Gould, Chris ORCID: 0000-0002-8433-0546 (2020) Thermoelectric cooling and heating of human body temperature. Journal of Physics: Conference Series, 1534. art 012009.

Official URL: https://iopscience.iop.org/article/10.1088/1742-6596/1534/1/012009

EPrint URI: https://eprints.glos.ac.uk/id/eprint/11335

Journal of Physics: Conference Series

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To cite this article: C A Gould 2020 *J. Phys.: Conf. Ser.* **1534** 012009

MicroTherm 2019 - Microtechnology and Thermal Problem in Electronics IOP Publishing
Journal of Physics: Conference Series **1534** (2020) 012009 doi:10.1088/1742-6596/1534/1/012009

Thermoelectric cooling and heating of human body temperature

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Abstract. The cooling and/or heating of human body temperature is of critical importance and interest in a myriad of applications, however, the use of thermoelectric cooling has made little impact in this area. Current solutions focus on the use of wearable materials that assist the natural temperature regulation of the human body, or the use of liquid cooling techniques reliant on refrigerant fluid or large quantities of dry ice, often used in astronaut spacesuits, worn by surgeons during long surgical procedures, firefighters, military personnel, and motor racing drivers. The motivation for this work is to investigate the feasibility of using thermoelectricity to achieve the cooling process, replacing the existing use of refrigerant fluid and associated compressor and refrigeration components or the use of large quantities of dry ice to create chilled or cooled water. A thermoelectric cooling/heating prototype system has been designed and tested, and successfully demonstrates the temperature of circulating water within small tubes incorporated into a person's vest undergarment can be used to regulate body temperature. The system briefly comprises: a small reservoir tank of water; a thermoelectric module, heatsink and electronic fan; a small electronic water pump; a proportional, integral, and derivative (PID) controller; interconnecting tubing to carry the circulating water; and a vest undergarment that is worn by the user to help regulate their body temperature. Results presented demonstrate the thermoelectric module successfully cools or heats the water circulating around the vest undergarment, which when worn by a user can be used to lower or increase their external body temperature and improve their temperature comfort levels. The thermoelectric cooling/heating system has several advantages over existing solutions including; a significant decrease in size and weight; system cost; accurate temperature control; ability to provide cooling or heating under user control; no moving parts within the thermoelectric module contributing to high reliability and reduced maintenance requirements; quiet in operation; the elimination of dry ice in the cooling process; and no use of refrigerate fluid or other harmful chemicals. Further work will optimize the design, scale the system to achieve specific cooling/heating targets, and demonstrate the effectiveness of the system in improving a user's temperature comfort levels.

1. Introduction and motivation

The cooling and/or heating of human body temperature is of critical importance and interest in a myriad of applications. The majority of current solutions focus on the use of wearable materials that assist the natural temperature regulation of the human body, i.e. by heat change through conduction, radiation, and convection by aiding the perspiration process or by wearing different types and layers of clothing to maintain warmth [1]. Solutions have also been developed using liquid cooling to regulate body temperature and is often implemented in astronaut spacesuits [2-3], or used by surgeons during long surgical procedures, firefighters, military personnel [4], and motor racing drivers [4-5]. Liquid cooled systems typically use small tubes sewn onto, or incorporated within, an undergarment vest that is worn underneath a person’s normal clothing. Refrigeration techniques are then used to create the cooling effect via a heat exchanger, compressor and refrigerant fluid, or may simply use a quantity of dry ice to create chilled water. This chilled water or refrigerant fluid is pumped through tubes contained within the undergarment and circulates around the undergarment, removing and carrying excess heat away from the user along with the circulating fluid via the thermodynamic process.

The motivation of this work is to investigate the use of thermoelectricity as an alternative method to provide cooling, and additionally heating, of human body temperature. Thermoelectricity, sometimes referred to as Peltier modules, has become an established technique to achieve electronic cooling and/or heating in small wine coolers, portable refrigerators, and cool boxes [6]. However, thermoelectric cooling has not penetrated the market significantly for human body cooling applications. In principle, it is possible to apply thermoelectricity to this application to achieve the cooling effect, replacing the existing use of harmful refrigerant chemicals or eliminate the need to use dry ice and the associated compressor and refrigeration components often found in existing solutions.

The paper is organized as follows; a short background theory of thermoelectric cooling and heating; the design of a thermoelectric cooling/heating prototype; the application of thermoelectric cooling/heating to regulate human body temperature; experiment test results; discussion; conclusions and further work.

2. Background thermoelectric cooling and/or heating theory

It has been known for some time the scientific area of thermoelectricity, and more specifically the Peltier effect discovered by Joseph Peltier in 1834, can be applied to cooling and heating applications [6]. However, limited work appears to have been conducted into the important area of human body cooling using thermoelectricity, and although thermoelectricity has become commercially successful in cooling applications, with portable cool boxes and miniature refrigerators now commonplace, there are several examples in the marketplace today of applications still reliant on the use of harmful refrigerant fluid or the use of large quantities of dry ice to create a cooling or chilled liquid effect. These applications could potentially benefit from the application of thermoelectricity to replace the use of refrigerant fluid or dry ice. Furthermore, low-scale localized heating is often implemented simply by passing electrical current through a conductor to create a heating effect. Thermoelectricity may be able to offer, amongst other advantages, a more controllable and safe method of localized heating. This section provides the main theoretical background into thermoelectric cooling and heating necessary to apply this technique.

2.1. Thermoelectric cooling and heating

A thermoelectric module can cool or lower the temperature of an object if the object is attached to the ‘cold side’ of the module, often referred to as T_C, and DC electrical power is applied to the module’s input terminals. Heat from the object will be absorbed by the cold side of the thermoelectric module and transferred or ‘pumped’ through to the ‘hot side’ of the module T_H due to the Peltier effect. Typically, the hot side of the module will be attached to a heat sink in order to reject this heat into the atmosphere, as shown in figure 1. If the polarity of the DC current applied to the thermoelectric module input terminals is now reversed, as shown in Figure 2, the module will now heat the object connected to the cold side of the module and the other side of the module will cool down. In this condition, the thermoelectric module is referred to as a thermoelectric heater. Hence, it is possible to use the same thermoelectric module for cooling and heating dependent on the polarity of the DC input voltage and therefore the direction of input current flow [6].

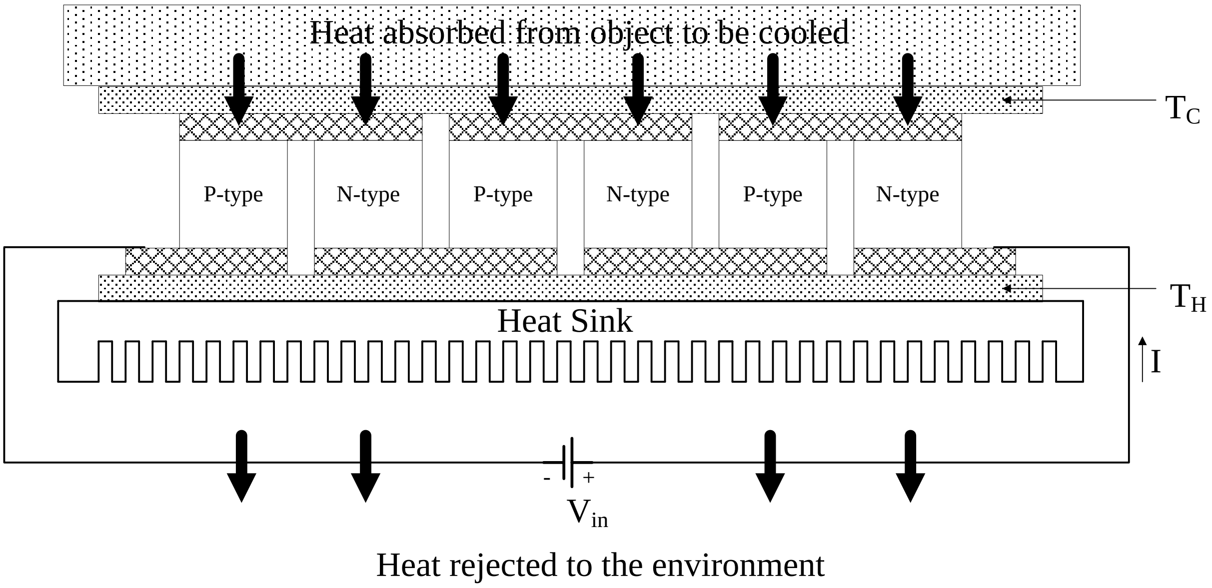

Figure 1. A thermoelectric module operating as a thermoelectric cooler or heat-pump.

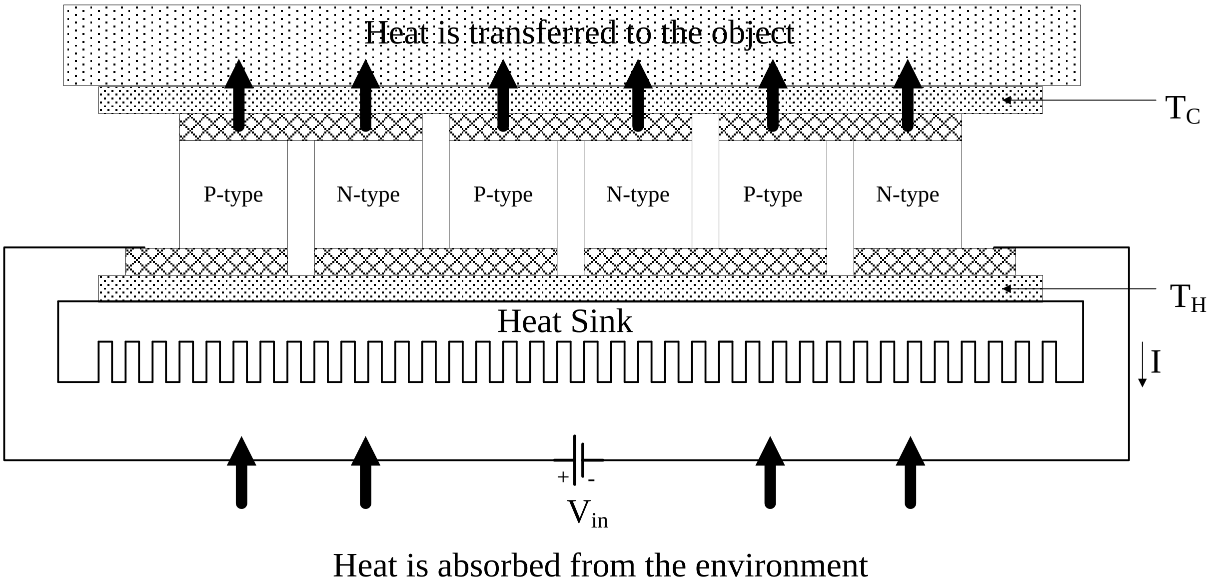

Figure 2. A thermoelectric module operating as a thermoelectric heater or heat-pump.

Practical thermoelectric modules are manufactured with several thermoelectric couples connected electrically in series and thermally in parallel. Arranging the thermoelectric couples in this way allows the heat to be pumped in the same direction. A single thermoelectric couple configured for thermoelectric cooling is shown in figure 3(a), and for thermoelectric heating in Figure 3(b). Similar to the operation of a thermoelectric module, when a DC voltage is applied to the thermoelectric couple's input terminals, electrical current flows from the positive terminal of the supply to the negative terminal and is shown as an anti-clockwise current flow in figure 3(a).

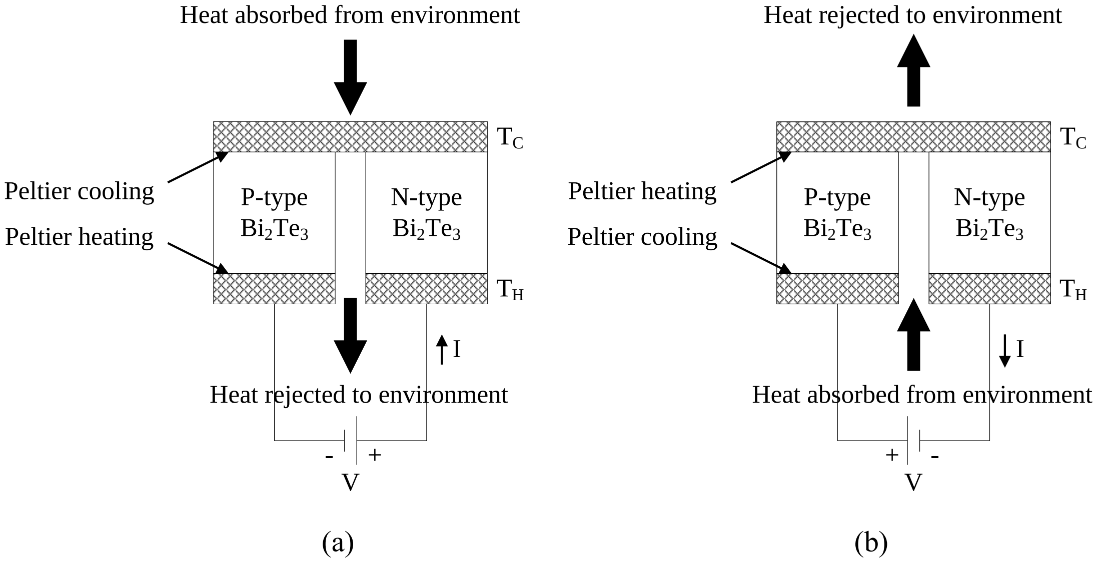

Figure 3. Single thermoelectric couple connected as a thermoelectric cooler (a) and a heater (b).

The negative charge carriers, i.e. the electrons in the n-type Bi_2Te_3 pellet are attracted by the positive pole of the supply voltage and repelled by the negative potential. Similarly, the positive charge carriers, i.e. the holes in the p-type material are attracted by the negative potential of the supply voltage and repelled by the positive potential, and move in an opposite direction to the electron flow. It is these charge carriers that transfer the heat from one side of the thermoelectric couple to the other side in the direction of charge carrier movement. In the n-type pellet, the negatively charged electrons are the charge carriers and absorb heat from the cold side of the thermoelectric couple and transfer or 'pump' this heat to the hot side of the couple in a clockwise direction. Similarly, the positively charged carriers in the p-type pellet, the holes, absorb heat from the cold side of the couple and transfer this heat to the hot side of the couple in an anti-clockwise direction. If the polarity of the DC current applied to the thermoelectric couple input terminals is now reversed, as shown in figure 3(b), the thermoelectric couple will now heat the object connected to the cold side of the couple, with the other side of the couple cooling down. In this condition, the thermoelectric couple is referred to as a thermoelectric heater. A single thermoelectric couple is of limited practical use as the rate of cooling or heating is quite small, therefore, practical thermoelectric modules are manufactured with several thermoelectric couples connected electrically in series and thermally in parallel to increase their effectiveness, with modules typically containing a minimum of three thermoelectric couples, rising to one hundred and twenty-seven couples for larger devices [6].

3. Thermoelectric cooling and/or heating system

A thermoelectric cooling/heating system can be used to achieve cooling and/or heating of circulating water in a liquid cooling system and replace existing refrigeration techniques which use a heat exchanger, compressor and refrigerant fluid, or to replace the use of dry ice to create chilled water. This section documents the design and operation of a thermoelectric cooling/heating system.

3.1. Cooling/heating and temperature regulation design principle

The natural biological regulation of human body temperature is a complex process, with the internal core body temperature maintained around 37°C [1]. This work does not aim to directly investigate the biological regulation of human core body temperature, as this natural process is critical to a person's health and wellbeing. Instead, this work is focused on improving the perceived temperature comfort level a person experiences, similar in principle to how a person may decrease or increase the amount of clothing they wear to feel cooler or warmer. The design principle investigated within this work is to control the temperature of water circulating around and within small tubes sewn onto a vest undergarment worn by the user. If the temperature of this circulating water is maintained below ambient conditions, i.e. by using some form of external cooling, and the user's body heat is above the temperature of the circulating water, some of the user's body heat will be transferred to the circulating water via the thermodynamic process, and this heat is effectively carried away from the user with the flowing water. Conversely, if the temperature of the circulating water is heated above ambient temperature, and the user's body heat is below the circulating water temperature, heat will be transferred from the circulating water to the user's body. This cooling and heating process is shown in figure 4 and can be considered a form of human body temperature regulation.

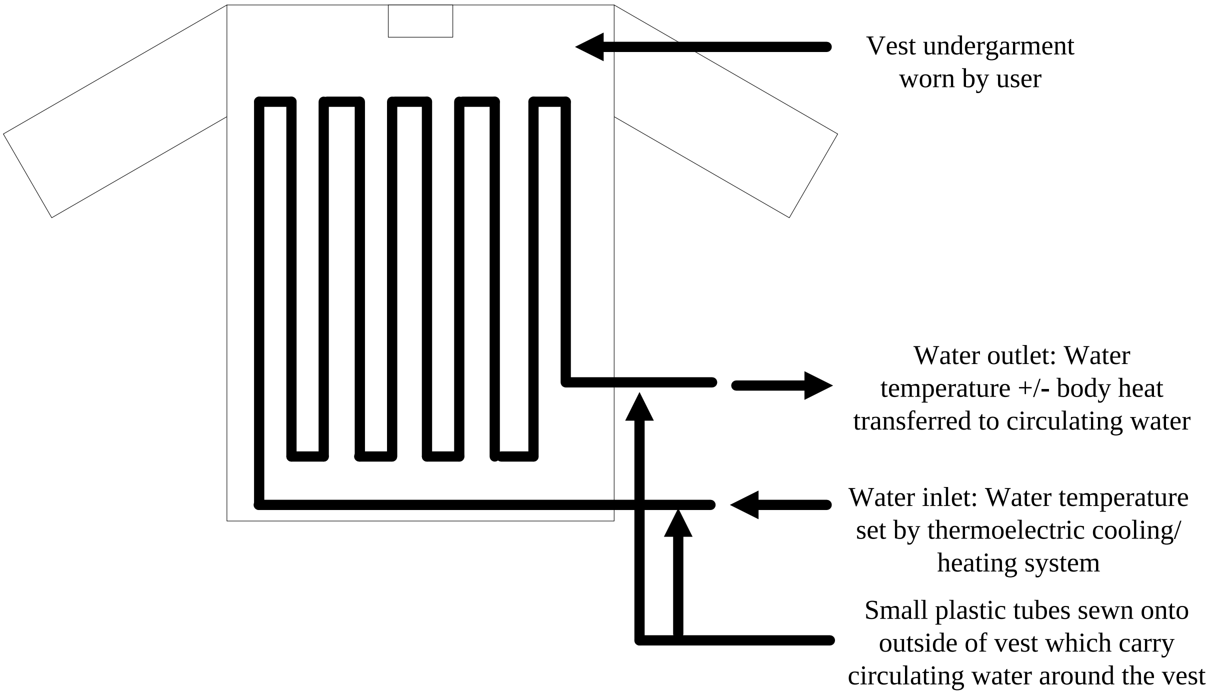

Figure 4. Thermal regulation of body temperature design principle.

3.2. Thermoelectric cooling/heating prototype design

A thermoelectric cooling/heating system has been designed and briefly comprises: a small aluminum water holding tank measuring 11cm x 6cm x 2.5cm (length, width, depth) holding 100ml of water; Laird Technologies CP1.4-127-045L 127-couple thermoelectric module measuring 4cm x 4cm x 0.33cm; a 10cm x 10 cm x 3cm heatsink and 12V electronic fan measuring 9cm x 9cm x 2.5cm; RS Components 12V, 0.5A, 2.8 liters per minute (max) electronic water pump; an optional proportional, integral, derivative PID controller to control the rate of cooling/heating; interconnecting tubing to carry the circulating water; and a vest undergarment containing small tubes filled with 100ml of water which is worn by the user to help regulate their body temperature and improve overall temperature comfort levels.

The system is shown schematically in figure 5. When a positive DC current is applied to the thermoelectric module, the module operates as a thermoelectric cooler, lowering the temperature of the aluminum water tank, and therefore the water contained within the tank, as heat is ‘pumped’ from the tank through the thermoelectric module and rejected via the module heatsink and electronic fan to atmosphere. Increasing the positive DC current to the thermoelectric module increases the rate of cooling. When the temperature of the water within the water tank has reached the desired value below ambient conditions, the electronic water pump is activated and pumps this ‘cooled’ or ‘chilled’ water from the tank around the small plastic tubes sewn onto the front and back of the vest and eventually returns to the water tank, circulating again around the vest in a closed-loop system until the water pump is turned off. If the user is wearing the vest, the water circulates around the tubes within the vest and an amount of body heat from the user will be transferred to this circulating water via the thermodynamic process, increasing the temperature of the circulating water as it returns to the holding tank. The water contained within the holding tank is subject to cooling via the thermoelectric module and the circulation of the water from the water tank through the tubes around the vest continues and the cycle repeats.

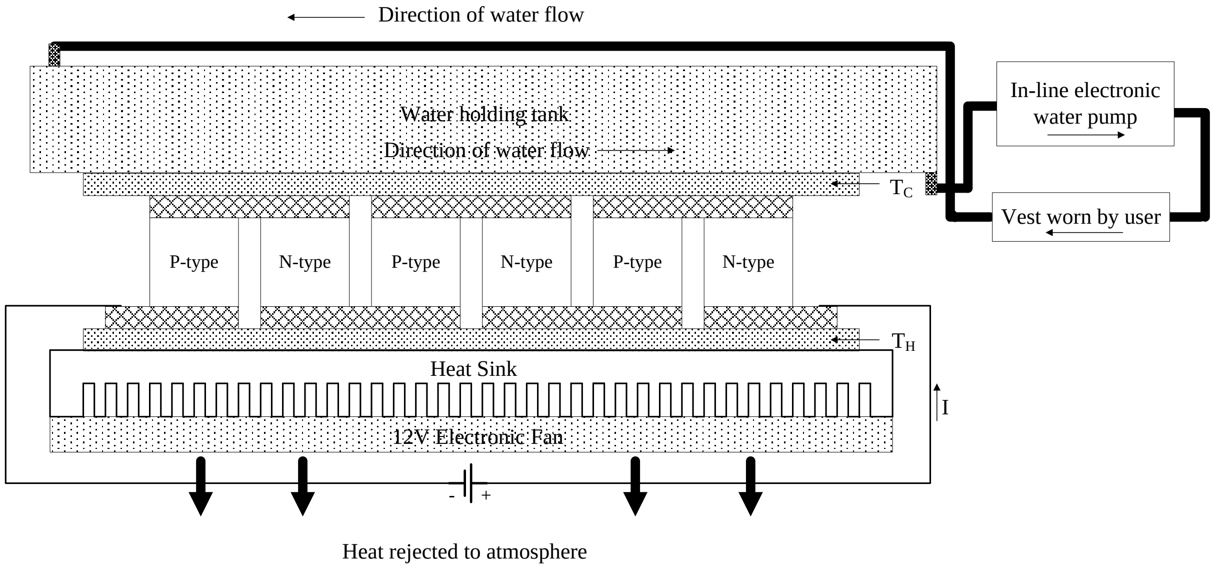

Figure 5. Thermoelectric cooling/heating prototype.

4. Results

The thermoelectric cooling and heating prototype has been subject to experimentation to validate the concept. The first experiment presented is when the thermoelectric module is subject to maximum cooling power and the water within the system is stationary and then circulating around the vest. The objective of this test is to practically demonstrate thermoelectric cooling can lower the temperature of circulating water around the vest below ambient conditions. The second experiment demonstrates the system can vary the rate of cooling and heating of the circulating water if the input current to the thermoelectric module is varied, and can operate as a cooler or heater dependent on the polarity of the thermoelectric module input current.

4.1. Maximum cooling power – non-circulating and circulating water

A single 127-couple thermoelectric module has been subject to maximum cooling power by applying the module maximum input current of 5.5A at 14.5V for one hour. This has reduced the surface temperature of the aluminum holding tank, and therefore the temperature of the water contained within the tank from ambient of around 25°C to 12°C. The electronic water pump was then activated and the ‘cooled’ or ‘chilled’ water from the water tank can be observed to circulate from the tank, through the small plastic tubes around the vest and return to the water tank. The temperature of the outside of the plastic tubes has been measured at the inlet, outlet, and mid-point of the vest, and demonstrate a reduction in temperature from ambient conditions as expected. Over time, the temperature of the circulating water settles at 21°C, 5°C below ambient. This is as expected, as the circulating water is returned to the holding tank and will contain ambient heat which has been carried with the water circulating within the plastic tubes, increasing the temperature of the water within the holding tank over time.

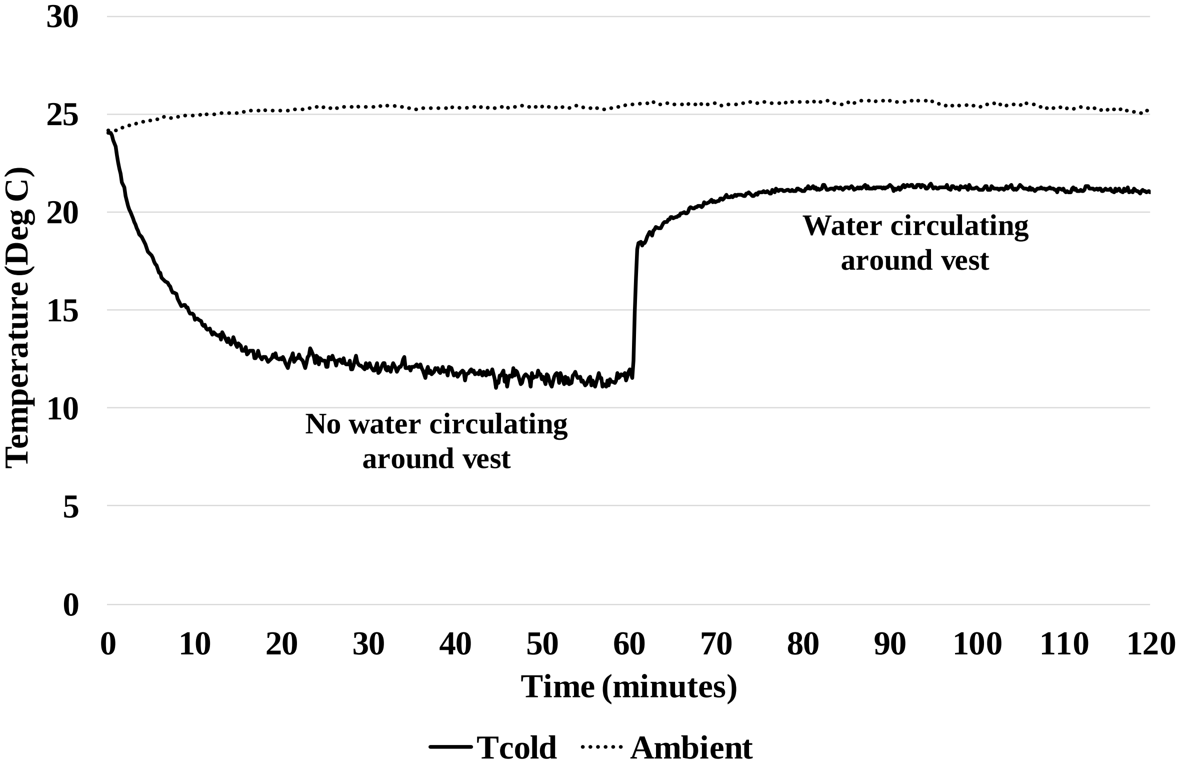

Figure 6. Temperature of the water within the holding tank when subject to maximum thermoelectric cooling under no-flow and flow of circulating water around the cooling vest.

4.2. Thermoelectric cooling and heating with circulating water around vest

Following on from the experiment presented in section 4.1, the thermoelectric module input current has been varied between +5.5A to 0A in 0.5A steps every 10 minutes to demonstrate the effect of different levels of thermoelectric cooling, and with the polarity of the input current to the module reversed, increasing levels of thermoelectric heating has been demonstrated as the input current is varied from 0A to -5.5A in -0.5A steps every 10 minutes. The results, shown in figure 7, highlight the system can provide controllable levels of cooling and heating as the input current to the thermoelectric module is varied. At maximum cooling power, the circulating water enters the vest at 21.5°C, 3.5°C lower than the ambient temperature of 25°C, and exits the vest at 22.0°C and returns back to the water holding tank. As the thermoelectric module cooling power is reduced, by reducing the DC current to the module, the temperature of the water circulating in the vest increases towards ambient temperature, and when zero current is applied to the thermoelectric module, the temperature measured at the inlet, mid-point, and outlet of the vest is approximately the same as the ambient temperature of 24°C. The polarity of the DC voltage to the thermoelectric module has then been reversed, and an input current of -0.5A is applied to the thermoelectric module input terminals, causing the water temperature at the inlet to increase to 25°C, 1°C above the ambient temperature. In this condition, the thermoelectric module is operating as a thermoelectric heater. As the negative input current to the module is increased in -0.5A steps every 10 minutes, the temperature of the circulating water increases further above ambient conditions, reaching approximately 40°C at the inlet to the vest at maximum heating power to the thermoelectric module with an input current of -5.5A.

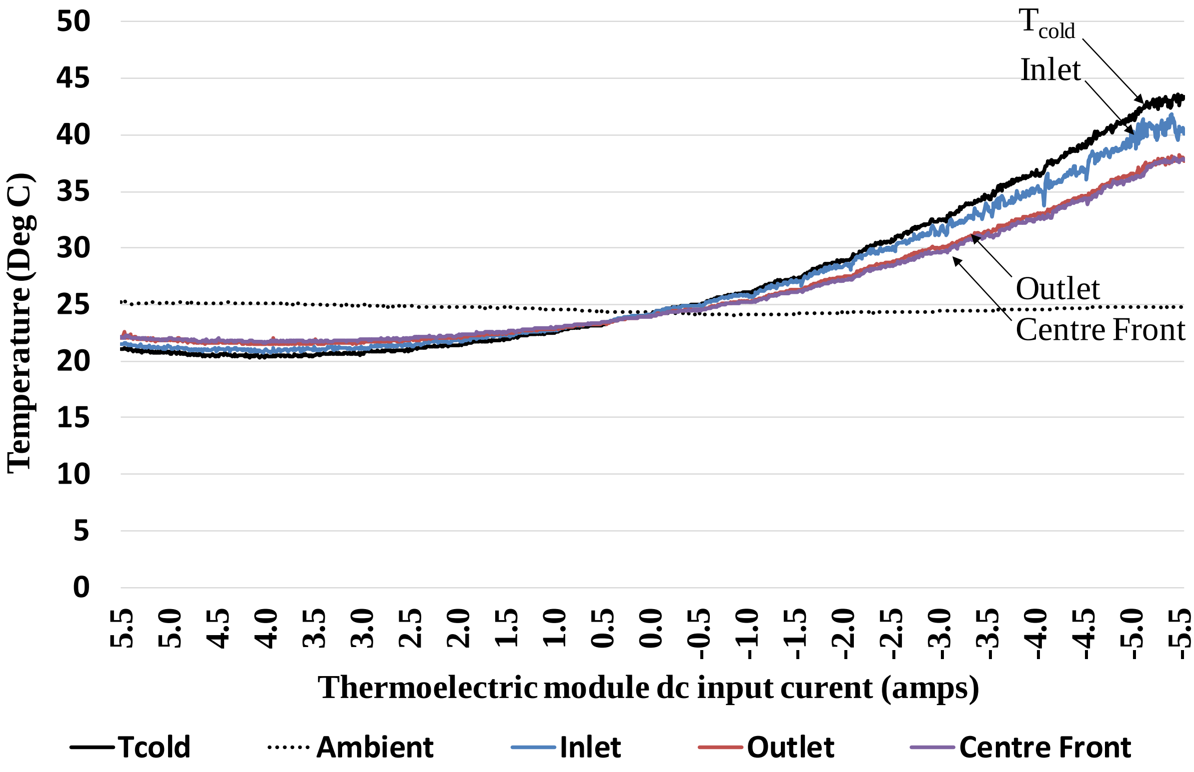

Figure 7. Temperature of the water within the holding tank, inlet / centre point / outlet of the vest when the thermoelectric module DC current is varied between +5.5 amps and –5.5 amps in 0.5 amp steps, varying the temperature of circulating water above or below ambient.

5. Discussion

The motivation for this work is to investigate the feasibility of using thermoelectricity to cool or heat circulating water around a vest undergarment, similar in principle to existing liquid cooling systems which use refrigerant fluid or dry ice. A thermoelectric cooling/heating prototype has been designed and the test results presented successfully demonstrate the cooling or heating of water circulating in small tubes around a vest undergarment. Further experiment results will be published to demonstrate the system cooling or heating to a temperature set-point via the PID controller, at different water pump flow rate settings, and when the vest undergarment is worn by a user to improve their temperature comfort levels.

A thermoelectric solution has several advantages over existing systems which use large quantities of dry ice or refrigerant fluid and associated refrigeration components, including; a significant reduction in physical size and weight; accurate temperature control; the ability to provide both cooling and heating using the same thermoelectric module; high reliability as the thermoelectric module has no moving parts; reduced maintenance requirements; the system can be used in hazardous environments as the thermoelectric module does not create electrical noise/sparking; the thermoelectric module is quiet in operation; no use of harmful chemicals or gases including refrigerant fluid; and no use of large quantities of dry ice. There is scope to optimize the prototype in the future to achieve a target rate of cooling or heating using a specific water holding tank size and quantity of water in the system, design, and number of thermoelectric modules, optimize the flow rate of the circulating water to suit user preferences, and to reduce and optimize the cost, physical size and weight of the system.

6. Conclusions

The thermoelectric cooling/heating prototype system successfully demonstrates the temperature of circulating water within small tubes incorporated into a vest undergarment can be cooled and heated from ambient conditions. The system has several potential advantages over existing solutions including; a decrease in size and weight; reduced system cost; accurate temperature control; ability to provide cooling or heating under user control; no moving parts within the thermoelectric module and cooling/heating process; high reliability and reduced maintenance requirements; quiet in operation; the elimination of dry ice in the process; and no use of refrigerate fluid or other harmful chemicals. Further work is required to optimize the design, scale the system to achieve specific cooling/heating targets, and to conduct further experiments to practically demonstrate the cooling/heating regulation of human body temperature and improvement of temperature comfort levels.

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