High Efficiency Thermoelectric Coolers for use in Firefighter Applications

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Firefighting personnel have long suffered physiological strain as a result of exposure to strenuous activity and harmful environments. Some of the strain is due to heat induced from lengthy exposure to high temperature environments and when performing strenuous work during long fire suppression activities. The results of these work conditions can lead to high internal body (core) temperature and cardiac events from overexertion, which has been identified as the leading cause to firefighter deaths. Thermoelectric refrigeration has been shown to have applications for portable cooling of firefighting personnel, having higher heat removal rates when compared to vapor compression refrigeration systems. This project focused on system design and analysis of a thermoelectric cooling (TEC) module using bulk thermoelectric materials. Specifically, a TEC system has been integrated into a closed-loop water circulation system. The closed loop system continuously cools the circulating water, which is used to absorb heat from a heat source represented by either simulated or actual volunteer fire fighting personnel. The cooling rate was characterized as a function of both water flow rate and TEC power input. To simulate operation of the TEC module in elevated temperature environments, tests were conducted in an environmental chamber under varying water flow rates and TEC input power. In addition, core temperatures were measured for each firefighter test subject. Corresponding heat removal rates and coefficients of performance are provided for each test. A heat removal rate of 160 W was achieved during firefighter cooling, while more than 250 W of heat was removed during environmental chamber tests. Maximum COP values of 0.6 and 1 were obtained from firefighter and environmental chamber experiments, respectively.

Nomenclature

α	=	Seebeck coefficient (V/K)
σ	=	electrical conductivity (1/Ωm)
ρ	=	electrical resistivity (Ωm)
κ	=	thermal conductivity (W/mK)

I. Introduction

At present the primary research, development and commercialization efforts regarding firefighter body cooling are concentrated on rehabilitation of heat-stressed firefighters in a rest and recovery context. The development and testing of personal cooling equipment that can operate during fire suppression activity has the

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overt goal of mitigating heat stress before it starts. Heat stress is one of the recognized factors that debilitate emergency responders in firefighting. The firefighter wears a fully encapsulated ensemble that protects the firefighter, but creates its own hazard. The firefighter's bunker gear is designed to protect against outside heat but in the process retains the metabolic heat produced by the firefighter's activity. The bunker gear prevents the evaporation of perspiration required for controlling core body temperature and inhibits heat removal. Heat stress has been shown to be a contributor to conditions of fatigue, overexertion, cardiovascular strain and physiological changes, which can compromise firefighter safety and health through increased risk of fire ground accidents, dehydration, sudden cardiac events, and decreases in long-term cardiovascular health[1]. Heat stress prevention is the only means by which detrimental effects on firefighter health and safety can be eliminated.

Firefighting provides a unique scenario in which cooling must take place within the confines of the protective gear microclimate. External cooling systems can improve performance by aiding the cooling process. Cooling firefighting personnel during their exposure to harmful environments is believed to reduce excessive core temperature elevation and help prevent physiological strain from occurring. While evaporative cooling is more efficient in humans, it is difficult to aid within bunker gear and current applications of cooling utilize conductive heat transfer processes.

II. Background in Thermoelectric Coolers

Thermoelectric (TE) coolers and heaters use electrical currents/voltages to create temperature gradients across the TE device. This phenomenon is known as the Peltier effect[2]. As shown in Figure 1, the cold side absorbs heat from a heat source; in this case the fluid circulating through tubes in the firefighter's clothing that are in contact with the skin. Heat is rejected at the hot side using a heat sink, such as a phase change material or a fan and finned surface. Thermoelectric devices, as both cooling/heating and electrical generation devices, are favorable in small-scale applications, where vapor compression systems are too bulky or too inefficient.

The performance of the cooler is described by its coefficient of performance (COP), which is the ratio of the heat extracted from the source to the expenditure of electrical energy. The heat extracted from the source is also referred to as the cooling power and its magnitude is of critical importance. The cooler can be operated for maximum COP or for maximum cooling power depending on the electrical current[2].

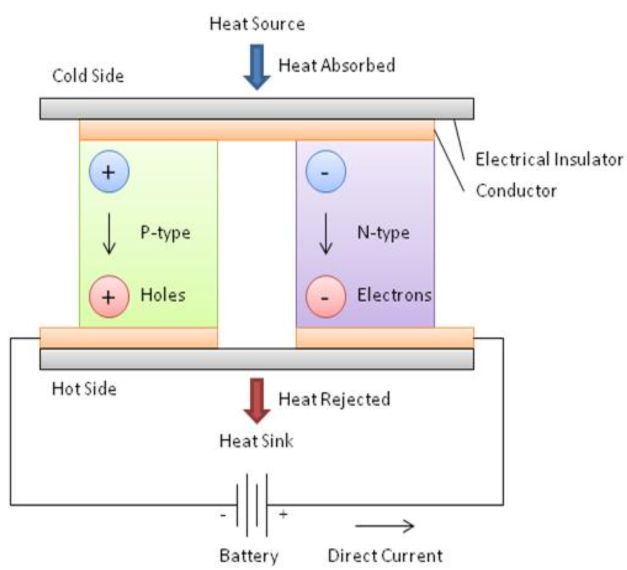

Figure 1. Conceptual schematic of a thermoelectric cooling junction with illustrated charge carrier motion

Efficiency of thermoelectric materials are a function of a parameter known as the figure of merit. Generally, the highest thermoelectric figure of merit for the device, Z (K^{-1}), can be reached by maximizing the figures of merit, z, of the n-type and p-type materials that comprise the TE elements in the cooler. The figure of merit is defined as

$$zT = \frac{\alpha^2 \sigma}{\kappa} T = \frac{\alpha^2}{\rho \kappa} T \quad (1)$$

Central to thermoelectric devices are their n-type and p-type thermoelectric materials. For low temperatures, the most widely used thermoelectric materials are alloys of Bi_2Te_3 and Sb_2Te_3, where the most commonly studied p-type and n-type compositions are near $(Sb_{0.8}Bi_{0.2})_2Te_3$ and $Bi_2(Te_{0.8}Se_{0.2})_3$. Peak zT values are typically in the range of 0.8 to 1.1.

Charge carrier motion within thermoelectric materials is responsible for cooling/heating and electric power generation. An ideal thermoelectric material is one with high electrical conductivity and low thermal conductivity (i.e. electron-crystal, phonon-glass). The material needs to avoid scattering electrons, to maintain high electrical conductivity while scattering phonons that carry heat to lower lattice thermal conductivity. Strategies that exist for decreasing lattice thermal conductivity include (1) creating rattling structures or point defects within the unit cell, (2) implementing complex crystal structures to separate the electron crystal from the phonon glass and (3) phonon scattering at material interfaces[3]. Both bulk and nano-scaled thermoelectric materials have application possibilities in Peltier cooling, but limitations in current technology have prevented the widespread use of high performance nano-scaled thermoelectric materials. Accordingly, present day TEC modules contain bulk thermoelectric materials.

III. Recent Developments in External Cooling Technology

In 2004, an evaluation of the state of the art in soldier cooling systems was conducted with results presented in Table 1[4]. Some of these technologies are not appropriate for the firefighting environment; for instance, evaporative cooling systems that are open to the environment can compromise the protective value of a firefighter's personal protective equipment (PPE). In the 2004 Natick study, the thermoelectric (Peltier) cooling system was ranked with the highest score for safety, reliability, and technical risk. It ranked lower due its high mass and low COP. The only other viable technology (according to the Natick evaluation) was vapor compression systems. From investigations of vapor compression systems, it has been discovered that there are very few portable vapor compression systems available even at the prototype level. The mechanical complexity, low reliability, and low availability of vapor compression systems make them less attractive[5]. The miniaturized compressor in these systems often displays isentropic efficiencies of less than 30%, which severely limits the COP they can achieve in high ambient temperature environments. These evaluations strongly suggest that thermoelectric cooling systems are the only technology currently available that can meet the basic microclimate cooling needs of firefighters. As such, this proof-of-concept study investigates the effectiveness of TE cooling as the primary cooling method within the confines of the firefighting PPE and in high-temperature environments.

Table 1. Personal Cooling Technology Assessment for Soldier Applications showing rankings of different external cooling technologies. Peltier cooling is shown in boldface font.

	Evaporative	Evaporative with Dessicant, Open	Vapor Compression	Magnetic	**Peltier**	Stirling
Safety (8)	4	4	6	8	**8**	7
Orientation (6)	6	6	5	6	**6**	6
Reliability (6)	6	6	5	4	**5**	5
Cost (3)	3	3	2	2	**2**	2
Mission Completion (5)	4	4	4	3	**4**	4
Technical Risk (3)	3	3	3	2	**3**	3
Acoustic (4)	3	4	3	4	**4**	3
EMI (3)	2	2	2	1	**2**	2
Clothing Compatability (4)	2	3	3	3	**3**	3
Logistics (6)	5	2	5	5	**5**	5
Control (4)	4	4	3	4	**4**	3
Total Quantitative	42	41	41	42	**46**	43
Cooler Mass (kg)	0.1	0.3	1.1	2.1	**1**	2.7
Motor Mass (kg)	0.1	0	0.1	0.1	**0**	0.2
Consumables (kg)	1.6	2.1	1.2	1	**3.2**	1.3
Total Mass (kg)	1.8	2.4	2.4	3.2	**4.2**	4.2
Thermal Signature (k)	0	1.8	11.3	12.2	**5.5**	17.9
Total Rating						
COP Net	25.8	7.7	2.4	3.4	**0.9**	2.7
Rank	1	2	3	4	**5**	6

IV. Experimental Methods – Environmental Chamber

An environmental chamber was constructed to produce elevated ambient temperatures to model firefighter work conditions and evaluate thermoelectric cooler (TEC) modules available for use in a portable cooling apparatus. Figure 2 is a schematic of the environmental chamber. The test setup consists of a 1 m^3 insulated enclosure that is temperature controlled to simulate a hot ambient environment. Ambient temperatures from 21 $\pm$0.3 ºC to 50 $\pm$0.3 ºC were set with a dedicated temperature controller that switched a resistance space heater on/off and activated inlet and outlet fans allowing the enclosure to exchange air from the laboratory.

A thin-profile TEC unit was placed within the center of the temperature controlled enclosure while a pump and flow meter supplied and measured the flow rate of water that passed through the TEC cooling plate. Water served as the working heat exchange fluid and was conductively cooled by contacting the TEC cooling plate. Thermocouples measured the temperature of the supply and return water as well as the ambient temperature within the enclosure. The waste heat from the TEC was rejected using an integrated fan and heat sink assembly. An open reservoir located outside the enclosure collected cold water returned from the TEC and supplied hot water to the TEC unit. A heater was used to heat the reservoir to simulate a human subject producing metabolic heat. A magnetic stirrer ensured the reservoir was maintained at a uniform temperature. Both simulated human and ambient temperatures were varied to help generate realistic temperature curves and heat removal rates.

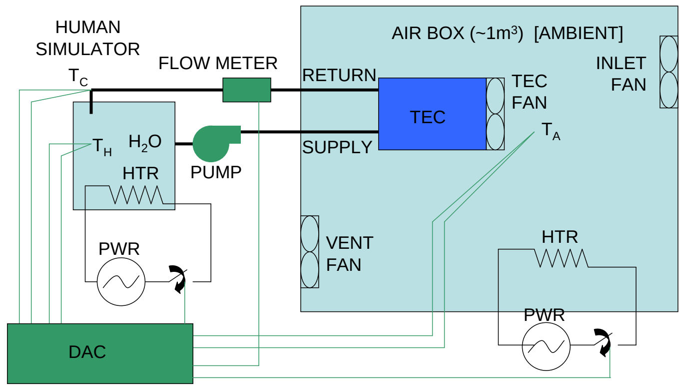

Figure 2. Apparatus to acquire TEC performance data for use in model development.

V. Experimental Methods – Portable Water Cooling System

In addition to evaluating TEC units in the enclosed environment, the water cooling system was also used in experiments with firefighter subjects. The TEC-based system evaluated in this firefighter portion of the study is shown in the sketch in Fig. 3. The TEC cooled water is pumped through well-insulated water lines connected to a cooling suit worn by firefighter test subjects. These water suits contain cylindrical Tygon® water tubing with multiple flow paths, allowing for un-restricted water flow. The water suits were worn underneath the firefighter's turnout gear to allow for heat removal through direct skin contact. Thermocouples integrated into the water circulation system measured the TEC device inlet/outlet water temperatures and the ambient room temperature. A flow sensor measured water flow rates downstream of a water filter, which eliminated contamination from entering the flow meter. A data acquisition (DAC) system recorded temperatures, module power input and water flow rates that were used to characterize heat removal and module efficiency.

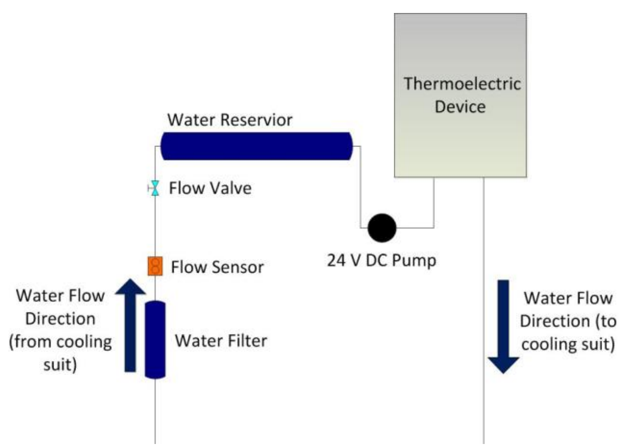

Figure 3. A schematic of the portable cooling system with integrated TEC, showing the direction of water flow.

Figure 4 is a photograph of the TEC module used in both environmental and firefighter experiments. The module is composed of a water channel cooling plate located on the bottom side of the device where a heat exchange process occurs between the device and the flowing water. The TEC module has a large exterior fan mounted on the top surface to intake ambient air and a heat sink assembly on each side to reject heat into the ambient environment. Relays are also mounted to regulate both module operation settings for heating/cooling applications. Inlet and outlet water lines are connected to water channels on the bottom of the module. The module was placed on a styro-foam insulation platform to help eliminate heat transfer from the water cooling plate to the cooling station desktop.

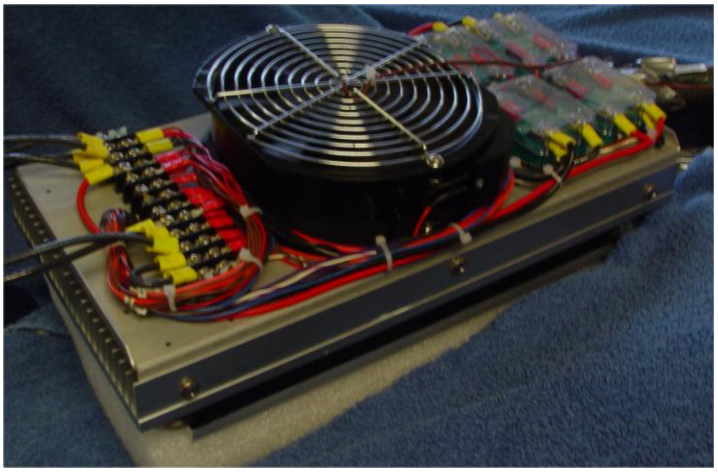

Figure 4. Thin-profile thermoelectric module used in environmental chamber tests and firefighter tests as part of the closed-loop water circulation system. TECA Inc. manufactured the cooler.

VI. Physiological Testing

Three healthy male firefighters were tested under strenuous exercise regimes with and without the cooling suit/TEC system to evaluate module cooling effectiveness. Aerobic tests were performed in a controlled testing room in the Human Performance Clinical/Research Laboratory at Colorado State University. Physiological work rate was characterized by acquisition of expired gases, heart rates and ratings of perceived exertion. Core temperature measurements were assessed using an ingested temperature monitoring capsule. The capsule transmitted core temperature readings. Tests with the TEC module required the firefighters to be tethered to the portable cooling system. Figure 5 shown below illustrates the firefighter during an aerobic exercise with the TEC system attached.

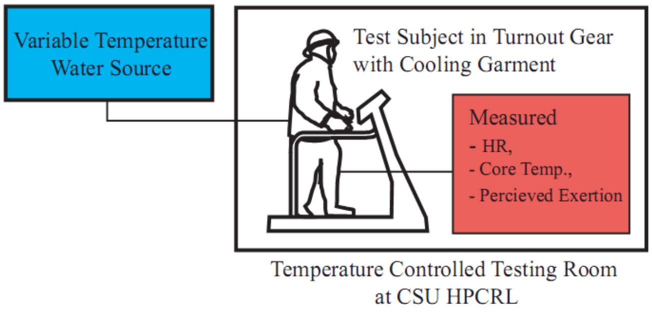

Figure 5. An illustration of a firefighter test subject tethered to the portable cooling system.

The subjects underwent a maximal exercise test to determine maximal aerobic capacity utilizing a modified Balke protocol with a self-elected speed and increasing grade on the treadmill to exhaustion. Expired gases were collected using a TrueMax 2400 system and maximal heart rate was acquired with a twelve-lead electrocardiography system.

There were three randomized exercise task trials after the maximal test. Twelve hours prior to each trial, the subjects ingested a CoreTemp capsule. During each trial the firefighters wore personal bunker gear with an air pack to mimic the attire and equipment weight during firefighting activities. During one trial the subjects wore only the bunker gear and air pack without the cooling suit. The other two trials utilized the cooling suit under the bunker gear at either the high (365 W) or low (250 W) power setting with varying water flow rates. The exercise task lasted

30 minutes. During the first ten minutes (first work load), the treadmill speed was 80.4 m/min (3.0 mph) with 3% grade and the next 20 minutes (second work load) the speed was increased to 88.4 m/min (3.3 mph) with 11% grade. Heart rates and core temperatures were collected each minute. Expired gases were collected at minutes 5-6 (in the middle of the first work load), 10-13 (at the end of the first work load and during the transition into the second work load), 19-21 (in the middle of the second work load) and 28-30 (at the end of the second work load). Collecting data at these intervals encompassed a wide enough data window to obtain the overall exertion of the firefighters.

VII. Results and Discussion – Environmental Chamber

Figure 6 contains test data collected with the TEC using the environmental chamber previously described. The TEC was supplied with 264 W of power (24 V, 11 A) using a voltage controlled power supply. This input power induced a 12 ºC (21.6 °F) change in the water temperature when the water flow rate was set at 0.2 Liter/minute. The flow rate and induced temperature change were used to calculate the heat removal rate from the water of 168 W and the coefficient of performance, COP, of 0.64 (168-W/264-W). A COP of 1.0 or greater is considered to be acceptable and would enable relatively good performance of a portable cooling system.

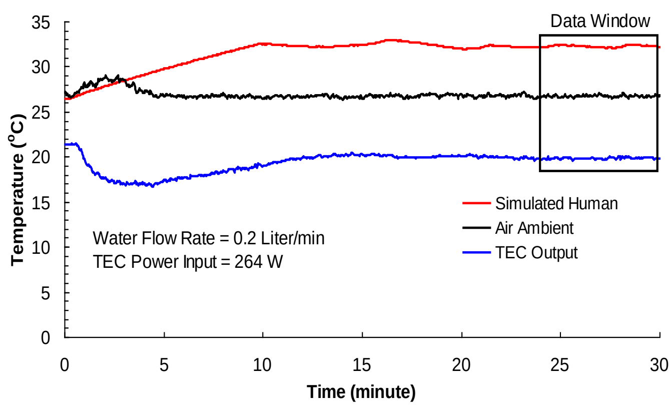

Figure 6. Typical test with TEC input power set to 264 W and water flow rate set to 0.2 Liter/minute. Note that the TEC is inducing a 12 °C drop in water temperature, which corresponds to 168 W of heat removal and a coefficient of performance (COP) of 0.64. Steady-state conditions were reached after ~10 minutes.

Figure 7 shows the results of nine tests, where the temperature change induced in the water flow was recorded as a function of water flow rate and ambient temperature conditions. These data correspond to a fixed-simulated-human temperature of 32 ºC (89.6 °F). As expected the temperature change induced in the water flow decreases as the flow rate increases. An interesting trend is revealed when the COP is calculated from the data in Fig. 7 and plotted against input power as is done in Fig. 8. Specifically, the COP increases substantially as the flow rate is increased. This occurs because the temperature difference between the cold side of the TEC unit and the water is higher on average at high flows compared to lower flow. Tests have shown COP values >1 can be achieved by the TEC unit under high flow conditions.

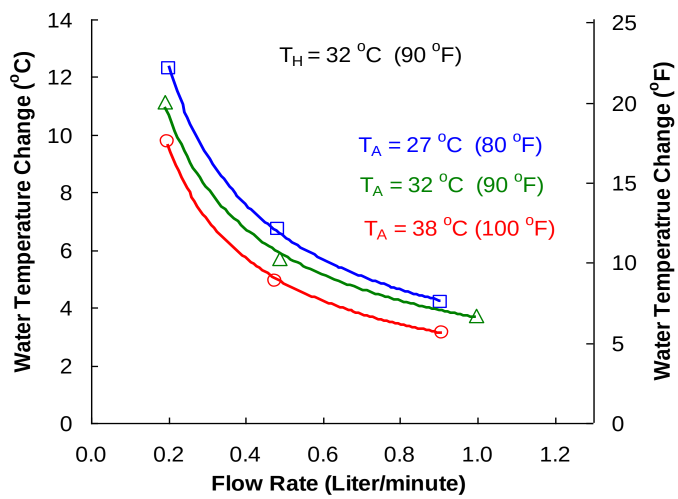

Figure 7. Typical water temperature difference induced by the TEC as a function of water flow rate and the ambient temperature of the enclosure. Simulated human temperature set to 32 °C.

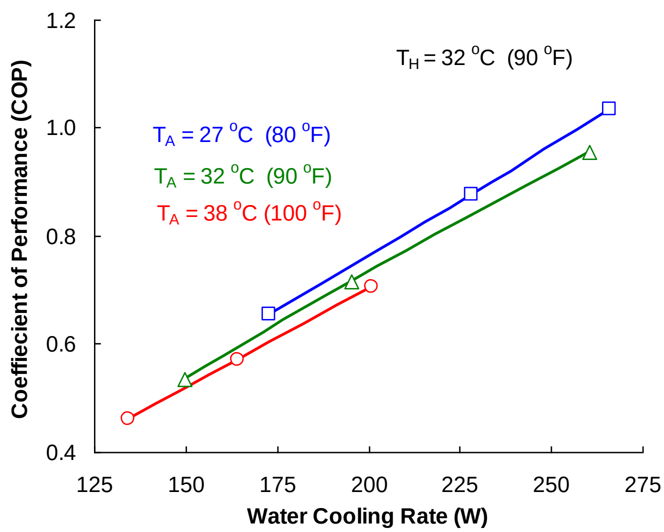

Figure 8. Effects of ambient temperature on COP. Note that COP of >1 is achieved at high flow rate and 27 °C ambient condition.

VIII. Results and Discussion – Portable Water Cooling System

Comparable data was taken during firefighter testing. Firefighter tests were performed at two different module input powers, 250 W (20V, 12.5A) and 365 W (24V, 15.2A), to determine the effect of input power on heat removal and COP. For actual service use, the TEC module would be operated to maximize heat removal rate. Figure 9 shows water temperature change as a function of water flow rate. Again, as expected, higher flow rates generate smaller temperature differences. When compared to the environmental tests, the change in water temperature is lower for the same flow rates (at approximately the same input power). Cooling water temperature changes of 9.5 °C (17.1 °F) were seen at the lower flow rate while changes of 3 °C (5.4 °F) were induced at the high flow rate. The smaller change in water temperature for the human tests is due to thermal resistance between the skin of the firefighter and tubing of the water suit, reducing heat transfer. It should be noted that Fig. 9 indicates temperature changes are nearly independent for the two input power levels when tested at the same flow rate.

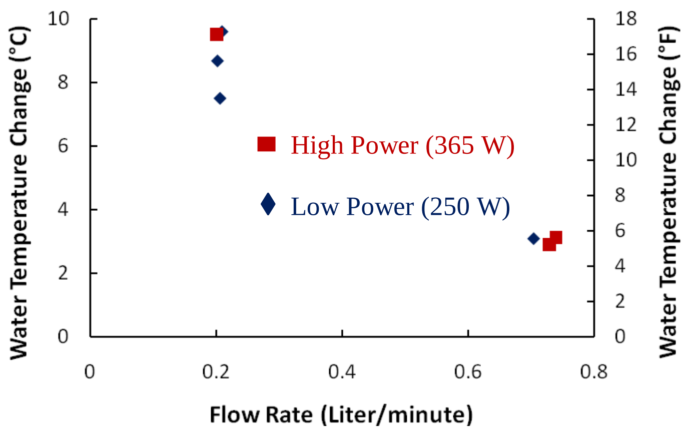

Figure 9. Water temperature difference for firefighter tests at both high and low power input. In agreement with environmental chamber tests, large temperature changes occur at lower flow rates.

Figure 10 shows COP as a function of heat removal rate for the firefighter tests. Interestingly, heat removal rates at high flow (0.7 L/min) have very little variance despite module power variation, with values between 147 and 160 W. It should be noted that the low flow (0.2 L/min) heat removal rate has a much larger variation with values ranging from 107 to 140 W**.** Despite variance in experimental data, it cannot be assumed that such variations will occur during field operation. Flow rate effect on heat removal rate and COP is important when attempting to determine module operation parameters. Conclusions can be made regarding the effect of flow rate on the magnitude of heat removal. Specifically, larger heat removal rates can be obtained during fire suppression activities if water in the cooling system is operated at higher flow rates, despite a lower change in cooling water temperature. These results suggest that service use of this portable TEC system should be done with the cooling water flowing at high rates. Confirmation of such data requires many more firefighter trials than presented in the current study. Figure 11 shows COP as a function of input power. As expected, the lower input power level produces larger COP values and high COP was produced at higher water flow rates.

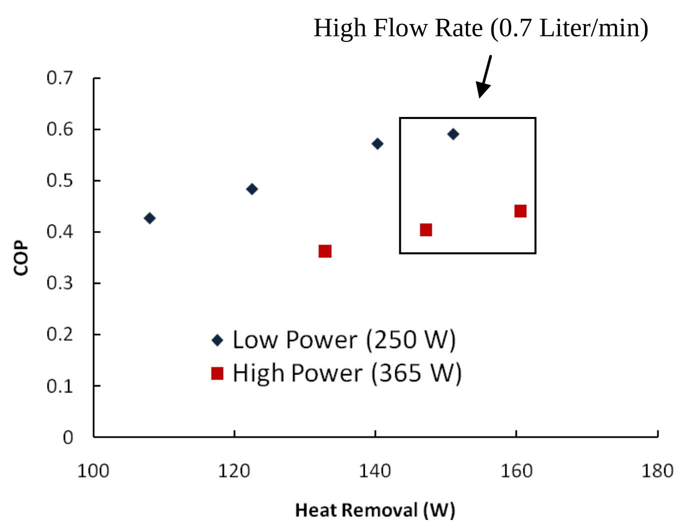

Figure 10. COP values as a function of heat removal rate at both 250 W and 365 W input power. High flow rate causes an increase in heat removal and COP greater than those of the low flow rate for the same input parameters.

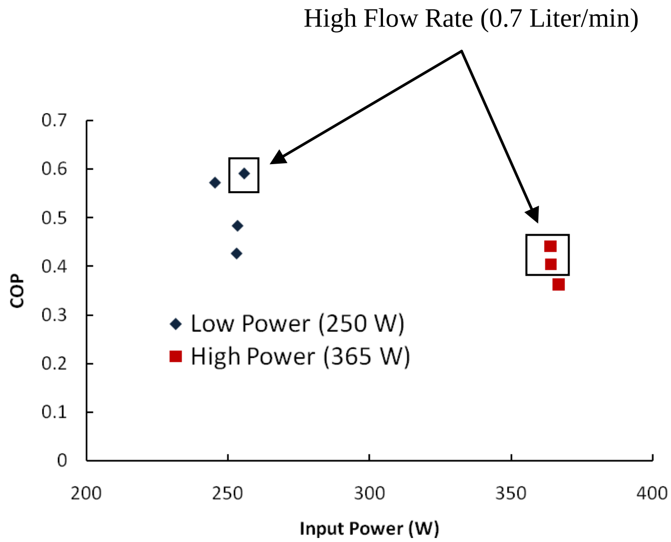

Figure 11. COP values as a function of input power at 0.2 L/min and 0.7 L/min. As expected, COP increases at the lower input power setting due to the decrease in electrical energy consumption.

In general COP values for firefighter tests are considerably <1. Despite lower COP, heat removal rates at high flow approach values of the environmental chamber tests. Factors such as perspiration rates and surface area contact between skin and water tubing for each firefighter can affect the conductive heat transfer process. Also, contact pressure (based on water suit sizes) can affect cooling.

It is important to discuss why heat removal rates appeared to be independent of TEC input power. Figure 10 shows constant heat removal rates despite varying TEC module input power, but shows significant cooling rate differences at the two different flow rates. These large differences in heat removal rate indicate the portable water cooling system has been receiving other cooling aid in addition to the TEC device. Water traveling within the cooling system lines passing through the cold plate of the TEC device might induce flow-based convection, thereby increasing heat removal rates at higher water flow rates. This means that heat removal created by the portable water cooling system might largely be a function of convective water cooling in addition to TEC input power. To test this hypothesis, further experiments should be done at different water flow rates without the TEC unit receiving power. Consequential heat removal rates can then be calculated for just pure convective water cooling within the suit plumbing. Should the hypothesis yield findings in favor of having significant convection cooling, COP values for the portable water cooling system would then need to include input power to the water pump.

IX. Results and Discussion – Physiological Tests

Commercialization of solid-state cooling devices like the thin-profile TEC for use in firefighting depends on their success at reducing heat stress in active firefighter personnel. Humans produce heat when they perform work. Heat stress is of particular importance in firefighters because of the high work intensity required and the high temperature of the work environment. Both of these elements drive the body's core temperature. Elevated core temperature can have lethal outcomes. The body has several ways to cool itself in an effort to maintain core temperature, but is greatly limited by the bunker gear used by firefighters during fire suppression activities. By removing heat from the skin, it is hypothesized that core temperatures could be more easily maintained. In this study the researchers hoped to demonstrate that the cooling suit would blunt core temperature increases and yield lower aerobic capacity and heart rates in comparison to the no suit condition by aiding the cooling of the body.

Effectiveness in firefighter cooling can be accessed by studying core temperature regulation. The difference in core temperature was assessed by examining the difference between the first and last core temperature readings during the exercise task. These differences were then averaged for each condition. Core temperature readings revealed the smallest difference in the cooling suit with the low power setting for the second task and for the entire trial, indicating better core temperature regulation. This difference was 0.76 ºC (1.37 ºF) compared to 1.09

ºC (1.97 ºF) for the largest difference. Wearing a cooling suit reduced the absolute increase in core temperature. To date the system has had little to no effect on aerobic capacity and heart rate values for firefighter test subjects.

Despite consistently removing heat from the water during the experimental tests, there was significant variability in core temperature measurements. Some factors that could be responsible for the great variation in core temperature response to TEC cooling include:

1. Differences in perspiration rates for individual firefighters
2. Individual firefighter body size differences
3. Fitness level variation among the test subjects
4. Lack of custom-fit cooling suit, leading to changes in tube to skin contact pressure
5. Unavoidable water leaks creating air pockets within water flow

Although many factors may have contributed to core temperature inconsistency, it is informative to note the general trend of measured core temperature throughout the duration of the testing. In particular, core temperatures for each test were all seen to increase during the aerobic testing period. This expected increase indicates accurate measurement of core temperatures. More studies with better fitting water suits might lead to more consistent core temperature readings. Also, more trials need to be conducted before proof of the cooling system effectiveness on firefighter core temperature regulation can be assessed.

X. Conclusion

A TEC unit was investigated as a primary method for external cooling in firefighting applications. An environmental chamber testing apparatus with temperature control was fabricated as a means of testing candidate TEC modules. In addition, a portable cooling system was setup to determine TEC cooling rates and efficiency on firefighter test subjects. Corresponding physiological data were taken in an attempt to generate consistent and observable heat stress reduction. Environmental chamber tests indicate COP values >1 are achievable with the TEC cooling technology with corresponding heat removal rates over 250 W. The portable TEC cooling system showed lower cooling rates and COP during human trials. Successful heat removal of over 160 W and COP values >0.6 have been achieved during firefighter tests. Thermal resistance and other testing factors, such as cooling suit size, have proven to slightly decrease the TEC cooling capacity on humans. High water flow rates should be used in actual service during fire suppression activities to maximize heat removal and COP. Physiological data indicates reductions in absolute core temperature increases are possible with the cooling system. Further trials will help to characterize the TEC module cooling when used with a portable water cooling system as well as give insight into the overall effectiveness of TE cooling on humans.

XI. References

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