early experiments identified critical challenges, such as designing efficient bubble-pumps and ensuring effective heat exchange, paving the way for subsequent improvements (Aman et al., 2018).

2.3 Integration of Solar Thermal Energy into DAR Systems

Beginning in the 1980s, efforts were initiated to power DAR systems with solar thermal energy. One of the earliest investigations, Bourseau et al. (1987), integrated a small ammonia–water–hydrogen refrigerator with a solar collector, demonstrating that solar heat could drive the cycle, although cooling was limited and intermittent. Later prototypes, developed in the 2000s and 2010s, continued to examine the performance of solar-driven DAR. For instance, Ben Ezzine et al. (2010) created a solar-powered DAR test setup using evacuated tube collectors and light hydrocarbons as the working fluid, achieving cooling outputs of a few hundred watts. They also conducted a numerical study of an ammonia–dimethylacetamide (R124–DMAC) working pair under solar input, showing that selecting suitable fluids could enhance COP by lowering the generator temperature. Overall, these studies demonstrated the potential of solar thermal DAR, while also revealing obstacles such as fluctuating solar inputs causing unstable cooling and low daily efficiencies.

2.4 Thermal Storage for Solar Cooling

Researchers have long recognised the importance of thermal energy storage for solar cooling systems, bridging the gap between peak solar energy and cooling needs. Phase change materials (PCMs) are extensively studied for storing energy because of their high latent heat and efficient storage capacity (Pintaldi et al., 2017). This is attributed to their capacity to store thermal energy at nearly constant temperatures, thereby enabling higher energy densities and more effective thermal regulation (Zhang et al., 2013). In addition, PCMs are typically non-toxic, non-corrosive, readily available, cost-effective on a mass basis, and provide long-term storage stability with minimal environmental impact (Yeşilyurt et al., 2019). Incorporating PCM-based thermal storage allows surplus heat during peak hours to be stored and later used for refrigeration during cloudy periods or after sunset. A review by Dhindsa (2021) highlight developments in PCM-enhanced solar absorption refrigeration, noting that typical PCMs like paraffin waxes, hydrated salts, or fatty acids can stabilise generator temperatures for effective system performance. A well-designed latent heat storage system can

keep the generator at its required temperature for hours without sunlight, enabling more continuous cold production.

2.5 System Studies

2.5.1 Experimental

An experimental study using the working fluid mixture consisting of ammonia-water-hydrogen and with notable design modifications of introducing bubble pump and heat exchanger improves system performance, achieving COP values around 0.28 - an improvement of 50% compared to the system without generator-bubble pump configuration (Chen et al., 1996). However, an experimental study conducted by Keith et al. (2016) have shown that COP decreases beyond 200 W input power (Figure 2-1), primarily due to incomplete evaporation of ammonia and liquid carryover through the circuit, which reduces both effective cooling capacity and overall efficiency for overpowered system.

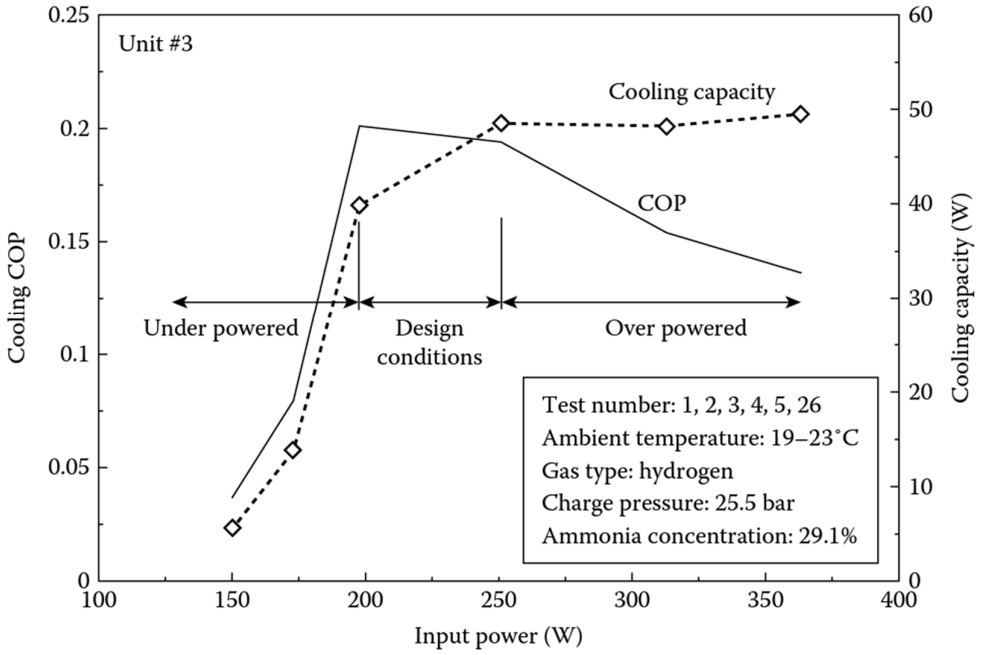


Figure 2-2-2: DAR performance data (Keith et al., 2016)

Another study of semi-empirical model developed by Freeman and Markides (2024a) was investigated to assess the performance potential of an ammonia–water–hydrogen solar-DAR system for rural India accounting for both steady-

state operation and dynamic start-up under solar-thermal input. Experimental calibration showed a maximum COP of 0.25 at 14 bar, while at a minimum heat input of 100 W, bubble pump activation was delayed by up to two hours, resulting in no cooling during this period.

2.5.2 Simulation Approach

In a numerical model simulation study conducted by Harraz et al. (2019), an extended model validation was conducted to examine the influence of key operating parameters on system performance, including generator heat input (150–700 W), cooling delivery temperature (5 °C and 23 °C), and system charge pressure (18 and 21 bar). The measured COP ranged between 0.02 and 0.29, while model predictions indicated a maximum attainable COP of 0.24 for the investigated pressures and cooling conditions.

Further modelling and simulation study by Yousuf et al. (2014), the performance of an ammonia–water–hydrogen diffusion absorption refrigeration (DAR) cycle was evaluated under steady-state operating conditions. This model was developed and analysed through simulation using the Engineering Equation Solver (EES) software pack, which stores thermodynamic properties of various fluids. The parametric analysis revealed that the DAR system performs effectively at generator temperatures between 70 °C and 160 °C, suggesting suitability for solar-thermal applications. The study also highlighted the critical influence of bubble pump operation on overall system behaviour, identifying it as an area requiring further attention.

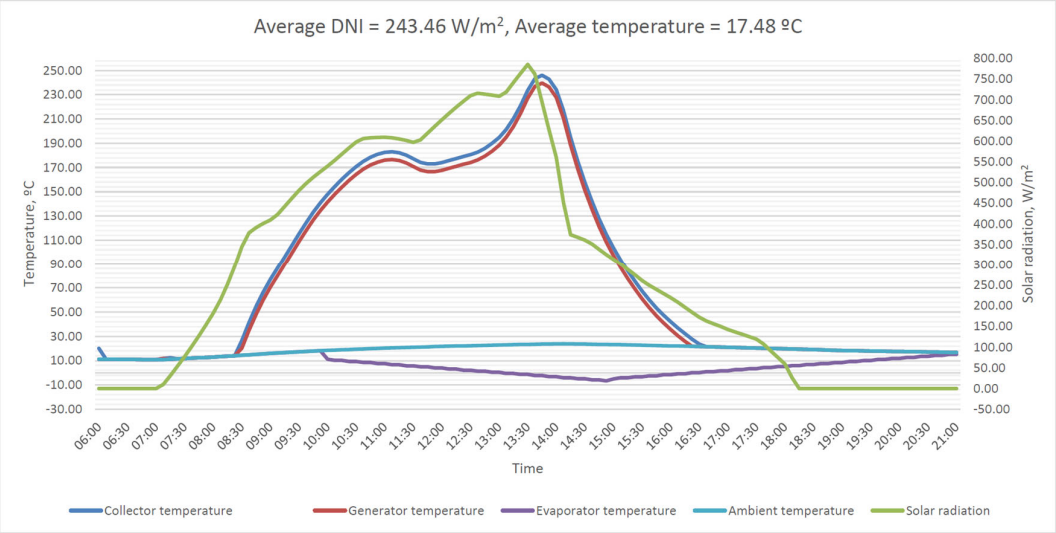


Figure 2-3: TRNSYS Data: Temperature profile on a cloudy day (Mate-Kole, 2024)

In a recent study on the existing DAR system rig at Cranfield University, Mate-Kole (2024) successfully simulated system performance using TRNSYS 18 simulation studio software, assessing its technical feasibility for off-grid applications in Kenya. The findings indicated that system performance in DAR system is highly dependent on solar radiation. Under sunny conditions (DNI > 500–700 W/m², ambient > 21 °C), the evaporator achieved a minimum of –16.95 °C, whereas partly sunny and cloudy days resulted in reduced cooling, reaching –12.22 °C and –6.65 °C respectively. These findings highlight that sufficient solar input and generator temperatures of 150–250 °C are critical thresholds for initiating and sustaining cooling in solar-driven DAR systems.

In view of the above, recent research has explored systems that combine diffusion absorption refrigeration units with PCM thermal storage. These systems aim to use PCM storage as a buffer for the thermal input to the DAR cycle, helping to mitigate solar energy intermittency and enhance overall reliability. Moser et al. (2019) presented a TRNSYS model of a novel PCM-based heat storage system employing stable supercooling of sodium acetate trihydrate (SAT) within a solar thermal for space heating and domestic supply. The model demonstrated that stable supercooling enables long-term, low-loss latent heat storage at ambient temperature, overcoming limitations of conventional thermal energy storage.

Although full-scale experimental demonstrations of hybrid DAR–PCM systems remain limited, existing studies consistently highlight the potential advantages of thermal storage. For example, Huang et al. (2024) found that retrofitting a PCM storage to a solar absorption refrigerator delivered 35.3% more heat for heating and 85.4% more for cooling, pointing to its greater heat storage capacity relative to the conventional hot-water storage tank. On the contrary, a key challenge lies in balancing the thermal conductivity and storage capacity. Techniques like adding fins and other porous materials may enhance heat transfer rates but reduce the effective PCM storage volume leading to increased system cost and complexity (Izadi et al., 2025).

2.6 Emergence of Smart Monitoring in Solar DAR Systems

As solar-driven DAR systems advance in complexity, the need for intelligent monitoring and control becomes increasingly critical. The generator–bubble pump section represents the most sensitive point for monitoring, since the applied heat input drives boiling of the ammonia–water–hydrogen mixture, producing bubbles that rise through the bubble pump. Close observation of this region provides valuable insight into system performance, as greater bubbling activity generally reflects stronger circulation and improved efficiency, thereby highlighting the importance of targeted monitoring. Traditionally, studies of boiling characteristics on heated surfaces have relied on visualization techniques, most notably high-speed video cameras, to investigate bubble dynamics such as growth, collapse, and departure, as well as broader boiling behaviours including natural convection, subcooled nucleate boiling, and saturation boiling (Baek et al., 2018).

More recently, Acoustic Emission (AE) sensing has emerged as a promising alternative. Since bubble growth, collapse, and two-phase flow transitions generate distinct acoustic signatures, AE enables external monitoring without intrusive instrumentation. Studies on acoustic emission (AE) monitoring of bubble dynamics by Mba et al (2010) have demonstrated that distinct AE events can be detected at the moment of bubble detachment. For example, signals captured by a proximal AE sensor showed clear waveforms corresponding to single-bubble

formation events at the nozzle (Figure 2-2). Using time–frequency analysis techniques, such as Gabor wavelet transforms, researchers observed characteristic frequency intensities over the signal duration, thereby providing deeper insight into the acoustic signature of bubble formation using AGU-Vallen software analysis.

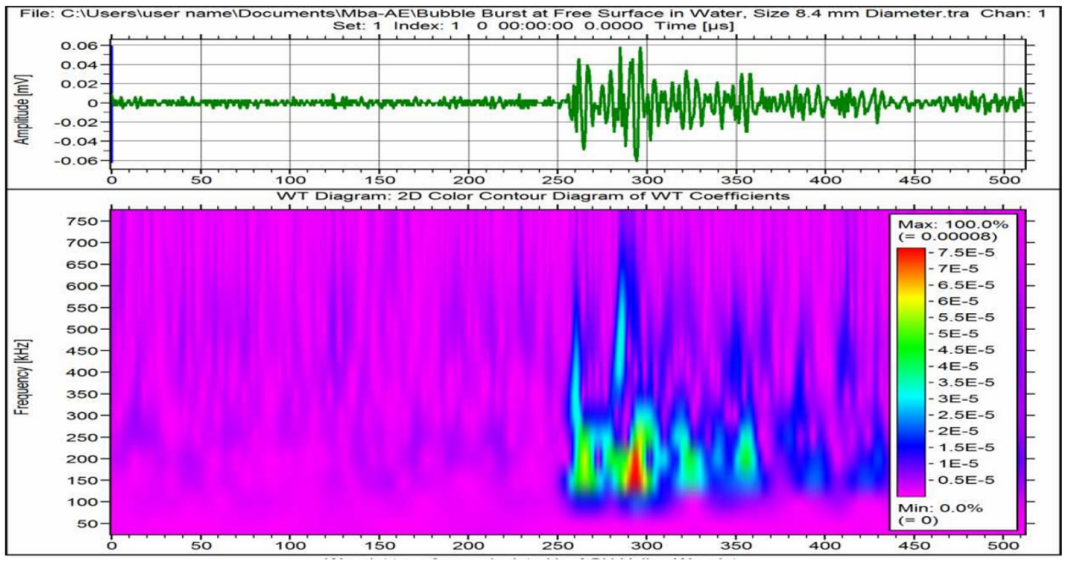


Figure 2-4: Bubble burst image from nozzle (Mba et al., 2010)

Research in boiling heat transfer demonstrates that different nucleation regimes and heat-flux conditions imprint unique spectral features, which can be analysed through AE signal processing and, in modern approaches, machine learning techniques to classify states and predict heat-transfer metrics non-invasively (Lim et al., 2025).

Hydrophones and contact AE sensors have also been successfully applied to detect the onset of boiling and to discriminate flow regimes in cooling systems, with clear rises in signal levels above background noise. For example, Rapisarda et al (2015), in the LIPAc protection study, found that hydrophones captured boiling activity with sufficient resolution to enable prompt detection and protective control, confirming that low-cost, externally mounted sensors can serve as reliable real-time indicators of phase-change activity.

Extending this concept, recent work suggests the use of affordable audio acquisition chains for solar-driven DAR systems. Simple setups combining a hydrophone (Model: AS-1) or contact pickup with commodity interfaces such as Zoom AMS-22 provides flat frequency response and adequate gain that facilitates continuous monitoring (Zoom Corporation, n.d). Coupled with widely available software like Audacity, such configurations enable practical, off-grid diagnostics and real-time visualisation of bubbling activity in the bubble pump, offering a cost-effective pathway toward smart monitoring in solar DAR applications.

2.7 Gaps in Literature

A major motivation behind solar thermal DAR research is to provide refrigeration in off-grid rural areas, such as those in Sub-Saharan Africa, where grid electricity is often unavailable. These regions have abundant solar irradiance, making solar-powered cooling attractive for preserving food and vaccines (N'Tsoukpoe et al., 2014). Several pilot projects have tested solar-driven absorption refrigeration in African climates. N'Tsoukpoe et al. (2014) reviewed these efforts and noted that while the potential is high, many systems have struggled with maintenance issues and high initial costs.

In an experimental trial, a solar-powered DAR unit for cooling farm produce achieved only a few hours of cooling per day due to the limited duration of sufficient solar heat (Freeman & Markides, 2024a). This finding aligns with further simulation studies by Freeman and Markides (2024b), who predicted that a basic solar DAR system without storage yields an overall solar-to-cooling efficiency below 1%. On a positive note, when PCM thermal storage and smart controls are incorporated, performance improves markedly. Mousavi et al. (2022) showed that a DAR system augmented with latent heat storage could provide more stable cooling output and extend operation into the night. As of 2024, solar thermal refrigeration installations in Sub-Saharan Africa remain mostly limited to pilot demonstrations, but continued advances in system design and decreasing costs are gradually improving their viability (Garcia et al., 2024).

3 Methodology

3.1 Research Philosophy

This thesis adopts a mixed-methods approach, integrating experimental analysis and validating the results using modelling software aiming to evaluate and optimize performance of a novel Diffusion Absorption Refrigeration system which utilises ammonia-water-hydrogen setup and dual system components.

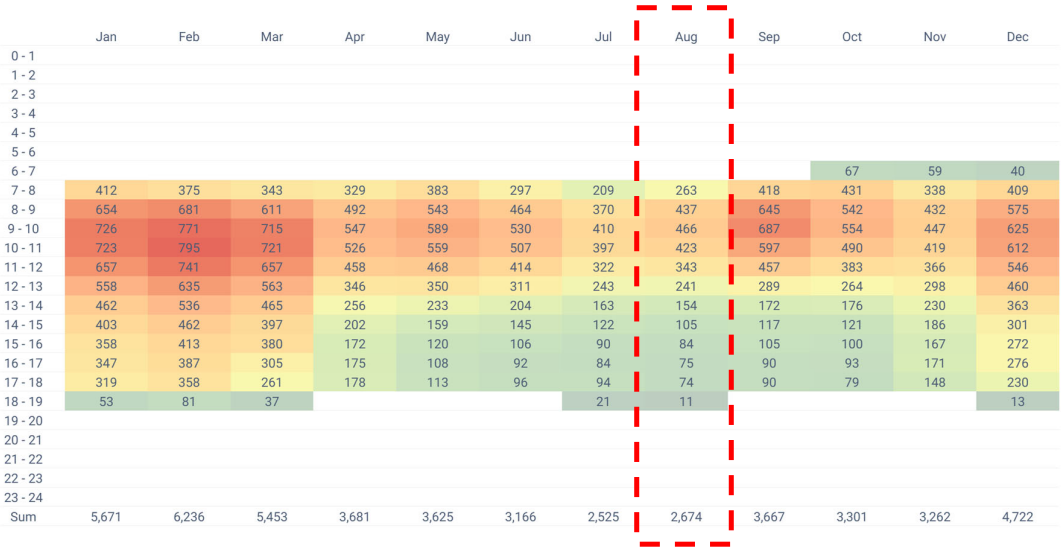
The approach towards the research is panned out into mainly four stages:

- Re-commission and run the DAR system rig:
    - Inspect and restore the DAR setup rig located in PSE Lab, Building B52 in Cranfield University.
    - Conduct a preliminary system run to verify functional integrity.
- Plan and conduct experimental trials to establish baseline performance:
    - Develop experiment plan defining key thermal and operational input parameters.
    - Record core performance outputs (COP, temperature, system behaviour)
- Compare new experimental results with existing TRNSYS model data:
    - Gather previous experiment logs and TRNSYS model data.
    - Reproduce similar test conditions to ensure comparison validity.
    - Perform validation with previous model data.
- Integrate thermal energy storage in the system to estimate its impact on extended cooling capability
    - Select and encapsulate an appropriate PCM into the model
    - Evaluate cooling retention performance to evaluate TES impact
- Assess the feasibility of integrating cost-effective monitoring feature:
    - Identify key operational signals related to bubbling activities.
    - Connect vibration/acoustic sensors to detect patterns of bubble activity.
    - Visualize and log sensor output to correlate with performance trends.

3.2 Data Collection

3.2.1 Location Information

The power input as per above tables and figures equate to the average hourly DNI profile in cloudy conditions in Kenya in August



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
0 - 1												
1 - 2												
2 - 3												
3 - 4												
4 - 5												
5 - 6												
6 - 7										67	59	40
7 - 8	412	375	343	329	383	297	209	263	418	431	338	409
8 - 9	654	681	611	492	543	464	370	437	645	542	432	575
9 - 10	726	771	715	547	589	530	410	466	687	554	447	625
10 - 11	723	795	721	526	559	507	397	423	597	490	419	612
11 - 12	657	741	657	458	468	414	322	343	457	383	366	546
12 - 13	558	635	563	346	350	311	243	241	289	264	298	460
13 - 14	462	536	465	256	233	204	163	154	172	176	230	363
14 - 15	403	462	397	202	159	145	122	105	117	121	186	301
15 - 16	358	413	380	172	120	106	90	84	105	100	167	272
16 - 17	347	387	305	175	108	92	84	75	90	93	171	276
17 - 18	319	358	261	178	113	96	94	74	90	79	148	230
18 - 19	53	81	37				21	11				13
19 - 20												
20 - 21												
21 - 22												
22 - 23												
23 - 24												
Sum	5,671	6,236	5,453	3,681	3,625	3,166	2,525	2,674	3,667	3,301	3,262	4,722

Figure 3-1: Kenya DNI data (Source: Global Solar Atlas 2.12, n.d.)

3.2.2 Assumptions Applied

- The lowest average monthly DNI for August was considered, as the experiment was conducted in this month.
- The efficiency of the solar collector is considered as 0.50.
- The combined electric heater rating was approximated as 340 W.
- The electric heater was taken as the sole heat source for the generator.
- Small wiring losses were ignored, and good thermal contact between the heater and generator was assumed.
- Heat losses from the generator housing to the ambient were considered negligible.
- Solution and vapour bubbles leaving the generator were assumed to be at the same temperature.
- The effect of hydrostatic pressure was assumed negligible.
- Pressure drops along the pipes were neglected.

- The hydrogen–ammonia gas mixture temperature before expansion was assumed to be 5 °C higher than after expansion.
- Gas mixture properties were evaluated using the ideal gas law.
- The bubble pump was assumed to be insulated.

3.2.3 Materials used

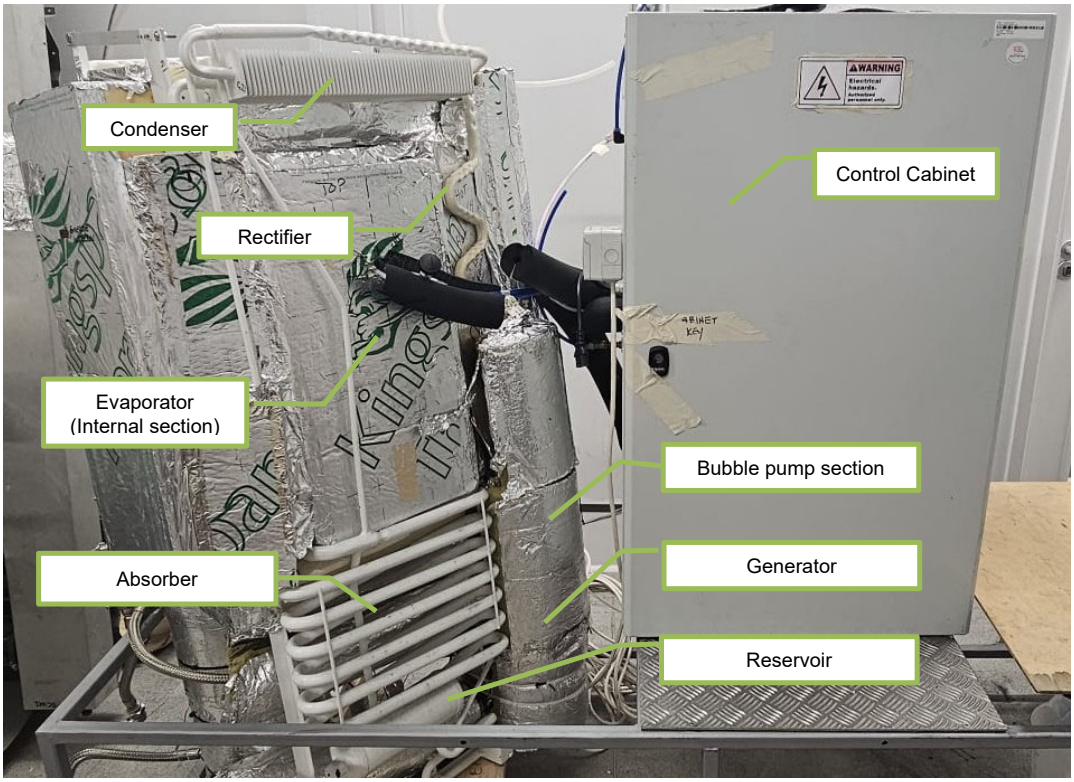
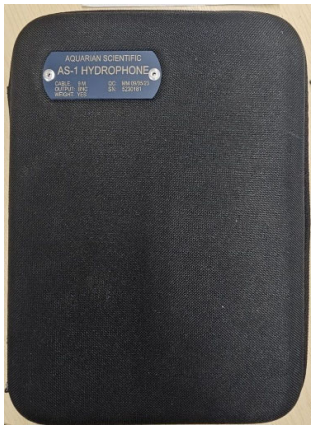


Figure 3-2: Experimental DAR rig

1



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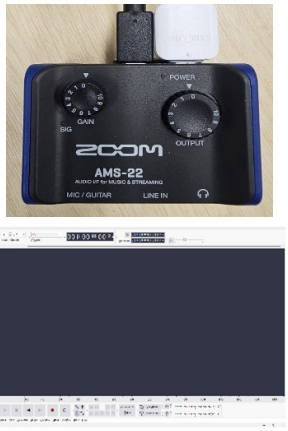

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4

5

6

Figure 3-3: Instruments used for experiments

Table 3-1: Experimental Devices use

SN	Instrument and Software	Use
1	DIM-1 Dimmer Switch	Input Control
2	AS-1 Hydrophone	Acoustic Sensor
3	Zoom AMS-22 Audio Device + Audacity	Acoustic Monitoring
4	Clamp Meter	Volt and Ampere readings
5	PicoLog Logger + Pico Software	Temperature plot
6	K Type Thermocouple	Temperature readings

3.2.4 Performance Metrics

The following parameters that evaluate the performance of the DAR system were plotted and discussed with:

- By Experiment:
    - Generator and Evaporator Temperature
    - Coefficient of Performance (COP) – efficiency measure of DAR systema and is defined as the ratio of cooling output to energy input to the system

$$\text{COP} = \frac{\text{Cooling Output (kWh)}}{\text{Energy Input (kWh)}}$$

    - Cooling Capacity / Output
    - Bubbling Activity Monitoring (Acoustic)
- By Simulation:
    - PCM integration into the TRNSYS model

3.3 Experimental Setup and Procedure

The experiments were conducted on a DAR system rig located in PSE Laboratory in Cranfield University, under controlled conditions. Prior to start-up, all connections and safety interlocks were verified against a pre-run checklist (Appendix B.1). The generator was then electrically heated, and variable heat input was controlled via a dimmer switch and quantified with an inline clamp meter to report net electrical input (Table 3-2) to the heater. The generator, evaporator and ambient temperature were measured using K-type thermocouples linked with inbuilt temperature sensors of the unit. Temperature signals were acquired via a PicoLog logger connected to a laptop for real-time plotting and data archiving in Pico software. In addition. to monitor bubble-pump activity, AS-1 hydrophone was affixed to the bubble-pump heat pipe and operated for a 60-minute observation window. The hydrophone output was routed through a Zoom AMS-22 audio interface to the laptop, where acoustic data were captured and subsequently visualised (time-waveform and spectra) using Audacity software.

Table 3-2: Variable Input data

SN	Voltage (V)	Current (A)	Power* (W)
1	76.4	4.4	336
2	68.8	4	275
3	65.8	3.8	250
4	58	3.45	200

* Power Input data rounded off.

3.4 Simulation Study Analysis

Month	Day	hour	hour
JAN	1	0	744
FEB	32	744	1416
MAR	60	1416	2160
APR	91	2160	2880
MAY	121	2880	3624
JUN	152	3624	4344
JUL	182	4344	5088
AUG	213	5088	5832
SEP	244	5832	6552
OCT	274	6552	7296
NOV	305	7296	8016
DEC	335	8016	8760

Figure 3-4: Simulation variable detail (TRNSYS manual – Volume 1)

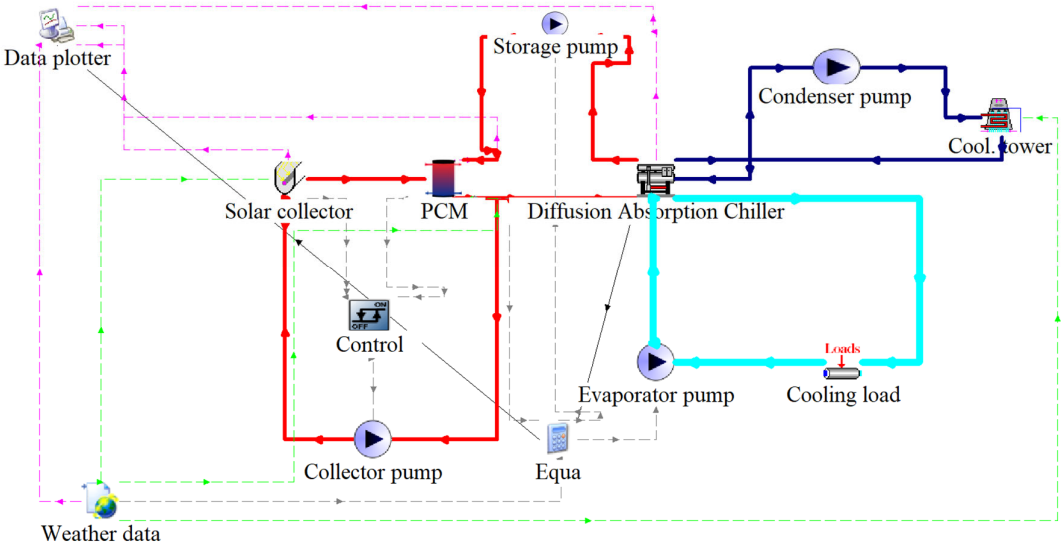

Figure 3-5: TRNSYS model with PCM Integration

Table 3-3: PCM - Paraffin Wax Properties (Kumar et al., 2019)

SN	Properties	Unit	Value
1	Specific heat capacity (Solid)	J/kg.°C	2950
2	Specific heat capacity (Liquid)	J/kg.°C	2510
3	Density of PCM (Solid)	kg/m^3	818
4	Density of PCM (Liquid)	kg/m^3	760
5	Latent Heat of fusion	J/kg	226000

The data obtained from experiments were then validated using the existing TRNSYS 18 model software exclusively used for the simulation of DAR model. In addition, the model was also modified to integrate PCM with the properties as mentioned in Table 3-3. Simulations were performed in existing TRNSYS 18 Simulation Studio model (Mate-Kole, 2024) to evaluate a DAR system coupled to PCM over a continuous 48-hour horizon (From Figure 3-4 data: 5670 h = 06:00, 25th Aug to 5718 h = 06:00, 27th Aug). A site-specific August weather data with direct normal irradiance, ambient temperature was imported (Figure 3-1) and interpolated to the simulation time step. Outputs were logged and runs were plotted at the end of 48 h window.

4 Results

This section presents the results obtained from laboratory experiments and simulation from TRNSYS 18 software. The data elaborates the performance of DAR system with reference to the generator and evaporator temperature on low DNI conditions. It also monitors the behavioural pattern within the system in relation to bubbling activity by acoustics means. Further, through TRNSYS, the effect of thermal energy storage (PCM) integration in the system is described.

4.1 Experimental Data Presentation

4.1.1 Effect of Heat Inputs on Performance

The system performance has been analysed through various experimental runs with the existing DAR rig replicating the actual cloudy-month condition. This has been depicted in tables and figures in this section. These data represent the performance trends and behaviour pattern of DAR system with various input parameters that is linked to weather conditions.

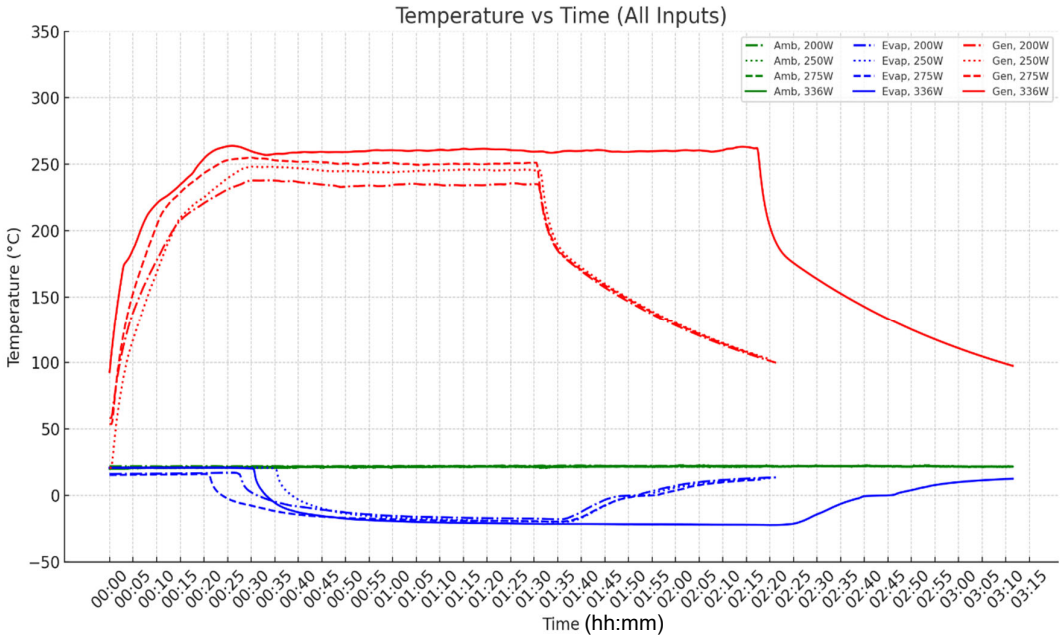

Figure 4-1: Temperature profiles at various heat input vs Time

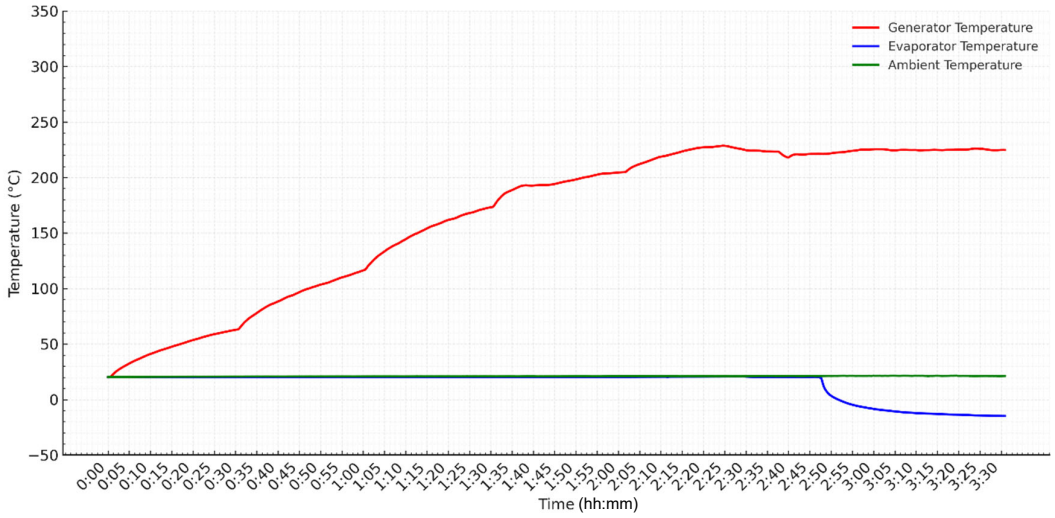

Figure 4-2: Progression Temperature profile vs Time

Table 4-1: Average Stabilised Temperature at defined heat inputs

SN	Power Input (W)	Generator temperature (°C)	Evaporator temperature (°C)	Ambient temperature (°C)
1	336 W	259.8	-19.45	21
2	275 W	254.9	-18.12	21
3	250 W	248.1	-16.87	21
4	225 W	237.7	-15.55	21

Table 4-2: Temperature data against progressive heat input

SN	Power Input (W)	Generator temperature (°C)	Evaporator temperature (°C)	Ambient temperature (°C)
1	13 W	62.8	20.1	21
2	35 W	116.3	20.2	21
3	64 W	173.1	20.3	21
4	102 W	204.5	20.4	21
5	125 W	224.6	20.6	21
6	175 W	225.4	-8.4	21
7	200 W	224.8	-14.7	21

The temperature profiles of the DAR system under different heat inputs against time are presented in Figures 4-1 and 4-2. The results clearly demonstrate that the thermal behaviour of the system is strongly dependent on the magnitude of the applied heat input. As per Figure 4-1, with the test period conducted for a span of about 2 hours, an increase in electrical input via the dimmer-controlled heater resulted in a progressive rise in generator temperature, which reached a steady condition after approximately 30 minutes of operation. Likewise, the evaporator temperature exhibited a sharp decline within the first 20–30 minutes, reflecting the onset of effective cooling, before gradually stabilising after around 60 minutes across all test cases. The corresponding average stabilised temperatures obtained from PicoLog measurements at each heat input are summarised in Table 4-1.

In Figure 4-2, the temperature profiles of the DAR system are shown for a continuous run of 210 minutes (3 hours and 30 minutes), with measurements recorded at 30-minute intervals under progressively increased heat inputs. The generator temperature rises steadily with increasing input, while the evaporator temperature remains close to ambient for the first 170 minutes of operation. A noticeable decline in evaporator temperature, indicating cooling, is observed only after the applied input exceeds approximately 170 W. From this point onwards, both generator and evaporator profiles approach steady behaviour. The corresponding transient and steady-state temperature values, at every 30-minute mark, obtained from PicoLog device are summarised in Table 4-2.

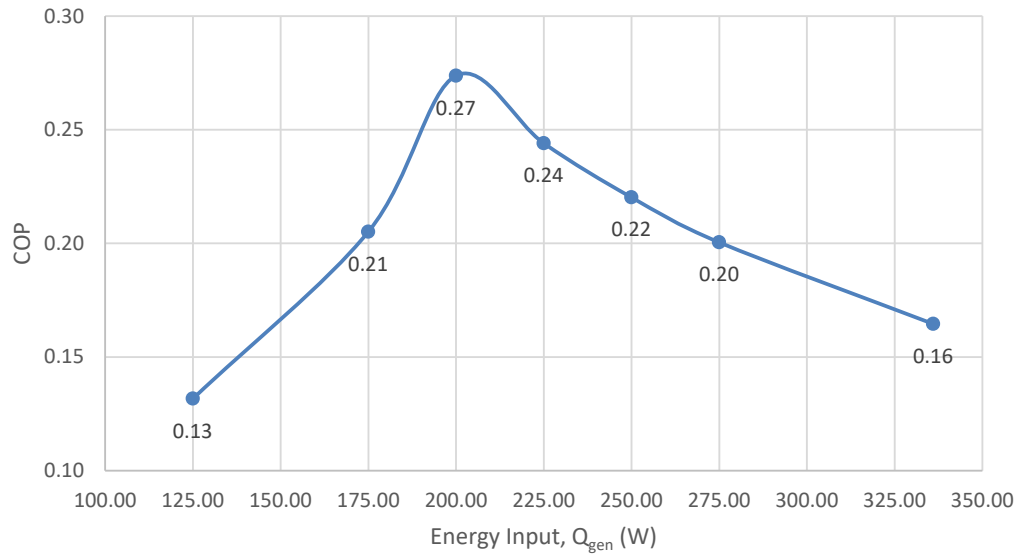

Figure 4-3: Energy Input vs COP

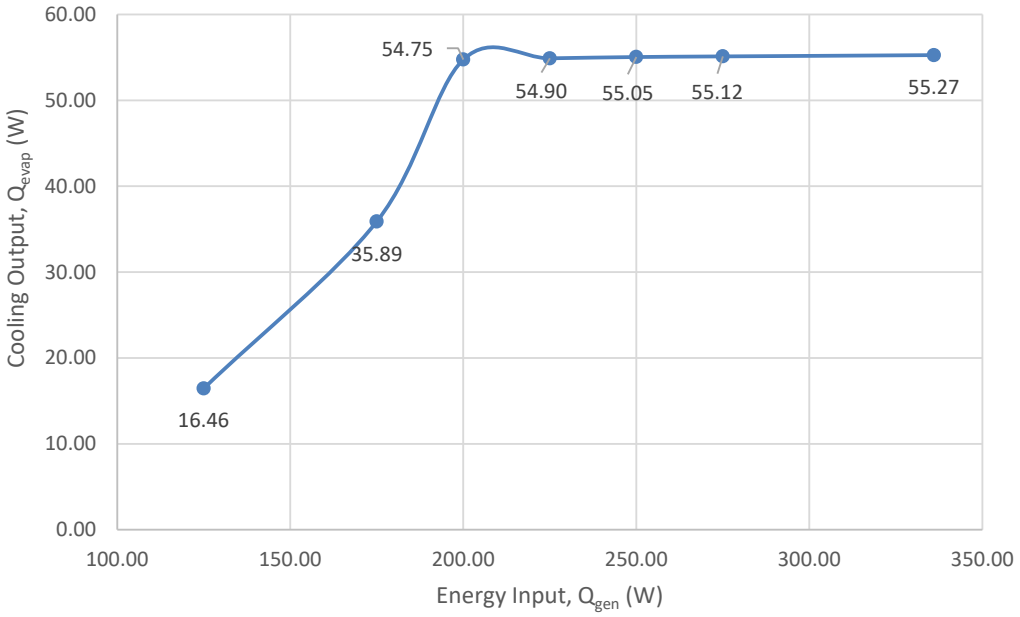

Figure 4-4: Energy Input vs Cooling Output

Table 4-3: COP and Cooling Output Data from various heat inputs

SN	Energy Input, Q_{gen} (W)	Cooling Output, Q_{evap} (W)	COP
1	125 W	16.46	0.13
2	175 W	35.89	0.21
3	**200 W**	**54.75**	**0.27**
4	225 W	54.90	0.24
5	250 W	55.05	0.22
6	275 W	55.12	0.20
7	336 W	55.27	0.16

The effects of heat input on COP and cooling capacity of the DAR system are illustrated in Figures 4-3 and 4-4, with the corresponding values presented in Table 4-3. The results clearly demonstrate that system performance is strongly dependent on the applied heat input. During the initial start-up phase, both COP and cooling capacity show a gradual rise, which can be attributed to the transient behaviour of the bubble pump and the time required for the working fluid circulation to stabilise. As the input power increases, a significant enhancement in both COP and cooling capacity is observed, reflecting improved thermal driving potential in the generator and more effective operation of the evaporator. The COP reaches its maximum value at an input of approximately 200 W, beyond which it exhibits a declining trend. In contrast, the cooling capacity remains relatively stable at its maximum value once the input reaches 200 W, showing minimal variation with further increases in heat supply. This behaviour highlights the practical significance of an optimum heat input range for achieving efficient DAR system operation. The calculations for Cooling output and COP done for the system are shown in Appendix B-2.

4.1.2 Effect of Performance by Acoustic Monitoring

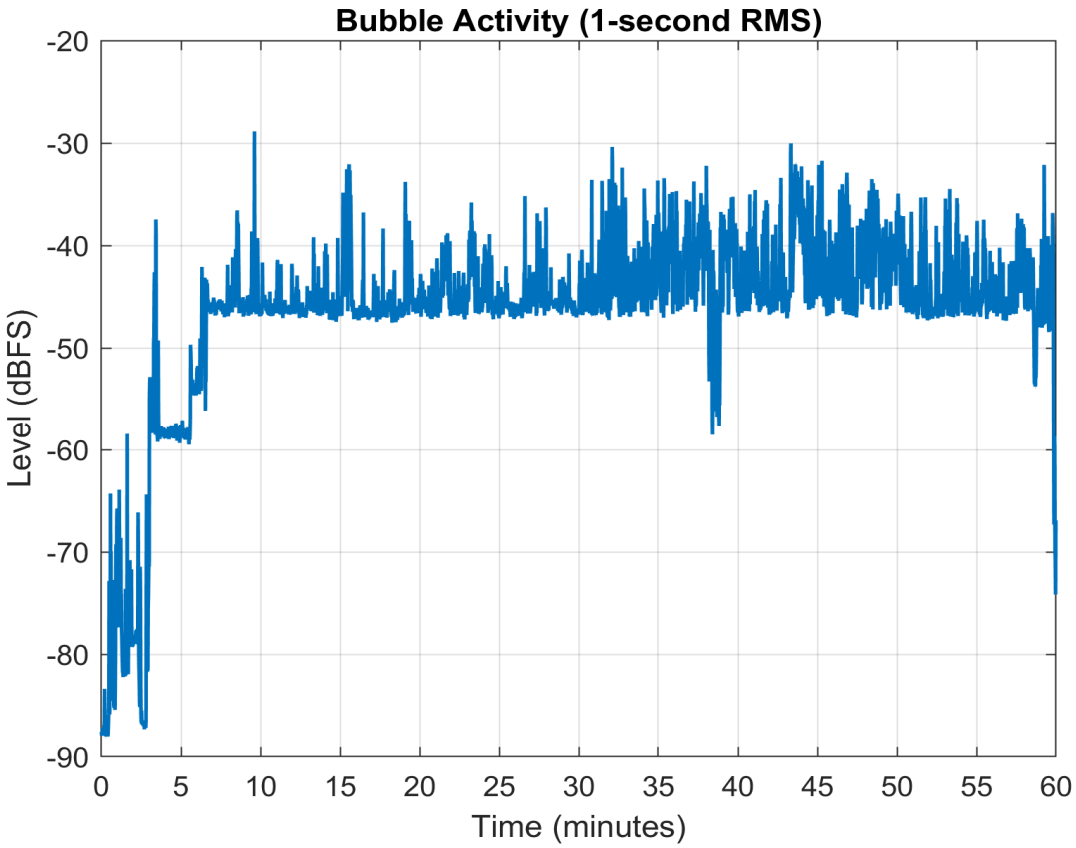

Figure 4-5: Acoustic Monitoring using Audacity

Figure 4-3 illustrates the monitoring activity conducted in the generator/bubble pump section of the DAR system under a heat input of 200 W. Prior to connecting the AS-1 hydrophone, baseline measurements of the acoustic environment were recorded (initial few minutes before sensor attachment) using Audacity software to establish the background noise level in the laboratory. These preliminary readings, ranging from –60 to –85 dBFS, reflected ambient disturbances unrelated to the rig operation. Subsequently, the AMS-22 sensor was securely attached to the external wall of the heat pipe section of the bubble pump, ensuring isolation from external noise sources.

Following the application of a 200 W input through the dimmer-controlled electric heater, the system was monitored continuously for a one-hour period. During this interval, the generator temperature rose progressively, initiating bubble formation

within the working fluid of the bubble pump. The onset of this activity generated distinct acoustic and vibrational signals, which were transmitted via the AMS-22 sensor and recorded using Audacity software. The measured signal intensity ranged from –45 to –35 dBFS, values that were clearly distinguishable from the background noise levels recorded earlier. These observations confirm active bubbling behaviour and validate the monitoring approach.

4.2 Simulation Data Presentation

The existing TRNSYS 18 simulation studio model of DAR system (Mate-Kole, 2024) has been run for the simulation similar to the cloudy region in Kenya, for the month of August with integration of PCM as thermal energy storage and plotted to understand the effect on cooling capacity of the DAR system for the defined parameters as shown in Table 3-3 in Methodology section.

4.2.1 Effect of PCM Integration on Performance

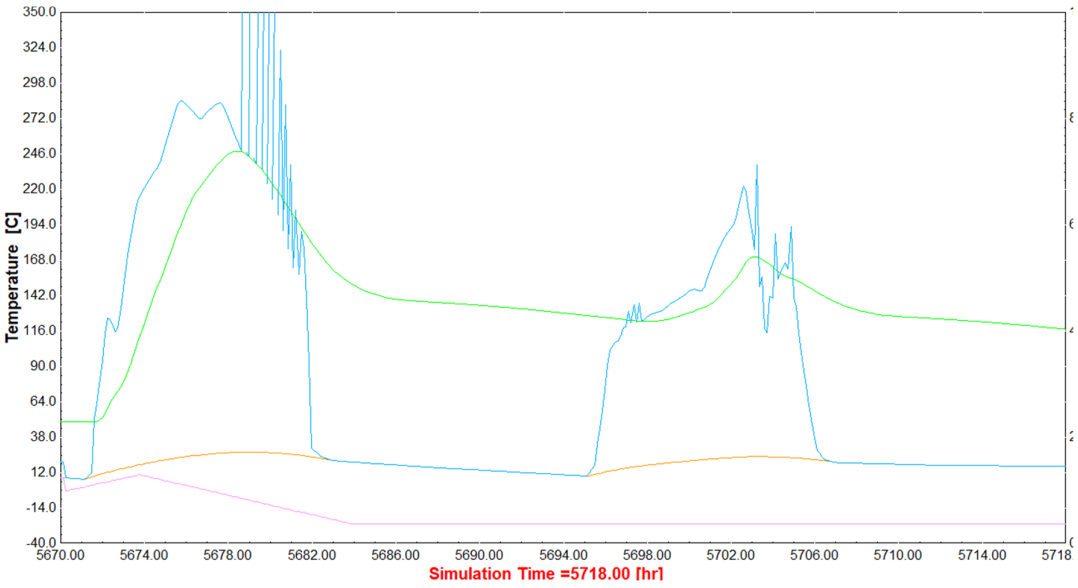

Figure 4-6: Simulation of PCM Integrated model

Figure 4-6 presents the TRNSYS simulation results of the DAR system integrated with thermal energy storage (PCM) over a 48-hour period, from 5670 hr (06:00 on 25 August) to 5718 hr (06:00 on 27 August). The results indicate that following an initial two-hour start-up period, the solar collector temperature begins to rise

sharply from around 08:00. The corresponding increase in storage temperature is observed approximately two hours later, reflecting the time lag for heat transfer to the PCM. The collector temperature reaches a peak of about 280 °C between 12:00 and 14:00, after which it gradually declines with the reduction in solar irradiation. A similar pattern is observed in the PCM section, where the temperature peaks at approximately 245 °C and remains within this range for around two hours between 14:00 and 16:00 before decreasing. Notably, during off-peak hours with no solar input, the PCM storage sustains temperatures between 130 °C and 150 °C. This thermal retention provides a continuous driving source for the evaporator, enabling its temperature to drop and remain steady in the range of around - 20 °C during extended no-sunlight periods. It shows the capacity of the integrated storage to extend cooling performance beyond daylight hours and enhance overall system efficiency.

4.3 Results Summary

4.3.1 Experimental Findings

Experimental results show that varying power input significantly affects the DAR system's thermal behaviour and performance. Higher heater power led to faster generator heat-up to higher equilibrium temperatures and deeper evaporator cooling (reaching sub-zero steady-state), with each input level exhibiting a transient warm-up period before steady operation). Cooling performance (COP, and cooling capacity) improved with increasing heat input and peaked at 200 W with COP of 0.27. Beyond 200 W, performance gains diminished, indicating thermal limits. Acoustic monitoring at 200 W detected characteristic bubble-pump vibrations (Figure 4-5), confirming active refrigerant circulation at optimum operational conditions.

4.3.2 Simulation Insights

TRNSYS 18 simulations with an integrated phase-change material (PCM) heat store complemented the experiments. The simulated collector and storage temperature profiles show that PCM absorbs heat at peak irradiation and releases it gradually, thereby extending cooling into off-sunlight hours. The PCM storage also moderated temperature swings and reduced reliance on continuous heat supply, supporting extended heat availability with latent storage. The results indicate that the DAR system's performance is optimal at 200 W power input, and that PCM thermal storage significantly enhances cooling duration and stability under intermittent heat input.

5 Discussion

This chapter discusses the experimental and simulation results presented earlier, examining their implications in the context of existing literature. The section evaluates the impact of heat input on system performance, variations in COP and cooling output, the potential of acoustic monitoring as a diagnostic tool, and the role of phase change material (PCM) integration in extending cooling operation. The findings are critically compared with published studies to establish broader relevance.

5.1 Effects of varying Heat Inputs

The experimental results demonstrated a clear dependence of the DAR system's thermal behaviour on heat input to the generator. These findings align observations from prior experimental studies. For instance, Freeman and Markides (2024a) reported that at very low heat input levels of around 100 W, a DAR system's bubble pump activation was significantly delayed and no cooling occurred during that period. This delay is consistent with observation of negligible cooling until sufficient heat input was provided, emphasizing the importance of overcoming the initial thermal inactivity and bubble pump start-up requirements.

Similarly, the literature emphasizes that DAR cooling output is highly sensitive to generator heating conditions. Similarly, Yousuf et al. (2014) found through simulation that effective operation occurs within a certain generator temperature band (approximately 70–160 °C), below which the cycle struggles to produce cooling. In present experiments, the generator had to exceed roughly 200 °C (achieved with ~170 W input) before the evaporator temperature dropped, indicating that system's operating conditions demanded increased temperature ranges. Once that threshold is crossed, the generator–bubble pump can sustain circulation, leading to the sharp evaporator cooling observed. In essence, current results confirm the literature consensus that generator heat input is a driving factor for system behaviour with inadequate heat leading to prolonged warm-up and little to no cooling. There is also evidence of an upper limit to useful heat input, beyond which additional heat does not translate to proportionate cooling

gains (Keith et al., 2016). This points to the existence of an optimal operating range of heat input for the generator, a topic which is closely tied to the system's coefficient of performance and cooling capacity trends.

5.2 Effects of COP and Cooling Capacity Trends

In the present study, both COP and cooling capacity increased with rising heat input initially, up to a point and declined at the highest inputs (dropping to ~0.20 at 275 W and ~0.16 at 336 W). This indicates diminishing returns and efficiency loss at excessive heat input levels. Physically, once the working fluid circulation and phase change are fully activated, extra heat can lead to inefficiencies such as over-pressure in the condenser or incomplete vaporization followed by liquid carryover, which do not contribute to additional cooling. Thus, the system exhibits a pronounced optimal heat input range (around 175–200 W for current setup) for maximal efficiency.

Such pattern in previous studies done by Keith et al. (2016) observed that a DAR system's COP decreases beyond about 200 W of input power, attributing it to incomplete ammonia evaporation and inefficient performance rates. This directly mirrors current findings that the drop in COP at high inputs decreases from the same phenomena of refrigerant flow inefficiencies when the generator is over-powered. The measured peak COP of 0.27 is also in line with the upper range of COP values reported in the literature for ammonia–water–hydrogen DAR systems.

It is also instructive to compare the cooling capacity trend. The cooling output high point of 55 W beyond a certain input implies the system has a maximum cooling capability given its size and design, regardless of further increases in heat supply. Other researchers have noted similar saturation behaviour. In a numerical parametric study, Harraz et al. (2019) found that while COP could vary between 0.02 and 0.29 over a wide range of operating conditions, the model-predicted maximum COP of 0.24 and associated cooling power levelled off beyond optimum conditions. This underlines a practical design implication noted by Freeman and Markides (2024b) and others – supplying heat beyond the optimal point only wastes energy and can even hurt performance, so any solar collector

or heater should be sized to meet but not greatly exceed the requirement for peak COP.

5.3 Effects of Acoustic Monitoring

The results demonstrated that a simple hydrophone-based acoustic sensor can effectively capture the bubbling activity inside the generator–bubble pump. During the 200 W heat input test, acoustic measurements showed the background noise levels (around –60 to –85 dBFS) being clearly exceeded by distinctive acoustic signals (peaking around –35 to –45 dBFS) once vigorous bubbling commenced. This confirms active refrigerant circulation indicating bubbling events produce audible vibrations that can be detected externally. In practical terms, this means we were able to verify the internal operation of the refrigeration cycle without any intrusive measurements or visual observation. The acoustic method thus proved to be a low-cost and non-invasive diagnostic tool for real-time monitoring of system performance.

Current approach and findings strongly correlate with emerging research on acoustic sensing in thermal systems. Researchers studied boiling and two-phase flow by direct visualization by use of high-speed cameras to watch bubble formation and detachment (Baek et al., 2018). However, more recent studies have highlighted acoustic emission (AE) as a powerful alternative for detecting bubble dynamics. Mba et al. (2010) demonstrated that individual bubble nucleation and collapse events generate distinct acoustic signatures that can be picked up by AE sensors, with characteristic waveforms corresponding to each bubble's formation and release. This supports the observation that the beginning of boiling in the bubble pump yields a detectable acoustic pattern. Likewise, Rapisarda et al. (2015) found that hydrophones attached externally could sense the initiation of boiling in a cooling system, with a clear rise in signal amplitude above the background noise, enabling prompt detection and control. Our use of an external hydrophone sensor (AS-1 type) with a simple audio visualization (Audacity software) reflects this technique. The clean differentiation between baseline noise and active bubbling in current data is exactly the kind of outcome

Rapisarda et al. noted, confirming that even low-cost audio sensors can reliably indicate vibrational activity.

5.4 Effect of Thermal Storage – PCM Integration

The simulation covering a 48-hour cycle (representative of a cloudy period in the Kenyan context) illustrated that during sunny hours the solar collector could charge the PCM (raising its temperature to around 245 °C in current model), and then during off-peak hours, the stored heat in the PCM kept the generator supplied with thermal energy. Consequently, the evaporator was able to maintain a temperature around –20 °C well into the night despite the absence of direct solar input. This result is crucial demonstrating that PCM integration can effectively extend the cooling operation beyond daylight hours, providing a form of thermal battery for the refrigeration system. In practical terms, a DAR fridge with a PCM store could continue to provide cooling through the night or through cloudy spells, which directly addresses one of the major limitations of solar-powered cooling systems (their reliance on immediate sunlight).

These findings strongly reinforce the consensus in the literature regarding the benefits of latent heat storage for solar cooling. The present simulation confirms what prior analyses have suggested that a well-designed PCM can absorb surplus heat when the sun is abundant and then release it later, keeping the generator at an effective operating temperature for hours without sunlight (Dhindsa, 2021). Notably, Mousavi et al. (2022) demonstrated in an experimental study that a DAR system coupled with a latent heat storage unit delivered much more stable cooling output and could operate into the night, exactly as current results predicted. By comparing the current study of PCM-integrated scenario with the baseline (no storage) case, the improvement is evident that without storage, the DAR unit could only cool during periods of direct irradiation (Freeman & Markides, 2024a), but with PCM, the cooling period is substantially prolonged. Freeman and Markides (2024b), projected that a basic solar-DAR without storage achieves a very low solar-to-cooling efficiency (<1% daily efficiency).

5.5 Validation of Experimental results with TRNSYS simulation

5.5.1 Solar Irradiance and Generator Temperature

Both the experimental data and TRNSYS 18 simulation (Mate-Kole, 2024) indicate that the DAR system's generator temperature closely follows the available solar energy under cloudy conditions. In the simulation results (average DNI of 243.5 W/m², ambient temperature of 17.5 °C), the generator remains relatively cool in early periods of low irradiance, then rises sharply once the sun intensifies. This simulation study by Mate-Kole (2024), with a cloudy day in month of August, similarly showed an initial start-up followed by a rapid generator temperature increase after about 08:00 when sunlight becomes stronger. In both cases the generator attained high temperatures in the order of 200–230 °C during peak solar input, then declined as cloudy condition reduced the solar irradiance. This dynamic is evident in the simulation, where the solar-heated generator peaked around midday and then gradually cooled later in the day as DNI dropped. The agreement suggests the experimental generator responds to intermittent sun just as the model predicts, reaching similar temperatures at comparable irradiance levels. Ambient conditions in the tests (roughly 17–22 °C) align with those in simulation study scenario (ambient >21 °C during daytime), so the experimental generator had a similar thermal driving force as the assumed in the model.

5.5.2 Evaporator Temperature and Cooling Performance

Critically, both present study experimental and simulation dataset (Mate-Kole, 2024) show that meaningful cooling in the evaporator occurs only once a sufficient solar input threshold is crossed. The simulation study reported that effective cooling in the solar-driven DAR was achieved only when DNI exceeded roughly 500–700 W/m². This corresponds with the observations of the evaporator temperature staying near ambient during periods of weak sun, and only began dropping once the solar radiation intensified. In lab-based terms, the evaporator remained at ambient temperature until the heat input was high enough to drive the bubble pump which line up with experimental observation of above 170 W heater input requirement to start-up the system. Once active refrigeration

attained, the evaporator temperature in the experiment drops well below 0 °C despite the cloudy weather. The TRNSYS model (Mate-Kole, 2024) for a partly cloudy day showed the evaporator cooling down to approximately –6.65 °C when momentary DNI spikes pushed the generator to full operation (with ambient just above 21 °C). The simulation results are consistent with this during sunnier intervals the evaporator achieved temperatures (range of –6 to –7 °C), demonstrating a cooling performance in line with the simulation. Notably, both the experiment and simulation reached these low evaporator temperatures even under moderate average solar input, featuring the system's reliance on intermittent high irradiance. Overall, this validates that under cloudy skies, generator temperature rising and falling with the solar irradiance, and the evaporator only dropping to freezer-level temperatures when solar DNI peaks above 500 W/m² shows strong agreement between the experimental data and TRNSYS 18 simulation model by Mate-Kole (2024).

6 Conclusion

6.1 Summary

The experimental and simulation results of this study demonstrate the critical influence of heat input on the performance of a diffusion absorption refrigeration (DAR) system and validate strategies to enhance its off-grid operation. Experimentally, the DAR rig showed a clear optimum operating range: as heat input increased, the generator reached steady-state faster and the evaporator cooled more deeply, but only above a threshold of about 170 W did substantive cooling begin. Both the coefficient of performance (COP) and cooling capacity rose with heat input and peaked when the generator was supplied ~200 W, yielding a COP around 0.27 and an evaporator cooling output of ~55 W.

The study introduced acoustic emission monitoring as a novel diagnostic for DAR systems. Using a simple hydrophone sensor, the onset of bubble pump activity in the generator was clearly detected. This confirms that non-intrusive acoustic sensing can reliably indicate active refrigerant circulation in real time. Such acoustic monitoring proved particularly suited for remote settings, given its simplicity and effectiveness in capturing system dynamics. This technique not only validated proper system function during tests, but also holds promise as a quantitative diagnostic method to detect faults in future implementations.

The TRNSYS-based simulations reinforced the experimental insights and highlighted the value of thermal storage integration. By incorporating a PCM storage, the DAR system was able to buffer intermittent solar input and sustain cooling beyond daylight hours. The 48-hour simulation (for a cloudy Kenyan climate profile) showed that the solar collector could charge the PCM to high temperatures (~245 °C) during sunny periods and the stored heat then kept the generator active when direct sunlight diminishes. In practical terms, a solar DAR refrigerator with PCM can continue preserving vaccines or perishable goods overnight, directly addressing the traditional limitation of solar cooling systems that only operate under sunlight.

6.2 Limitations of the study

The key challenges towards the present study could be summarised as below:

- This work used a laboratory-scale DAR rig and a TRNSYS model with findings reflecting controlled conditions and may not fully capture field variability.
- Heat input and operating pressures were explored over limited ranges, so the identified optimum output is rig-specific.
- COP and cooling capacity were assessed under short test windows; long-term stability, fouling, and maintenance were not evaluated.
- The TRNSYS model employed simplifying assumptions (e.g., input parameters, losses), which can over/under-predict part-load and transient behaviour under cloudy conditions.
- PCM benefits were demonstrated only in simulation, not experimentally.
- Acoustic monitoring was validated qualitatively. However, quantitative correlations to flow rate or COP were not calibrated.

6.3 Future Recommendations

Building on these findings, future development should focus on refining the DAR system's design for greater efficiency and resilience.

6.3.1 System Design

A top priority is improved heat input management: solar collectors or burners should be sized and controlled to supply the generator's optimal thermal input without significant oversupply. Therefore, designs must ensure sufficient heat during peak sun to exceed the activation threshold (~170 W in this setup) but incorporate measures (such as variable concentrating collectors, thermal regulators, or heat dump mechanisms) to prevent continuous over-driving of the generator

6.3.2 Control Strategies

The establishment of an optimal operating window for the DAR system highlights the need for intelligent control strategies to maintain optimum operation.

Developing a simple but robust control system for thermal input is recommended. For example, a thermostat or feedback loop could be implemented to modulate the heat source (such as adjusting the flow rate of a heat transfer fluid, the tilt of a solar collector, or cycling an auxiliary heater) so that the generator temperature stays near the ideal range corresponding to peak COP. Such control would prevent the long delays in cooling observed and mitigate the efficiency losses seen at excessive inputs, thereby keeping the system in its high-performance range.

6.3.3 Enhanced PCM materials

Selecting PCM materials with phase-change temperatures suited to the generator's operating range and high latent heats is essential for effective energy storage. improving heat transfer into/out of the storage (for instance with fins, encapsulation techniques) will help the PCM charge and discharge more quickly, though designers must balance this against storage capacity and cost penalties.

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Appendices

Appendix A Ethical approval letter

4 June 2025

Dear Mr Thomas ,

Reference: CURES/25507/2025
Project ID: 28990
Title: Experimental evaluation of a novel Absorption Refrigeration system with Integrated Thermal Energy Storage and Smart Performance Monitoring

Thank you for your application to the Cranfield University Research Ethics System (CURES).

We are pleased to inform you your CURES application, reference CURES/25507/2025 **has been reviewed. You may now proceed with the research activities you have sought approval for.**

If you have any queries, please contact CURES Support.

We wish you every success with your project.

Regards,

CURES Team

Appendix B

B.1 Checklist for DAR system startup (Solar Polar, 2025)

SN	Item Details/Actions	Category
1	Verify all components installed correctly and securely; no visible damage or leaks	Pre-startup
2	Confirm insulation is intact and properly done	Pre-startup
3	Verify that the electrical plugs in the control cabinet and heater are rated for 220/240V and comply with a 13A, 3-pin socket standard.	Pre-startup
4	Ensure laptop is plugged in and USB Pico loggers are connected properly.	Pre-startup
5	Verify all MCBs in the consumer panel are OFF except main switch and first MCB labelled sockets.	Pre-startup
6	Power on the laptop, open Pico Log software and Connect thermocouples from Pico Loggers to see the relative thermocouple (TC) temperature on Pico Log screen.	Pre-startup
7	Place the AS-1 hydrophone attached to the bubble pump pipe section for acoustic sensing of bubbling activity.	Startup
8	Connect the AS-1 hydrophone via AMS-22 audio device, to the laptop, for acoustic monitoring.	Startup
9	On laptop Pico Log screen, press red dot to start recording data; select "until disk full" option if available.	Post-startup
10	Use chart icon in Pico Log software to visualize data and add operational notes	Post-startup
11	Monitor Generator TC temperatures rising and Evaporator TC temperatures falling on Pico Log chart.	Post-startup
12	Plot the desired acoustic graph by Audacity software.	Post-startup

B.2 Calculations

B.2.1 Calculations of COP

$$COP = \frac{Q_{evap}}{Q_{gen}} \quad \textbf{(6-1)}$$

- Q_{evap} - Cooling Output

$$Q_{evap} = \dot{m}\,(h_{out} - h_{in}) \quad \textbf{(6-2)}$$

- Q_{gen} - Energy Input (Power Input to generator)

Evaporator temperature (°C)	Enthalpy - Liquid, h_{in} (kJ/kg)	Enthalpy - Vapour, h_{out} (kJ/kg)	Mass flow rate, $\dot{m}$ (kg/hr)*
-19.45	94.47	1420.97	0.15
-18.12	99.50	1422.47	0.15
-16.87	102.03	1423.22	0.15
-15.55	107.07	1424.69	0.15
-14.70	112.11	1426.15	0.15
-8.4	142.56	1434.52	0.10
20.6	277.45	1462.35	0.05

* Initial mass flow rate assumed low reflecting start-up phase and then mass flow rate considered uniform for subsequent analysis.

Cooling Output, Q_{evap} (W)	Energy Input, Q_{gen} (W)	COP
55.27	336.00	0.16
55.12	275.00	0.20
55.05	250.00	0.22
54.90	225.00	0.24
54.75	200.00	0.27
35.89	175.00	0.21
16.46	125.00	0.13