A Lightweight, Low-Cost Liquid-Metal Personal Cooling System for Prolonged Cooling

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I. Abstract—The impact of global warming on personal health is a growing concern, as high temperatures can cause heat stress disorders. Personal cooling systems are a promising solution in environments where air conditioning is not available or infeasible such as the outdoor working environment of utility workers, and treatment of hyperthermia for athletes. However, current untethered personal cooling systems are expensive, heavy, or have a limited cooling duration due to high power consumption. Here, we have designed and prototyped a lightweight and low-power active personal cooling system that uses the non-toxic gallium-based liquid-metal, Galinstan, as the coolant. The Galinstan absorbs body heat as it is pumped through tubing attached to a cooling vest by a low-power DC pump. After absorbing the body heat, the warm Galinstan is cooled by passing it through a network of tubing embedded in cold phase-change material in a cold pack. The cold pack is insulated from the external environment, allowing heat absorption from only the warm liquid metal. To the best of the author's knowledge, the liquid metal active personal cooling system is 1/3rd of the weight, 1/8th of the price, and cools for 4 times longer compared to the current state-of-art commercial active personal cooling systems.

II. INTRODUCTION

Extreme climate events, including heatwaves, have increased in frequency. For example, in August 2019, the southern United States experienced temperatures as high as 118 °F [1]. Moreover, mortality associated with extreme heat events is increasing due to global climate change [2]. When the human body is exposed to high heat, there is discomfort, and heat strain due to increased body temperature may lead to reduced performance, heat-related sicknesses such as hyperthermia, and even death [3]. This problem is solved using air conditioning indoors. However, air conditioning is not feasible in the outdoors, or indoor locations where air conditioning is challenging, such as workshops and factories. Furthermore, construction and utility workers engaged in outdoor power utility work or indoor electrical utility work in boiler rooms are at a greater risk of sickness due to occupational heat exposure. The preventive and definitive treatment for heat-related illness is core body cooling. In these situations, a useful solution is personal cooling systems (PCS) [4], [5].

PCS can be categorized as active and passive. Active cooling uses electrically powered pumps or chillers to pump and cool down the liquid or gas coolant, such as ventilated cooled air cooling and circulated liquid cooling [6]–[8]. The most popular active PCS uses a water-glycol mixture as a cooling medium and a thermal management unit using vapor compression to cool down the coolant [7]. However, this PCS is quite heavy and expensive; it weighs 16.9 lbs with limited battery and 27 lbs with full-scale battery (allowing a maximum of 2 to 4 hours of cooling), and costs more than $8000 per unit [7], [9]. On the other hand, passive cooling uses different materials such as ice, frozen gel, salt, wax, and phase change material (PCM) [4], [8], [10] as the cooling medium in clothing. Most passive PCS are free from external connections, instead PCM is used to cool down the wearer. Among the passive methods of cooling, the best cooling performance is achieved by PCM [5]. However, the duration of cooling is limited to 2 to 5 hours, and depends on PCM mass and the latent heat. Also, the duration of cooling varies with the ambient temperature and decreases in a high-heat environment [11]. Besides, passive PCS loses cooling capacity as soon the cold pack is exposed to ambient temperatures, making it undesirable for on-site use by the workers and first-aid responders at a later time.

The majority of commercial high-performance wearable PCS has not focused on the general population; instead, these systems are meant for professionals such as defense personnel, firefighters, athletes, and medical professionals. These PCS prioritize operational performance, largely ignoring cost. As a result, commercially available PCS which can meet the requirements of general users is expensive. The ideal PCS should have a lightweight ergonomic design, thermal control, and long-duration cooling (at least 8 hours). It should also be durable, inexpensive, and ensure mobility and dexterity of the user [12].

Here, we have designed and prototyped an active PCS which has all the functionality mentioned above. The prototype uses the non-toxic liquid metal, Galinstan (an alloy of 68.5% Ga, 21.5% In, 10% Sn) as the cooling medium. Liquid metal passes through the tubes attached to the garment and absorbs body heat from the wearer. After absorbing the body heat, the warm Galinstan is cooled down by passing it through a network of tubing submerged in cold PCM in a cold pack. The cold pack is kept in a thermally insulated double-layer container carried by the wearer in a waist-belt pouch bag. Therefore, the cold pack which cools the liquid metal is isolated from the external environment maximizing the cooling efficiency. The cooling garment is designed to provide cooling for 8 to 10 hours without a refill. However, the current prototype is capable of 6 hours of cooling due to heat leakage in the current PCM container. The liquid metal active personal cooling system is 1/3rd of the weight, 1/8th of the price, and cools for 4 times longer compared to the current state-of-art active PCS. The liquid metal PCS also preserves its cooling capacity for up to 48 hours at ambient temperatures.

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temperatures, making it suitable for remote onsite use.

III. DESIGN, OPERATION, AND CAPABILITIES

A. Design and Operation

Air temperature, radiant temperature, humidity, and air movement are the four environmental variables that affect human response to thermal environments. On the human side, metabolic heat generated by activity and the clothing worn by a person is the important variables. The environmental variables may not be controlled for human comfort. Also, metabolic heat generation varies according to the level of effort and may not be controlled externally. Therefore PCS integrated into clothing is best for controlling the thermal environment for human comfort. PCS regulates the thermal body temperature of workers inside heat entrapped clothing and high heat working environments. Here, we designed an active PCS technology that conserves the cooling energy stored in PCM from the external environment and uses a high thermal conductive liquid metal coolant to distribute the cooling energy to the wearer body on demand. Also, a low power pump actuation distributes the coolant resulting in highly efficient cooling for longer durations with less battery power and less weight.

Figure 1 shows the design and working cycle of the liquid-metal PCS. As mentioned in section-I, the liquid-metal PCS uses liquid-metal Galinstan as the cooling medium. Galinstan has a high thermal conductivity of 16.5 W/m·K, which is 28 times higher than water [13]–[15]. The high thermal conductivity of Galinstan is leveraged to develop an active PCS which combines the mobility of passive cooling with the long duration and controlled performance of active cooling. Here, cold liquid metal is pumped through tubing (3/32” inner diameter, 5/32” outer diameter, Tygon) in the interior of the garment (Fig. 1a). The liquid metal absorbs body heat and flows through a network of tubing submerged in a PCM cold pack. The warm liquid metal quickly cools in the PCM cold pack (a stainless-steel double-layer vacuum container) and recirculates (Fig. 1b). Unlike most commercial passive PCS, the PCM cold pack is isolated from the external environment using a thermally isolated container.

The PCM container works as the cold pack for the hybrid cooling shirt. Circulating liquid metal cools down while passing through the cold pack. The container is designed to be manufactured using double-wall vacuum insulated stainless steel (1Cr18Ni9), which has corrosion resistance, high surface strength, and strong resistance to scouring in the presence of Galinstan (Fig. 2) [16]. Also, 1Cr18Ni9 stainless steel has a relatively low thermal conductivity, which is suitable for heat insulation of PCM. In addition, it is rust-resistant and does not react with PCM material. The PCM container has been designed in a rectangular shape for ease of carrying in a waist pouch bag. It has two thermal insulating caps giving access to its contents. These caps should be unscrewed when the cold pack is refilled or the PCM is cooled in a freezer. The PCM container has a double-wall vacuum-insulated detachable cover for liquid metal tube insertion and maintenance. A robust umbilical cord connects the container to the pump module and the cooling shirt. The dimensions of the container are designed to hold 4.2 lbs. of PCM designed to provide over 8 hours of cooling. Also, the PCM container increases the cooling efficiency of the PCM by 40% compared to passive PCS which uses PCM packs for cooling.

B. Specifications and Capabilities

The liquid metal PCS has been designed for extended use by the general public. The cooling system has the following specification and capabilities:

i. Non-toxic, high thermally conductive liquid metal (Galinstan) as a cooling medium.

ii. Thermally conductive tubing for liquid metal flow (3.0 W/m-K), and PCM for cooling the liquid metal.

iii. Proof-of-concept prototype can provide cooling for 6 hours; the next version is designed for 8 to 10 hours of cooling without refill of the PCM.

iv. Active, on-demand, and controllable cooling. No external connection required.

v. Low-power DC pump allows over 12 hours of active cooling with a 12V, 9 amp-hour power supply.

vi. The ergonomic design consists of a thin layer of tubing
inside the garment, ensuring mobility and dexterity.


viii. Thermally isolated PCM cold pack cools the liquid metal while isolated from the environment providing highly efficient cooling.

ix. The initial prototype full-load weight is 9.25 lbs. including fire-resistant clothing.

x. Combines the best features of active cooling (long and controlled cooling) with the best features of passive cooling (no external connections and minimal impact on wearer dexterity).

IV. PROTOTYPE AND EXPERIMENT

A. Prototype

We have fabricated an initial prototype and tested it in a lab environment as a proof of concept. The results show superior performance compared to the current-state-of-art active PCS. Figure 3 shows the cooling shirt prototype in the lab. The liquid-metal PCS is integrated into a long-sleeve fire-retardant shirt, which is commonly used in industrial settings such as manufacturing facilities, shipyards, and construction sites. Tygon tubes (3/32” ID, 5/32” OD) are used to flow the liquid metal. Although the thermal conductivity of Tygon tubing (0.33 W/m-k) is lower than water, it was used for convenience. Thermally conductive tubing will be used for the commercial version of the PCS. Four sets of tubes embedded in the shirt are connected to a low-power DC pump which moves the liquid metal in a closed-loop network through the PCM and the tube network at the interior of the shirt (Fig. 3). The pump is powered with a 9 amp-hour lithium battery which can run the pump for 12 hours on full load. The pump, power supply, pump control unit, and the PCM cold pack is housed in a waist pouch bag.

The pump is controlled using a pulse-width-modulated (PWM) DC voltage with an adjustable duty cycle (adjustable range 10–100%), which controls the pump flow rate. The PWM frequency is 13 kHz. The cooling temperature of the shirt is controlled by varying the liquid metal flow rate. The current prototype has four pump control positions (off, low, medium, and high), which the user can adjust for comfortable cooling.

B. Experiment

The cooling performance of the active liquid-metal PCS along with a market-leading PCM passive cooling vest was tested and compared in the laboratory. The PCM cooling shirt was purchased from the Amazon [17]. The experiment was carried out at 95 °F room temperature. First, a male-form mannequin was wrapped with PVC film (thermal conductivity of 0.19 W/m-k) to raise the thermal conductivity of its surface to resemble human skin more closely [18]. Second, the mannequin was dressed in either the liquid-metal PCS or the PCM cooling vest, as shown in Fig. 4. Next, when the cooling systems were in operation, the surface temperature of the mannequin was measured until the temperature rose to 86°F. Both the liquid metal cooling shirt and PCM cooling vests used 4 lb. of PCM for cooling. However, the PCM container has been designed to hold 4.2 lbs of PCM in the next revision of the prototype.

![Fig. 3. Liquid metal cooling shirt prototype. (a) Front view of the shirt showing the inner tubing on the front-left side for liquid metal flow. (b) Back view of the shirt showing the waist pouch back which carries the DC pump, portable power supply, and PCM cold pack for cooling liquid metal.](image)

![Fig. 4. Experiment setup. (a) The temperature was measured at the five points marked with white circles. A 0.5-inch by 0.5-inch window was cut open at the test points, in between the cooling tubes, as shown in the inset. (b) The temperature was measured from a 6-inch distance using an IR thermometer with a traceable laser pointer.](image)

V. RESULTS

Figure 5 shows the laboratory test results for the cooling performance of the liquid-metal PCS prototype and the PCM cooling vest. The liquid-metal PCS was able to maintain cooling 40% longer than the commercial PCM cooling vest. During the experiment explained above (Fig. 4 & 5) the mannequin surface was cooled to a minimum of 70°F. The maximum measured temperature on the mannequin surface throughout 7 hours of operation was 86°F. The average temperature was 95°F, and the average mannequin surface temperature was 76.1°F throughout the experiment. Thus, the liquid metal cooling system achieved an average difference between room temperature and the mannequin surface at 18.9°F. The maximum measured temperature on the mannequin surface was 82.6°F. The heat load of a fluid system cooling in BTU/hr can be expressed as,

\[ h = c_p \cdot \rho \cdot q \cdot \Delta t, \]

where, \( h = \text{heat load (BTU/hr)} \),

\[ c_p = \text{specific heat of LM = 0.0707 BTU/lb.°F (296 J/Kg.K)}, \]

\[ \rho = \text{density of LM = 53,774 lb/USgal (6440 Kg/m³)} \],

\[ q = \text{LM volume flow rate = 2.69 US gal/min (170 ml/min)}, \]

\[ \Delta t = \text{temperature difference = 10°F}. \]
The cooling load is calculated to be, 

\[ h = 0.0707 \frac{\text{BTU}}{\text{lb}} \times 53.774 \frac{\text{lb}}{\text{USgal}} \times 2.96 \text{USgal/hr} \times 15.2 \text{°F} = 171.516 \text{ BTU/hr} = 50.27 \text{ watts} \]

The proof of concept liquid-metal PCS prototype was able to provide an average of 50.27 watts of cooling for 7 hours with fully loaded weight only 9.25 lb (Fig. 5).

The PCM cooling vest initially cools the wearer more, up to 4 hours, but it has no thermal control, and it begins losing its cooling capability after 4 hours. The vest itself is also rigid, which may make it uncomfortable.

To increase the cooling capability of the liquid-metal PCS, the tube length inside the PCM cold pack can be increased. In the current prototype, 12 feet of tubing (occupies 22.5 sq. in. area, liquid metal weight 0.32 oz.) containing liquid metal was passed through the PCM cold pack. We can pass up to 18 feet of tubing (occupies 33.35 sq. in. area, liquid metal weight 0.47 oz.) through the PCM cold pack to achieve stronger cooling.

The total cooling is limited by the weight and latent heat of the PCM material. The liquid metal PCS prototype is 2 times heavier than the passive cooling vests (Fig. 5), but only 1/3rd weight compared to the state-of-art active cooling vests providing 40%, and 75% longer duration cooling compared to passive and active mentioned above [5], [7]. Current commercial state-of-art passive cooling vests are rigid, hampering the dexterity and mobility of the wearer. Also, the current commercial active cooling system is quite heavy (27 lbs for 2 hours of untethered operation), as they contain a thermal management unit and a battery pack; these concentrated masses hinder the mobility of the wearer [9]. In contrast, the liquid-metal PCS has its weight more evenly distributed, which is more comfortable to the wearer. In addition, the liquid-metal PCS is flexible, conforms to the body, and comparatively light.

VI. DISCUSSION

The use of liquid metal (Galinstant) as the cooling medium results in superior cooling performance. This is achieved due to the thermal conductivity of Galinstan, which is ~27 times that of water, while the dynamic viscosity is only twice that of water. Thus, the convective heat transfer coefficient is remarkably enhanced with a minor penalty of pumping power, allowing longer cooling with less power consumption. Currently available active PCS are developed for niche applications, making them costly. The liquid-metal PCS would price 1/8th (includes 50% profit margin) compared to current state-of-art active PCS and provide personal cooling for the duration of an entire workday without refill or recharge.

REFERENCE


