

Wearable Bio-Inspired Pulsating Flow Cooling for Live Garments

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Abstract—In human experience, it has been well known that temperature induced aggravations, such as heatstroke, heat cramps, dehydration, and frostbite, are among the most common health hazards. For those who live or work in prolonged and extreme temperature conditions, the aggravation may lead to fatal consequences. Temperature control systems such as air conditioning and central heating have been investigated and implemented to provide people a comfortable, and more importantly, livable temperature. However, these systems could be cumbersome to implement in an outdoor or confined environment. Moreover, they lack flexibility such mobility and adaptable temperature for individual needs. In this study, a wearable bio-inspired pulsating (discontinuous) flow cooling system with superior heat exchange efficiency to conventional steady (continuous) flow system, is proposed. Based on a novel array of the cooling tubes, an empirical approach is adopted to avoid complex numerical analysis of the thermal fluid dynamic involved. The prototypes of the two cooling flow systems are built and their performances compared. The results show that the proposed system not only demonstrates better cooling, but also offers potential flexibility that allows personalized temperature conditioning in a ‘live’ garment.

Index Terms—bio-inspired systems, pulsating cooling, personalized cooling, wearable temperature conditioning, live garment, empirical approach.

I. INTRODUCTION

Temperature induced aggravations to human bodies have raised considerable public concerns for past decades. In thermally challenging environments with extremely high or low temperatures, it is crucial to keep the bodies within bearable, if not comfortable, limits. The commonest method would be use air conditioning means to control the ambient temperatures. However, there are special circumstances where air conditioning is hard to implement, and hardly adequate to satisfy the individual’s requirements for temperature, mobility, and practicality. It is therefore highly desirable to have a portable/wearable system that can provide a personalized, adaptive temperature control.

Many designs have been developed for wearable systems used in garments [1]–[5], hats or neck-worn accessories [6]. Potential users of such systems include but are not limited to the military, fire brigade, astronauts, personnel working in

mines or on construction sites during extreme conditions [7]. Simple and economic solutions have been implemented for people in case of heat wave [8]–[11]. In the light of these personal temperature control applications, it is important to have the best efficiency possible while limiting the weight and bulkiness in order to provide good mobility and agility for the wearer. The efficiency of active cooling systems that use power input tend to be higher than those passive cooling systems, as reported in Teunissen’s work which compares a garment with a Phase Change Material (passive solution) with a vest with liquid cooling [12]–[15]. According to Teunissen, active cooling systems need a power supply (battery, engine and fuel tank, fuel cell, etc.) and possibly a heat sink or heat exchanger that can be cumbersome. Miniaturising these components is a challenging work of reducing the bulkiness of such garments while improving their efficiency.

There are various thermal management methods that can be applied to improve the cooling efficiency of the personal garment. Among these applications, fluid cooling system is one of the most common cooling systems for personal garments and it is easy to implement. According to Luo [1], garments with integrated pipes, in which liquid flows are used as the medium to transfer heat to or from the body, and can achieve a better efficiency than other systems. One example of such a system is the Liquid Cooling Garment (LCG) built by Bartkowiak with the particularity of a knitted fabric that surrounds the tubes [16]–[19]. This garment also possesses different layers with different thermal resistance to maximise the heat transfer between the body and the fluid and to minimise the one between the fluid and the environment. Another example of LCG is the one developed by Ernst that consists of a garment with refrigerant lines cooled by a vapor-compression system [20]. One advantage of this system is that it integrates all the components to the garment such as the power source consisting of the small-scale engine and its 2L fuel tank and the condenser transported on the back of the garment. All these garments are designed to acquire relatively high cooling properties. However, there are still challenges remain for the garments such as their bulkiness due to the presence of the tubes integrated in the fabric as well as the pump, the cooling module used for cooling the liquid exiting the pipes, and other components needed for their functioning. The other challenge

This work is funded by the Engineering and Physical Sciences Research Council, Ref. EP/T006382/1.

is that the cooling efficiency is hard to be improved for the traditional cooling flow system [7], [21]–[23].

In this paper, a novel design of improving the efficiency of fluid cooling system is proposed and implemented. Previous research studies mainly focus on using new coolant materials while this paper proposed novel flow patterns to improve the cooling effect. Instead of the traditional steady continuous flow cooling system, this work proposes a bio-inspired discontinuous or pulsating coolant flow through an array of parallel tubes in a novel ‘sweeping’ manner, such that each tube queues for its turn to transport the coolant from the inlet to the outlet. Whilst the discontinuous flow is inspired by the circulatory system in our own bodies and that of other animals where the heart generates a pulsating blood flow to the organs, the ‘sweeping’ action seems to show an interesting multiplying effect for the Reynolds number of the fluid flow to increase drastically, thus resulting in turbulent flow and enhanced heat exchange. The frequency of the ‘sweeping’ seems to have some interesting but not fully understood effects on the Reynolds number. The proposed system’s superior thermal efficiency is experimentally validated against a control reference, and is compared with the performance of steady continuous flow which is used as the benchmark.

II. MODELS

Bio-inspired discontinuous flow has been studied for cooling applications with varying degrees of success. The thermo fluid dynamics for a pulsating flow with various control parameters could be highly complex and is beyond the scope of this paper. Indeed, the physics behind pulsating flow on thermal efficiency is still rather poorly understood. In this study, an empirical is adopted to investigate the proposed bio-inspired cooling concept on a personal garment as shown in Fig.1. The efficiency of the proposed method is to be validated by comparing the heat transfer efficiency of two different types of flows: a common continuous flow travelling through a serpentine (as the benchmark) and the bio-inspired discontinuous flow passing sequentially in each of the five parallel tubes at a time, via the same inlet and outlet.

The model of the bio-inspired discontinuous flow and the traditional steady continuous flow is shown in Fig.2. The continuous flow in a serpentine pipe is one of the most common cooling methods in the tubular heat exchangers as it offers a high area of contacting surface in a limited space and it is easy to implement. It can be applied to domestic heater, cars radiators, power plant cooling systems, etc. Fig.2(a) shows the pump driving the fluid to go through the serpentine pipe where the heat source, a heating pad in this study, is placed under the serpentine pipe. The heat generated by the heat source is transferred to the fluid due to the conduction of heat. The heated fluid flows into a cooling module (aluminium water block) and then flows back to the pump to start another cycle. The main issue with this system is that the water is heated up along the serpentine pipe which means that the cooling effect is not evenly distributed along the serpentine pipe and the heat source. The cooling efficiency of the surface located at the end

of the serpentine pipe is lower than that of the surface at the start.

The proposed bio-inspired discontinuous flow model is shown in Fig.2(b). The discontinuous flow is inspired by the circulatory system of animals where the heart pulses the blood flow to the different arteries. It is shown in Fig.2(b) that the model is composed of five parallel tubes covering the surface where the heat exchange takes place. All these tubes are connected to an inlet coming from the pump and an outlet going to the cooling module. Each tube is implemented with a valve to control the pulsation time of the flow. The valves are controlled by an integrated controller and they are turned on one by one in sequence allowing the fluid to go through only one segment of the array at a time, i.e. in a ‘sweeping’ manner. The proposed method allows the system to have the overall same flowrate with the continuous flow method. The proposed method gives the fluid a lower temperature at the start of each tube which leads to a more evenly distributed cooling effect and a more efficient cooling process. The main drawback of this technology is that it requires valves to control the pulsation flow, thus more components need to be implemented into the cooling system which increases the weight for the cooling garment. However, with the advances in additive manufacturing and micro-pumping technologies, it is envisaged that the proposed system has the potential for the additional components to be integrated and implemented into the garment with very acceptable weight and space penalty. Moreover, this method significantly increases the cooling efficiency of the fluid cooling system which can potentially reduce the requirement of the weight of the coolant and the water block.

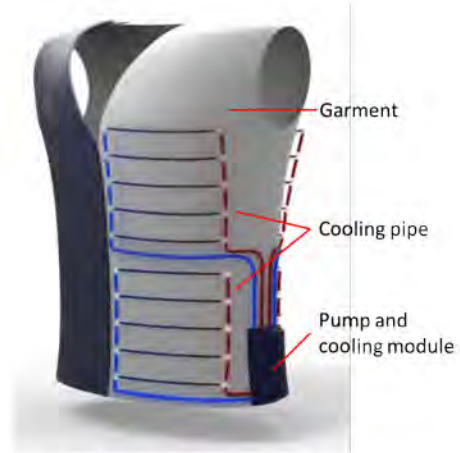


Fig. 1: Cooling system for garment

III. METHODS

A. Design of cooling systems

The piping and instrumentation diagram of the cooling system is depicted in Fig.3. The designed diagram for the continuous flow is shown in Fig3(a). The system works as follows: the coolant fluid is pumped out from the pump and

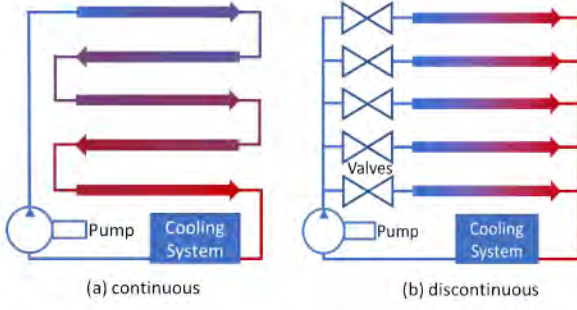


Fig. 2: Flow cooling models for continuous and discontinuous flow

flows into the heat transfer tubes. The heat transfer tubes are put on the top side of a heating pad, which simulates the body temperature. The coolant fluid absorbs the heat generated from the heating pad and thus cools the heating pad. Then the heated fluid flows into a water block and Peltier module to cool down for the next cycle of cooling. A flow rate meter is connected with the pipe to measure the flow rate of the coolant fluid. The design diagram for the discontinuous flow model is shown in Fig.3(b). The discontinuous model is mostly identical to the continuous model shown in Fig.3(a). The difference is that the discontinuous flow diagram uses a parallel tube connected with valves instead of the serpentine shaped tube used in the continuous flow diagram. The parallel tube with valves can apply a more evenly distributed cooling effect on the heating pad and generate a pulsation flow for the cooling system.

B. Experimental set-up

The experimental set-up for the cooling system is shown in Fig.4. The prototypes were meant to be wearable. But for the sake of convenience for easy comparison, the two cooling systems were installed on a plywood board in order to make it easier for components to be mounted and replaced during the experimental development stage. The length, width and height of the board used are $610 \times 310 \times 12 \text{ mm}$ respectively. A heating pad is put in the middle of Fig.4 to work as a reference heating source. The steady continuous flow system is built on the left-hand side of Fig.4 with a heating pad put under the serpentine tubes. The discontinuous flow system is built on the right hand side of Fig.4 with a heating pad put under the tubes as well. The heating pad is implemented with an integrated thermistor that needed to be wired and programmed to calculate the temperature of the pad. In this study, the heating pad is connected in series with a resistor $R_s = 100 \text{ k}\Omega$. The output of the heating pad is the voltage across the thermistor and the data is collected by a microcontroller ATmega1280. The resistance of the thermistor can be calculated by equation (1).

$$R = \frac{V * R_s}{V_0 - V} \quad (1)$$

where V is the measured voltage of the thermistor, V_0 is the reference voltage $V_0 = 5V$. According to Steinhart and Hart

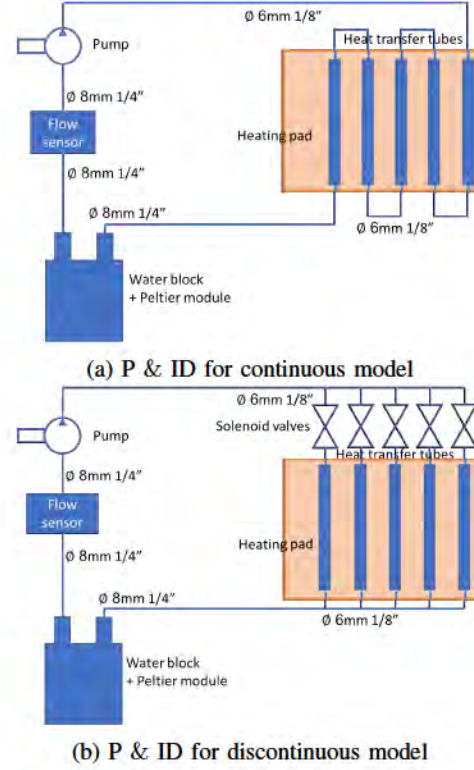


Fig. 3: Piping and instrumentation diagram for cooling systems

equation [24], the temperature (in Kelvin) of the heating pad can then be calculated by equation (2).

$$T = \frac{1}{\frac{1}{T_0} + \frac{1}{B} \ln\left(\frac{R}{R_0}\right)} \quad (2)$$

where $T_0 = 298.15K$ is the room temperature, $B = 3950$ is the constant of B -coefficient, $R_0 = 100k\Omega$ is the resistance of the thermistor at room temperature T_0 . The temperature in Kelvin can be easily transferred into degrees Celsius by $T(K) = T(^{\circ}C) - 273.15$.

The microcontroller ATmega1280 is used to control the valves and to collect data from the sensors (flow sensors and thermistors). The main advantage of ATmega1280 is the increased number of the pins compared with the commonly used board Arduino Uno. It requires a program to be written in the Arduino Software (IDE) to drive the microcontroller. The solenoid valves are OTH-060 which can form an open-valve action when supplied with 12V voltage. The pumps manufactured by Jadeshay can apply a flow rate of 2L/min with a power supply of 12V. The pumps were alimented in water by tanks made from plastic bottles glued to the inlet of the pumps. This simplified the filling of the circuit as any air bubbles were naturally removed in the tank. Several types of tubes were used in the building of the prototype: 6mm inner diameter (ID) flexible tubing (outer diameter OD 9mm) for piping the inlet and the outlet of the heat transfer tubes and to connect the flow sensor to the water tank. 8mm ID flexible tubing (OD 11mm) for piping the connections to the water

block. 6mm Heat shrinking tubing used for the heat transfer tubes as they had thinner walls than any other plastic tubes found on the market for reasonable prices, which applies a better heat transfer than the plastic tubes. The cooling module of water block is TEC1-12706 Thermoelectric Cooler. The flow rate of the two hydraulic circuits is measured using a YF-S401 Flow sensor.

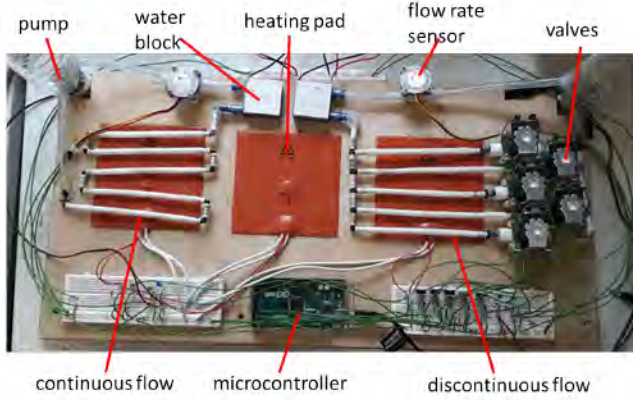


Fig. 4: Experimental set-up of cooling system

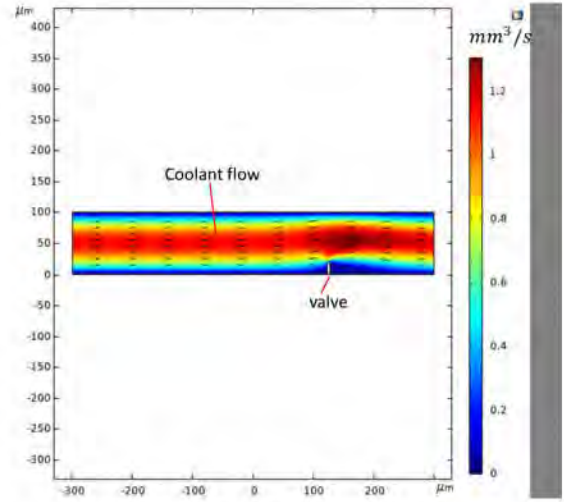
IV. IMPLEMENTATION AND RESULTS

A. CFD model of valving action

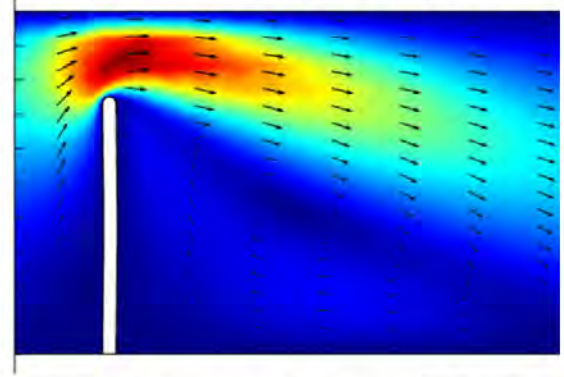
Although this study adopts an empirical approach to implement the proposed cooling system, CFD modelling is employed to provide a first-order estimation into the flow behaviour during the continuous flow and discontinuous flow. This will give insightful information on the complex thermo fluid dynamics when ‘sweeping’ control on the cooling tubes is implemented. The CFD models are built simply as a tube with a valve that can be controlled for on/off positions as shown in Fig.5. The pressure at the left end and right end of the tube is set to be 10^5 Pa and 0 Pa respectively. In Fig.5(a), the fully open position shows that the fluid is a laminar flow, and the heat transfer is by means of conduction. In Fig.5(b), the process of turning the valve partially closed to a certain position is simulated. It shows that closing the valve creates a counter flow which can break the laminar flow into turbulence. Thus, the heat transfer turns into convection transfer which is more efficient than the conduction heat transfer of the laminar flow. So, when using solenoid valves to create a pulsation flow for the cooling system, it is also easier to create a turbulence inside the tube which leads to a higher heat transfer efficiency.

B. Optimisation of pulsation time

In this study, an empirical approach is adopted to search for the optimal ‘sweeping’ frequency for maximum thermal efficiency. The microcontroller is programmed to implement the variation of the sweeping frequency. To analyse the influence of the ‘sweeping’ frequency on the thermal efficiency, a range of the pulsation times from 0.2s to 5s are implemented.



(a) Laminar flow during valve fully open



(b) Turbulent flow during dynamic closing of valve

Fig. 5: CFD models providing insight into pulsating flow

The temperatures of the heating pad cooled by the discontinuous flow and continuous flow, and that of the reference (control) heating pad with no cooling are measured in real time and the temperature differences of each flow against the reference is calculated. The results of the temperature difference profile measured in real-time for three pulsation durations (0.2s, 2s and 5s) are shown in Fig.6. The temperature difference between the discontinuous flow and the reference temperature is plotted in blue color in fig.6. The temperature difference between the continuous flow and the reference temperature is plotted in red color. When the pulsation time is 0.2s and 2s, the temperature difference of the discontinuous flow (blue) is higher than the temperature difference of the continuous flow (red) during the whole measurement. This illustrates that the cooling efficiency of the discontinuous flow is higher than that of the continuous flow. However, when the pulsation time is increased to 5s, the temperature difference of the discontinuous flow (blue) is higher than the temperature difference of the continuous flow (red) at the beginning 4 minutes and becomes the same after 7 minutes. To analyse the influence of the pulsation time for the discontinuous flow and optimise the cooling efficiency of the system, a group

of control experiments have been carried out. The variable of the experiment is the duration of the valve opening time. Five opening pulsation duration is selected as 0.2s, 0.5s, 1s, 2s, 5s. The difference between the temperature of the discontinuous flow and the reference temperature measured and calculated to analyse the cooling efficiency. The average temperature every minute is shown in Fig.7, where the temperature difference of valve opening duration of 0.2s and 0.5s are almost the same. According to all data collected from the average temperature every minute, the temperature difference is increasing when the valve opening duration increases from 0.5s to 2s. Then the temperature difference drops back to the same level with 0.2s valve opening duration when the duration increases to 5s. This indicates that the optimised sweeping frequency occurs around when pulsation duration is around 2s for the discontinuous flow cooling prototype under study.

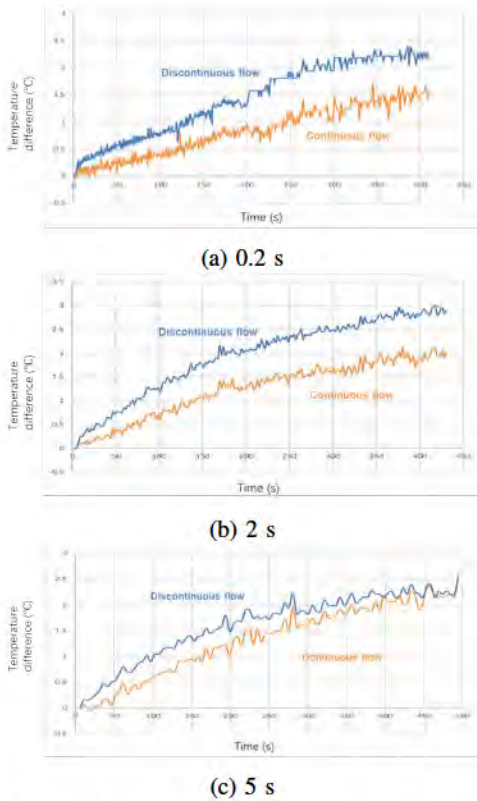


Fig. 6: Variation of temperature difference against control with increasing 'sweeping' period

V. DISCUSSION

The cooling efficiency of the proposed bio-inspired system has been shown better than that of the conventional continuous systems. Based on previous calculated data, the pulsation time of the valve has been selected as 2s to optimise the cooling effect of the system. Fig.8 gives an overall performance comparison over the test period of 7 minutes. The experiments have been repeated several times and the temperature data is averaged to reduce measurement errors. The temperature of the

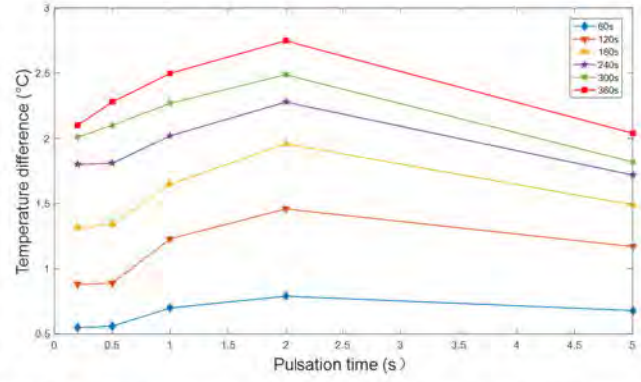


Fig. 7: Temperature difference between discontinuous flow system and reference temperature

heating pad is increasing with the time spent because of the Joule heating effect. According to Fig.8, both the continuous cooling system and the discontinuous cooling system show a lower temperature than that of the reference heating pad, which means both the cooling systems work effectively to absorb heat from the heating pad of each system. The temperature of the continuous flow system is almost identical with the reference temperature in the first 50 seconds. However, the temperature of the discontinuous flow system is lower than the temperature of continuous system and the reference temperature since the beginning of the measurement process. Moreover, the temperature difference between the discontinuous flow system and the continuous flow system is becoming larger with the heating time spent. The temperature difference between the discontinuous flow system and the continuous flow system is increased to 1.5°C after cooling for 7 minutes. The temperature difference between the discontinuous flow system and the reference temperature is increased to 3.5°C after cooling for 7 minutes. This result illustrates that the proposed discontinuous flow cooling method not only has a faster cooling effect but also an overall better cooling efficiency than those of the traditional steady continuous flow cooling method. The mechanism of this bio-inspired cooling method is that a pulsation flow has a higher sudden flow rate which can easily create turbulence inside the cooling pipe while the steady continuous flow is normally a laminar flow in a low Reynold number system. The efficiency of convectional heat transfer of turbulence is much higher than the efficiency of conduction heat transfer of the laminar flow. In addition, as shown in the CFD models, the on-off dynamic switching action of the valves implemented in the discontinuous flow system can also create counter flows and thus lead to turbulence and thus higher thermal efficiency.

This prototype shows a better cooling efficiency than that of the traditional cooling method. However, challenges still remain to build the prototype into a live garment. The first challenge is that a live garment requires a portable and power efficient system. This study only focused on the cooling efficiency and more researches on the power consumption need to be carried out in the future work. The second challenge is that

the instruments and components need to be miniaturized for a live garment. The optimised component should be selected in the future work.

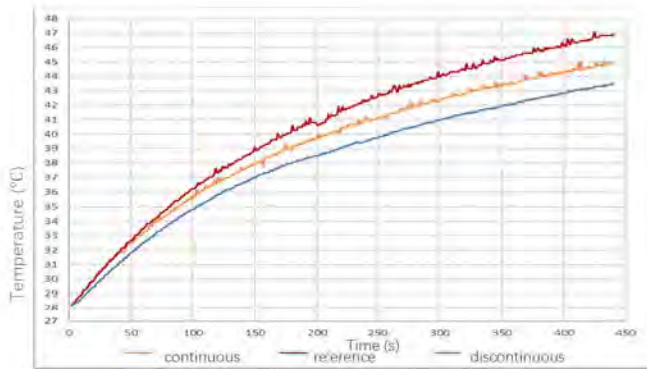


Fig. 8: Temperature of all modules

VI. CONCLUSION

This study proposes a bio-inspired discontinuous flow cooling method for the temperature management of personal garments. A prototype is built to demonstrate the high thermal transfer efficiency between the bio-inspired discontinuous flow going alternatively through parallel tubes connected to the same inlet and outlet and the continuous flow travelling through a serpentine. The prototype was designed, built, and tested to perform an effective cooling process. Experiments were carried out with different values of opening times of the valves controlling the discontinuous flow. The results showed that the sample with the discontinuous flow provides better thermal transfers with the heating surface than the sample with the continuous flow, especially when the valves have open times around 2s. This system is easy to be implemented to a garment for managing personal temperature. It can potentially apply not only cooling effect but also warming effect by injecting higher temperature fluid into the system. A more precise control of the temperature of the surface can be achieved in the future work by controlling the pulsation flow.

ACKNOWLEDGMENT

This work is funded by the Engineering and Physical Sciences Research Council, Ref. EP/T006382/1. The experimental work prepared by Geoffroy D'Haussey is gratefully acknowledged.

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2022-06-30

IEEE

<https://doi.org/10.1109/I2MTC48687.2022.9806517>

Luk PCK, Tang J. (2022) Wearable bio-inspired pulsating flow cooling for live garments. In: 2022 IEEE International Instrumentation and Measurement Technology Conference (I2MTC), 16-19 May 2022, Ottawa, Ontario, Canada