The following publication Guo, Y., Chan, A. P. C., Wong, F. K. W., Li, Y., Sun, S., & Han, X. (2019). Developing a hybrid cooling vest for combating heat stress in the construction industry. Textile Research Journal, 89(3), 254-269 is available at https://doi.org/10.1177/0040517517743685

Developing a hybrid cooling vest for combating heat stress in the construction industry

Abstract

Many frontline workers in Hong Kong construction industry have to perform physically demanding work under hot working conditions, which could reduce work efficiency and time and increase the occurrence of heat cramps, heat exhaustion and heat stroke. This study aimed to develop a hybrid, new cooling vest (NCV) to combat heat stress in the construction industry. Following the functional clothing design process, the problem identification was conducted. Preliminary ideas were formed through the analysis of available types, research, survey, literature review, and brainstorming. The design was refined through the use of desirable phase change material packs, fans with high wind velocity/long duration, and fabrics with thin, vaporpermeable, wind/water/abrasion-resistant properties, and UV protection, as well as clothing ergonomic design that considers fit, mobility, convenience, and safety. The desirable thermal functional performance in NCV was previewed through a computer-aided design platform (CAD) S-smart system. The design criteria were established and the prototype was developed. The environmental chamber testing results showed that in a hot environment, the mean skin temperature (35.8 °C vs. 36.59 °C), heart rate (110 beats/min vs. 116 beats/min) and core temperature of the subjects with NCV were significantly lower than those with the control (without NCV). A significantly longer exercise time was obtained with NCV compared with the control (22.08 min vs. 11.08 min). The significant improvements in levels felt coolness, dryness, comfort, and physical recovery were observed with NCV. Results suggest that NCV can reduce the thermal stress of construction workers and improve their work performance and comfort.

Keywords: heat stress; cooling vest; functional clothing design process; water proof and breathable fabrics; comfort

1. Introduction

Many frontline workers in Hong Kong have to perform physically demanding work under hot working conditions, which can be as high as 35.4 °C and 95% relative humidity in summertime [1]. The hard work combined with hot/humid weather reduced work efficiency and time [2], and could increase the occurrence of heat cramps and heat exhaustion, thereby resulting in high cardiovascular demand and the possibility of heat stroke [3]. A search in local newspaper archives using the search engine WISENEWS shows at least 282 heat-related incidents (including 40 fatal cases) between 1998 and 2011 across all industries [4]. Of the 282 heatrelated incidents, construction contributed to 73 cases, 22 of which were fatal. Thus, measures to combat heat stress in the construction industry deserve considerable attention from all parties concerned. A properly designed personal cooling system (PCS) is one measure that can reduce the risk of heat-related injuries and illnesses.

Various studies have been conducted that centered on various PCSs, such as battery-driven ambient air fan-based cooling vests without external connections [5]; [6] and passive cooling systems that employ phase change materials (PCMs) (e.g., ice, frozen gels) in vests/clothing [7]; [8]; [9]; [10]; [11]. Attempts have been made to introduce these products into construction workplaces, where workers endure a hot environment [12]. However, the effectiveness and applicability of these products in the construction industry have yet to be verified. Construction work is tough and demands additional requirements on a cooling vest. A cooling vest should have good cooling performance, lightweight, durable, and easy to maintain. And the vest has to be heavy task and sufficiently fit the body shapes of workers to avoid posing as a hazard around moving parts while still providing flexibility. However, a cooling vest that is suitable for sports may not necessarily be appropriate for construction workplaces. Accordingly, developing a

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tailor-made cooling vest to protect construction workers from heat-related injuries while working in a hot environment is necessary. One method to realize this goal is to apply an objective and structured approach in the development of a new cooling vest.

The investigators in the textile and clothing fields have applied design process principles in their studies. Huck and Kim [13] developed a coverall for wildland or grass firefighting by applying the design process of Dejonge [14]. The preferability of the newly designed prototype coveralls to the current coveralls worn was based on the perceptions of fit and comfort and evaluated using objective and subjective measurements. LaBat and Sokolowski [15] applied a three-stage design process (problem definition and research, creative exploration and development, and implementation) to an industry–university textile product design project: optimizing an athletic ankle brace. The results led to the redesign and improvement of the product, as well as the reduction of product returns. Other clothing items, such as occupational clothing for female pear farmers [16], thermal protective flight suits [17], and bicycle patrol uniforms [18], were designed to address the expectations of the wearer by employing the functional design process approach. Thus, the literature provides a systematic method to develop functional clothing.

The current study, which involves designing anti-heat stress clothing (a new uniform: a tshirt made of moisture-wicking technical fabric and trousers made of Dry-Inside technical fabric) for construction workers in hot and humid weather, accurately followed the functional clothing design process of Dejonge [14]. Moreover, the recent research further complemented this process by placing equal premium on fabric and design rather than on merely the latter in response to design situations [19]. Fabrics with excellent heat/moisture-transporting properties and clothing ergonomic design (previewed and optimized using S-smart, a computer-aided design platform (CAD), before a formal design), which are associated with mobility, convenience, and safety, maximized the comfort of the wearer and improved the functionality of the clothing. Anti-heat stress clothing has been implemented in actual wearing conditions by the Construction Industry Council (CIC) in Hong Kong (Fig. 1A). Accordingly, this clothing was used as basis of this research to design a hybrid, new cooling vest (NCV) for construction workers, who will wear the cooling vest outside of the anti-heat stress clothing during considerably hot days in Hong Kong (criteria: daily maximum temperature \geq 33.0 °C) [20]. The six-step process of Lamb and Kallal [21] was followed, and the design criteria establishment of Dejonge [14] was integrated into the development of the cooling vest.

2. Materials and Methods

According to Lamb and Kallal [21] and Dejonge [14], the modified seven-step process includes the following components (Fig.s 2):

- 1) Problem identification
- 2) Preliminary ideas
- 3) Design refinement
- 4) Design criteria establishment
- 5) Prototype development
- 6) Evaluation
- 7) Implementation

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In the development of anti-heat stress clothing, the used textile technology in fabric testing and CAD with regard to the inheritance and development of the existing knowledge was continually employed and further expanded to test the battery-driven ambient air fan and PCMs for NCV.

2.1. Step 1: Problem identification

The construction workers of Hong Kong have to undertake physically demanding activities in hot and humid conditions. Workers performing tasks in a hot and humid environment are at risk of heat-related injuries and illnesses. In a hot environment, regulating body temperature at a stable level is important for the human body. Hence, failure to do so can lead to several detrimental effects, such as dehydration, heat stroke, and elevated heart rate. A recent survey showed that 5% and 23% of construction workers had suffered from heat stroke and experienced signs and symptoms of heat stroke, respectively [4]. Consequently, the increase in the number of heat-related incidents in the construction industry has led to public concern. After considering additional requirements of the construction workers to combat heat stress and reduce the risk of heat-related injuries and illnesses in the construction workers to combat heat stress and reduce the risk of heat-related injuries and illnesses in the construction industry.

2.2. Step 2: Preliminary ideas

In the second step of the process, preliminary ideas are formed from such techniques as sketching, brainstorming, research, survey, and question-and-answer sessions to achieve the goals [21]. These techniques were used in the present study.

Chan et al. [22] conducted a meta-analysis and found that the natural air-cooled garments and phase change material cooling garments were more suitable to most occupational workers because the workers move frequently. Furthermore, the cooling effect of a cooling vest with 2 fans and 3 ice packs was investigated in four industries of Hong Kong, including construction, where the workers undertook the wear trials and performed their usual work routines [23]. The cooling vest was perceived a long effective cooling time and the workers felt less clammy, sticky, damp, heavy, scratchy, rough, stiff, tight, and interferential with regard to job performance. These studies suggest that designing a hybrid cooling clothing based on vests with PCM packs and two fans is considerably suitable for construction workers. Therefore, the preliminary ideas were sketched after the discussions of the research team, and PCM packs, fans, fabrics, and clothing design in NCV will be refined.

2.3. Step 3: Design refinement

For all the aforementioned factors, this step should result in a few ideas that can then be tested for the fabrics, PCM packs, fans and clothing design.

2.3.1. Fabrics

The aim of this research was to design NCV for construction workers, who will wear this vest during extremely hot days in Hong Kong; the design demand of this vest is the same as the recent design for anti-heat stress clothing [19]. Many factors in the development of anti-heat stress clothing, such as thermal function provided by thin and vapor-permeable fabrics, UV protection, and abrasion resistance, were also determined as important concerns in the design of NCV. Therefore, fabric properties, including weight, thickness, air permeability, thermal

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conductivity, water vapor permeability, ultraviolet protection factor (UPF), and abrasion resistance, were tested to determine the effects of fabric on comfort and protection in a steady state. Moreover, applying fabrics with high water repellency is well understood because two fans with lithium batteries are used.

The researchers identified and tested 19 commercially available fabrics (i.e., 11 for shell fabrics and 8 for lining fabrics) to select the ideal fabrics for use in NCV. The fabrics in a commercially available cooling vest with similar structure were also tested for comparison. Thus, a total of 21 fabrics were tested. Table 1 lists the fabric description, color, and mean physical characteristics. Prior to performing the various tests, all specimens were conditioned for at least 24 h in an air-conditioned laboratory at a temperature of 21 ± 1 °C and a relative humidity of 65 \pm 2%. A total of 10 specimens for each fabric were tested in the laboratory required by ASTM D1776 [24].

- 2.3.1.1 Weight and thickness. The fabric weight for all the fabrics was measured in accordance with ASTM D 3776 Standard Method for Mass Per Unit Area of Woven Fabric. A Mettler balance, Shimadzu (Shimadzu Corporation, Kyoto, Japan), accurate to 0.001 gm, was used. Fabric thickness was measured by a dial micrometer accurate to 0.0001 inch according to ASTM D 1777.
- 2.3.1.2 Air permeability. The air permeability of the textile fabrics was tested using KES-F8 API (Kato Tech Co., Ltd., Kyoto, Japan). The test of air permeability is used to measure the flow of air passing through a specific area of materials. It is used to determine the ability of materials to penetrate air. During the test, Automatic Air Permeability Tester gives out air flow from high pressure to low pressure and the resistance of materials to pass the air

are determined by the tester. The flow of air passing through a unit area of material at a unit pressure difference across the tester over a unit period of time is recorded. During each time, the suction and discharge of air is carried out in 5 seconds, in order to measure the air pressure loss by the air resistance ability of material. The air resistance value 'R' would be displayed on the panel directly. A specification regarding a cooling vest design indicated that fabric property should prevent air leakage and protect wind out [25], which makes PCM and wind from two funs form a cooling clothing microclimate. A fabric with substantially high air resistance should be employed because a considerably high air resistance means significantly low air permeability.

2.3.1.3 Thermal conductivity. Thermo Labo II (Kato Tech Co., Ltd. Kyoto, Japan) was used to measure the thermal conductivity of fabrics in this study.

The thermal conductivity was calculated using the following equation:

$$K = \frac{W \times D}{A \times \Delta T} \quad (W/ \text{ cm} \cdot {}^{\circ}\text{C}) \tag{1}$$

where *K* is the thermal conductivity, *W* is the power, *D* is the thickness of fabric in cm, *A* is the area of the hot plate (5 cm × 5 cm = 25 cm²), and ΔT is the temperature difference between the top and bottom of a hot plate (10 °C). For details, see Chan et al. [19].

2.3.1.4. Water vapor permeability. Water vapor permeability tests the rate of water vapor that is diffused through the specimen. In accordance with ASTM E96 [26], 10 measurements of each fabric were performed by sealing fabrics over the open mouth of a dish that contains water and placing them in the standard testing atmosphere. After a period of time to establish

 equilibrium, successive weightings of the dish were collected and the rate of the water vapor transfer through the specimen was calculated.

2.3.1.5. UPF. UPF can be used to determine the rated UV protection factor of sun protection fabrics, which are designed to absorb or reflect the UV radiation of the sun as a means to protect the skin from damage. Three UPF protection categories are presented as follows [27]:

I. Range of 15–24: Good protection, effective ultraviolet radiation (UVR) transmission of 6.7% –4.2%

II. Range of 25–39, Very good protection, effective UVR transmission of 4.1% –2.6%

III. Range of 40–50, 50+: Excellent protection, effective UVR transmission of $\leq 2.5\%$

2.3.1.6. Abrasion: Abrasion weight loss percentage (%) was measured. NCV, accompanied by anti-heat stress clothing, will be mainly worn from June to September in Hong Kong. Each ensemble will be actually worn approximately 60 days due to alternate washing. In 15000 times abrasions, the weight loss percentage of fabrics of below 8% without the broken holes is an acceptable and sufficient protection for the actual wearing situation [19].

2.3.1.7. Water repellency and wettability (Spray test): This method measures the resistance of porous textile materials (or garments) to wetting by water and is shown as grades 0 to 5 [28]:

I. Grade 5: No sticking or wetting of the upper surface, thereby indicating the maximum water repellency

II. Grade 0: Complete wetting of the entire upper and lower surfaces, indicating the lowest water repellency

PCM is a material which has a high heat of fusion through melting and solidifying at a certain temperature to allow to store and release enormous amount of energy. Heat is absorbed when the material changes from solid to liquid, or released from liquid to solid; thus, PCMs are classified as "latent" heat storage materials [29]. Numerous PCMs absorb and release heat at a nearly constant temperature, and melt with a heat of fusion in any required range. Moreover, a few of these materials exhibit economic advantages, such as low cost and large-scale availability [29]. Thus, using PCM packs in NCV is a logical approach.

In the current study, three commercially available PCMs were initially selected for comparison. Two out of the three PCMs were excluded due to unaffordable price and leaked packing. ClimSel[™] C28 (Climator Sweden AB, Sweden), a salt hydrate-based PCM that works by either charging or discharging of energy at different temperatures, was eventually used. This PCM is affordable and showed the following desirable properties:

- I. Moderate thermal conductivity
- II. Compatible with the packing material

III. Easy maintenance and no known lifetime limit on PCM packs:

A. PCM packs can be stored in an air-conditioned room in construction sites with 10 $^{\circ}$ C-26 $^{\circ}$ C to be solidified for use (Lower storage temperature is better in hot weather depending on need).

B. If PCM packs are correctly handled and the packaging remains uncompromised, then the product will continue to cycle as intended time with no known lifetime limit.

Table 2 provides a list of the PCM size, main components, typical temperature stabilization span, and physical characteristics.

2.3.3. Fans

This study initially selected two types of commercially available fans for comparison: fans that are driven by four AA alkaline batteries from a commercially available cooling vest with similar structure, and fans that are driven by four rechargeable lithium batteries. Their wind velocities were continually tested using an anemometer (Beijing THY Science & Technology Co., Ltd, Beijing, China). Two types of fans have adjustable wind velocity from high (grade 4) to low (grade 1). The wind velocity and duration of grade 4 in two types of fans were tested, as shown in Fig. 6. Table 2 lists the physical characteristics.

2.3.4. NCV ergonomic design

This study aims to design a hybrid cooling clothing of PCM packs-based vest with two fans, in which conductive and convective heat loss mechanisms are involved. Clothing ergonomic factors are also important for the improvement of the functionality of NCV.

2.3.4.1. Design for conduction: Conduction is the heat transfer that occurs if a temperature gradient exists in a solid or stationary fluid medium. In this study, a temperature gradient exists between the skin and PCM packs. When placing the PCM packs considerably close to the body skin, heat flows in the direction of the PCM packs from the skin to decrease body temperature. Thus, NCV was designed to appropriately fit the human body. Moreover, opening zippers were designed on the two sides of the body, thereby making the PCM packs significantly close to the body for cooling and the size adjustable.

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2.3.4.2. Design for convection: For the human body, heat transfers from the skin to the ambient air by convection through fabrics and garment openings [30]. Two fans were installed in NCV, in which heat transfers out from the garment openings located on the collar and cuff of a sleeve. Moreover, two air vents on the back were added to transfer more hot air and enhance evaporation rate and heat dissipation.

2.3.4.3. Design for the clothing ergonomic factors: The recent research identified the ergonomic factors of anti-heat stress clothing, which includes mobility, convenience, and safety [19]. These factors also apply to the present study. The fit description in Section 2.3.4.1 is also included. Narrow elastic bands in the collar and cuff of a sleeve were applied to make the clothing considerably elegant and convenient to body activity. Wide and high resilience elastic bands in the waist can appear neat and tidy, keep the wind out, and enhance safety due to the reduction of falling objects in the worksites. Fans were firmly installed as if the cloth and fan are one, thereby enhancing the safety. Moreover, washable retroreflective strips with different patterns on the front and back surfaces were incorporated into NCV to enhance differentiation degree for safety reasons, which complies with the Specifications for Supply and Delivery of Worker Uniforms for Construction Industry Council in Hong Kong. CIC advised that the washable retroreflective strips should be incorporated onto the polo shirts, vests and winter jackets for workers [31]. Fig. 1 (B, C, and D), Fig. 7, **Table 2**, and Section 3 present the detailed designs.

2.3.5. Preview of the NCV thermal functional performance using a virtual CAD system

The S-smart system as a CAD tool was developed to design and preview multi-layered clothing assemblies to achieve desirable thermal functional performance in a virtual space [32]; [33]. The coupled heat and moisture transfer processes in clothing and the external environment

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have been considered based on the mathematical models developed by Gagge, Stolwijk, and Nishi [34] and Hensel [35]. Subjective perception of thermal comfort is predicted by applying a fuzzy logic system, in which a set of inference rules was developed by analyzing the subjective records of a group of people in the experiment [32]. The previewed results include core temperature, skin temperature, skin relative humidity, and subjective comfortable sensations before the real NCV was engineered to screen and determine the NCV fabrics and design with desirable thermal functional performance.

In the pre-processing of a user-friendly interface (Fig. 3), the wear activities (1, what to do) were arranged based on the real metabolic rates described in a recent field study [36]:

Resting (metabolic rates: 42 W/m^2)

Working (metabolic rates: 234, 248, 230, and 167 W/m^2)

Resting again (metabolic rates: 55 W/m²)

Environment (2) and subjects (3, who) were also provided by the current study. Garment (4) was only the fit design, and the shell and lining fabric testing data, such as thickness, were inputted in the fabric design (Table 1 and Fig. 3). PCM was also selected in the fabric specification. The control and boundary conditions were defined. Thereafter, simulation (5) was started.

2.4. Steps 4 and 5: Design criteria establishment and prototype development

The design criteria were established and the prototype was developed based on the studies on the PCM packs, fans, fabrics, and predicted results by computational simulation for the NCV thermal functional performance. Section 3 describes these processes in detail.

2.5. Step 6: Evaluation

Design evaluations were conducted inside an environmental chamber and in the construction worksites. Healthy participants volunteered to participate in the studies after being informed of the experimental procedures. These procedures were approved by the Human Subjects Ethics Sub-Committee of the university.

2.5.1. Evaluations inside an environmental chamber

A total of 12 healthy participants randomly carried out 2 stage exercises on a motorized treadmill with/without NCV in an environmentally controlled chamber (37 °C, relative humidity: 60%, WBGT: 32.4 °C) after 30 min of pre-exercise rest on a chair. The chamber condition simulated a practical WBGT collected during wear trials in the Hong Kong construction sites [23].

Stage 1: Without NCV: *6 min warm up* (subjects exercised on a motorized treadmill at 6 km/h walking speeds for 3 min with 2% slope and 3 min with 4% slope); *48 min work* (6 km/h walking speeds for 3 min with 8% slope and 3 km/h walking speeds for 3 min with 2% slope, alternately performed until the desired core temperature (i.e. 38.5 °C) and maximum heart rate were achieved. This simulated a previous study, in which 38.5 °C was reached [36]; *6 min active recovery* (3 km/h and 2 km/h walking speeds for 3 min, respectively, with 1% slope)

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Passive recovery: With/without NCV: 30 min rest on a chair. Cooling/no cooling intervention was implemented

Stage 2: Without NCV: 6 min warm up, 48 min work, 6 min active recovery (repeat Stage 1 protocol)

This protocol simulated the real working situations of the HK construction workers. In a given workday, they work during the entire morning and afternoon, and 15 min and 30 min breaks are intermediately provided. NCV was used only during the passive recovery period (the simulated break). We assume that cooling during passive recovery could provide a relatively low initial core temperature to enhance the working performance of the workers for the succeeding exercise period. Skin temperatures were measured using temperature probes (Nikkiso-YSI, Japan) attached to the chest (Tchest), upper arm (Tupper arm), upper leg (Tupper leg), and lower leg (Tlower leg) at a sampling frequency of 30 s. Mean skin temperature was calculated using the formula of Ramanathan [37]: 0.3 Tchest + 0.3 Tupper arm + 0.2 Tupper leg + 0.2 T lower leg. Core temperature was collected through an ingestible core body temperature capsule (HQ, Inc., Palmetto, FL, US) and recorded at a sampling frequency of 30 s. In order to ensure the functionality and accuracy, the capsule was calibrated before use. It was put into a water cup at temperatures ranging from 30 to 42°C and recorded the temperature values continually. The recorded values were compared by a certified temperature probe with an accuracy of $(0.15+(0.002 \times T) \circ C \text{ (Lutron}^{\otimes}, \text{ Taiwan)}$. The capsules falling outside a degree of accuracy of \pm 0.1°C were not used in the test. The participants swallowed the calibrated capsule with warm water 4–6 hours before the testing to avoid the confounding effect of food and drinks [38].

2.5.2 Evaluations by wearing NCV in construction sites

A total of 173 construction workers (171 males, 98.84%; 2 females, 1.16%) from two training centers in Hong Kong participated in wear trials during the summer. Their average age, height, and weight were 32.1 years (SD = 9.2), 171.7 cm (SD = 5.5) and 69.7 kg (SD = 13.9), respectively. The trade distribution comprised screw-plate workers (N = 70, 40.46%) and rebar workers (N = 103, 59.54%).

In one out of the two experimental days (the environmental WBGT: 31.56 °C), the construction workers performed their usual daily routine works approximately three hours for the morning and afternoon, respectively. A total of 15 min and 30 min breaks in the morning and afternoon, respectively, were provided intermediately. The construction workers randomly wore either NCV on the outside of the anti-heat stress clothing or the anti-heat stress clothing only (control) during the two breaks. At the end of the two breaks, the participants rated their levels of coolness, dryness, comfort, and physical recovery based on a rating scale of "1" (poorest possible rating) to "7" (best possible rating) [19]; [39]; [40]. For the NCV group, the participants answered whether they prefer NCV and whether NCV fits their body sizes and facilitates the dissipation of heat with 7-point rating scales.

2.6 Statistical analysis

For the core temperature and exercise time, Two-way ANOVA with repeated measures (Condition × Time) was conducted to detect the differences between NCV and control. The significance level was accepted at p < 0.05. For subjective evaluations in the wear trials of construction sites, change NCV from control (%) was conducted.

3. Results and discussion

3.1. Objective measurement of the fabric properties and preview of the NCV thermal functional performance

As suggested in Section 2.3.1, the fabric properties used in NCV are as follows:

- 1) Thin and vapor-permeable
- 2) High air resistance
- 3) High water repellency
- 4) Very good UV protection and abrasion resistance

With reference to Table 1, among the eight lining fabrics tested, L2 was the thinnest and had high water vapor permeability. Thus, L2 was selected as the lining fabric in the real cooling vest and simulation. Among the 11 shell fabrics tested, the thickness was divided into two groups: S1–6, S10 < 0.1 mm; S7–9, S11 > 0.2 mm. S1–5 were poor air resistance with low values, and S6–11 were good air resistance with high values or infinity. Water vapor permeability was divided into three groups: S6–8 < 800; 800 < S1–5 < 1000; S9–11 > 1000 g/m²/day. UPF was > 40 for all shell fabrics except S6, and abrasion resistance of all shell fabrics was excellent (< 5%). With regard to the representatives of different levels of thickness and water vapor permeability, S2, S4, S7, S8, S9, and S10 were selected and entered to the simulation for the prediction of thermal functional performance by the S-smart system to determine the final selection of shell fabric.

Fig. 4 shows the predicted core/skin temperatures and skin relative humidity when wearing the virtual cooling vest. In hot conditions, core/skin temperatures increased from resting values

(37.2 °C and 33.0 °C, respectively) to top working values (38.1 °C and 36.3 °C, respectively). Skin relative humidity also increased from 55.25% at the start of the resting period to 80.3% by the top of the working period. The results indicate that the considerably high metabolic rates during the working period significantly elevated core/skin temperatures and skin relative humidity. Temperature values were lower in S10 compared with those of CACV and other fabrics, thereby suggesting that body heat dissipation is faster in fabric S10. The skin humidity resulting from S10 was 3% to 5% lower during 40–70 min and 5% to 10% lower during other times than those from CACV and other fabrics (except S4), thereby indicating that fabric S10 could maintain the dryness of the skin most of the time. S10 was light, thin, and had very good water vapor permeability and excellent UV protection and abrasion resistance. Furthermore, S10 had high air resistance and water repellency (Grade 5). Thus, S10 was eventually selected as the shell fabric based on the fabric testing results and computer simulation for thermal functional performance.

Fig. 5 presents the predicted comfortable sensation when wearing the virtual cooling vest. Comfort value is acceptable when wearing NCV, which could be associated with low skin relative humidity. Skin humidity reached 100% during difficult tasks in the recent research [19]. In the present study, two fans may accelerate the processes of sweat evaporation; however, skin humidity was merely 80.3% by the top of the working period. Therefore, comfort value is acceptable because humidity is the driving force behind comfortable or uncomfortable perceptions. Previous studies reported that a significantly positive relationship existed between increasing humidity and the perception of discomfort of the subject [41]; [42].

3.2. Fans and PCM packs

Fig. 6 shows the average wind velocity and duration of the two types of fans. The fans with lithium batteries (Shen Zhen Ideal Energy Co., Ltd., Shen Zhen, China) are eventually used because they have higher and more stable average wind velocity and longer duration compared with those of the fans with alkaline batteries (3.26 vs. 1.27 m/s and 7 vs. 4 h, respectively), which have gradually declining wind velocity.

Corcoran [43] reported that workers have some concerns which may restrict the use of cooling garments in the market: spend more time on waiting for the vest to activate and does not function. The construction workers can wear NCV for one week on a single charge when it is worn during the two morning and afternoon breaks because the fans with lithium batteries can work seven hours under stable wind velocity. This type of storage battery can be easily charged by the workers in their weekends, thereby increasing the availability of NCV.

Construction sites in Hong Kong are furnished with air-conditioned rooms of approximately $20 \text{ }^{\circ}\text{C} - 24 \text{ }^{\circ}\text{C}$ for meeting and toolshed. The PCM packs can be stored in the air-conditioned rooms to be solidified for use when NCV is not worn. Thus, NCV is workable in the construction sites in Hong Kong.

3.3. Design criteria establishment and prototype development (Steps 4 and Step 5)

Considering various factors for the PCM packs, fans, fabrics, and design features, computational simulation for the NCV thermal functional performance in Section 3.2 has demonstrated desired effects on the body temperature, skin relative humidity, and comfortable sensation. The design criteria for NCV were established (see Table 2). Moreover, Section 2 suggests that the PCM packs, fans, and shell fabrics selected have to address the functional

criteria listed in Table 2. Thereafter, the NCV prototype was developed and illustrated in Fig.s 7 and 1 (B, C, and D).

3.4. Evaluation (Step 6)

3.4.1. Evaluations inside an environmental chamber

The environmental chamber testing results showed that during the passive recovery, the mean skin temperature and heart rate following NCV (35.8 °C and 110 beats/min, respectively) were significantly lower than those following control (36.59 °C and 116 beats/min, respectively; p < 0.001 for all measurements). The difference of core temperature between NCV and Control was insignificant during the 30 min pre-exercise rest and Stage 1 exercise. However, a significantly lower core temperature was obtained during the passive recovery and Stage 2 exercise for NCV compared with the control (p < 0.001 for both; Fig. 8A). The difference of exercise time between NCV and control was insignificant during the 30 min gradient during the Stage 1 exercise. However, a significantly longer exercise time was obtained during Stage 2 exercise for NCV compared with the control (p < 0.001 for both; Fig. 8A). The difference of exercise time between NCV and control was insignificant during the Stage 1 exercise. However, significantly longer exercise time was obtained during Stage 2 exercise for NCV compared with the control (22.08 min vs. 11.08 min, p < 0.001; Fig. 8B).

In the present study, the cooling intervention was not implemented during the 30 min preexercise rest and Stage 1 exercise, and thermoregulatory responses were insignificant between NCV and the control. The core temperature was merely 37.3 °C, which is a nearly normal value during the 30 min pre-exercise rest and before Stage 1 exercise (Fig. 8A). Thus, employing a cooling intervention on the Stage 1 exercise is unnecessary. However, the core temperature elevated to over 38 °C at the end of the Stage 1 exercise. Thus, the cooling intervention was immediately implemented and lasted during the passive recovery. Cooling wearing NCV during passive recovery in a heated environment significantly attenuated the increase in core/mean skin

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temperatures and heart rate during this period. The properties and design of NCV contributed to the results. NCV possesses PCM and two fans. In the present study, the used PCM was 28 °C. According to the prediction with S-smart, in hot condition, skin temperature increased from resting values (33.0 °C) to top working values (36.3 °C), which means a temperature gradient of about 8°C between the skin and PCM packs during working period. When placing the PCM packs considerably close to the body skin, heat flowed in the direction of the PCM packs from the skin and heat was absorbed when the material changes from solid to liquid, thus body temperature was decreased. Fit design and opening zipper on the sides of the body made the PCM packs considerably close to the body for cooling. The latter accelerated the processes of sweat evaporation and heat dissipation. The effects of conductive and convective heat transfer wearing NCV in the heat are suggested to reduce thermal strain in the subjects.

Furthermore, cooling wearing NCV during the passive recovery also delayed the increase in core temperature and contributed to the prolonged work time during the Stage 2 exercise. The results were in agreement with that of Webborn et al. [44], thereby showing that the mean core temperature and perceived exertion were lower during cooling wearing the ice vest before exercise (precooling) compared with the no cooling control. The authors suggested that reduced perceived exertion may translate into improved functional capacity. For the present study, cooling wearing NCV during the passive recovery can be seen as a precooling for the Stage 2 exercise.

3.4.2. Evaluations by wearing NCV in construction sites

Table 3 presents the results of the subjective ratings in the wear trials of the construction sites.

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During the break, significant improvements in levels felt coolness, dryness, comfort, and physical recovery were observed for the morning and afternoon. The NCV changes from control (%) were 28.66, 23.37, 28.13, and 18.76 in the morning, and 27.91, 23.41, 24.12, and 21.35 in the afternoon. The scores that the participants provided with regard to their preference of NCV, and whether NCV fits their body sizes and facilitates the dissipation of heat were 5.04, 4.89, and 5.13 in the morning; and 4.69, 4.84, and 4.95 in the afternoon. The responses were positive for wearing NCV.

Previous literature reported that the subjective perceptions of warmth and wetness underneath the clothing correlated with objective measurements of temperature and relative humidity, and discomfort was strongly associated with the amount of moisture on the skin [41]; [42]. The reduced body temperature and moisture from the double heat dissipation effects of both conduction and convection with the aid of fit design with opening zipper/air vents wearing NCV in Section 3.4.1 contributed to the improved coolness, dryness, comfort, and physical recovery levels in the current study. Therefore, the participants prefer NCV in the hot environment and high activity levels.

Other deliverables sharing common background and methodology, but mainly focusing on the laboratory human study and the on-site worker survey indicated that thermoregulatory, physiological, and perceptual strains were significantly lower in NCV than those in Control during the recovery session ($p \le 0.022$), which were accompanied by a large effect of cooling (Cohen's d=0.84-2.11). The rise in physiological strain index was reduced by 0.11 ± 0.12 unit min⁻¹ (p = 0.010) following the use of NCV. The details on the laboratory human study and the on-site worker survey were described elsewhere [45]; [46]; [47].

4. Step 7: Implementation

NCV will serve as work clothes in the construction sites in Hong Kong. The team will mainly focus on realizing the goal of successfully applying the current research into practical use, particularly in addressing industrial issues. The university may license the NCV technology to CIC in Hong Kong based on the experiences from the anti-heat stress clothing. Consequently, CIC will further promote the technology to contractors for site adoption to enhance the health and well-being of construction workers. NCV may also receive extensive attention from academics, industries, and the public through a series of promotion, exhibition activities, and awards. Thereafter, an official launch of NCV may be conducted during the Construction Safety Week in Hong Kong. CIC may initially produce a few NCV for workers, and the contractors may further produce additional clothing for use in construction sites.

5. Conclusions

The objective of this research was to design a new cooling vest for construction workers during extremely hot days in Hong Kong. Problem identification was undertaken after considering the additional requirements of the construction industry, as well as following the functional clothing design process of Lamb and Kallal [21] and integrating the design criteria established by Dejonge [14]. Preliminary ideas were formed based on the analysis of available types, research, survey, literature review, and brainstorming: designing a hybrid cooling vest with PCM packs and two fans. Design refinement was obtained by selecting the available PCM packs with the ideal price and desirable properties; employing fans with high wind velocity and long duration; screening the used fabrics with thin and vapor-permeable properties, excellent air resistance, water repellence, UV protection, and abrasion resistance from 19 commercially

available fabrics; and identifying clothing ergonomic design with fit, mobility, convenience, and safety. The desired effects on the NCV thermal functional performance was previewed through the S-smart system software platform. The design criteria for NCV were established and the prototype was subsequently developed. The NCV prototype evaluations were conducted using treadmill testing by human subjects inside an environmental chamber and wear trials in the construction sites under actual wearing conditions. Significantly low core/skin temperatures, low heart rate and long exercise time, and significant improvements in levels felt coolness, dryness, comfort, and physical recovery were observed in wearing NCV.

The effects of conductive and convective heat transfer wearing NCV in the heat are concluded to reduce thermal strain in the subjects, which have profound influence on the work performance and subjective perception of discomfort. In the future, NCV could be implemented by licensing the technology to the industry and conducting a series of promotion, exhibition activities, and awards.

The novelty of this study is the development of a new vest system which combines PCM and fan ventilation. The cooling effectiveness of this new vest system can be validated by the results of the laboratory human study and the on-site worker survey, which were described here and elsewhere [44]; [45]; [46].

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This paper forms part of the research project titled 'Developing a Personal Cooling System (PCS) for Combating Heat Stress in the Construction Industry', from which other deliverables will be produced with different objectives/scopes but sharing common background and methodology. The authors also wish to acknowledge the contributions of other team members including Dr Michael Yam, Dr Daniel Chan, Dr Edmond Lam, Dr Del Wong, Dr Jackie Young, Dr Song, W.F., Dr Yi, W. and Miss Zhao, Y.J.

References

- 1. Hong Kong Observatory, 2012. Monthly Weather Summary. http://gb.weather.gov.hk/wxinfo/pastwx/mwsc.htm (accessed 10.02.17).
- 2. Yi, W., Chan, A.P.C., 2013. Optimizing work-rest schedule for construction rebar workers in hot and humid environment. Build Environ. 61, 104-113.
- 3. Fogleman, M., Fakhrzadeh, L., Bernard, T.E., 2005. The relationship between outdoor thermal conditions and acute injury in an aluminum smelter. Int. J. Ind. Ergonom. 35, 47-55.
- 4. Wisenews, 2012. Number of heat related incidents between 1998 and 2011 in Hong Kong, Wisenews, July 2012.
- Shapiro, Y., Pandolf, K., Sawka, M.N., Toner, M.M., Winsmann, F.R., Goldman, R.F., 1982. Auxiliary cooling: comparison of air-cooled vs. water-cooled vests in hot-dry and hot-wet environments. Aviat. Space Environ. Med. 53(8), 785-789.
- 6. Hadid, A., Yanovich, R., Erlich, T., Khomenok, G., Moran, D.S., 2008. Effect of a personal ambient ventilation system on physiological strain during heat stress wearing a ballistic vest. Eur. J. appl. Physiol. 104, 311-319.
- Bennett, B.L., Hagan, R.D., Huey, K.A., Minson, C., Cain, D., 1995. Comparison of two vests on heat-srain reduction while wearing a firefighting ensemble. Eur. J. Appl. Phsyiol. 70, 322-328.
- 8. Webster, J., Holland, E.J., Sleivert, G., Laing, R.M., Niven, B.E., 2005. A light-weight cooling vest enhances performance of athletes in the heat. Ergonomics 48, 821–837.
- 9. Choi, J.W., Kim, M.J., Lee, J.Y., 2008. Alleviation of heat strain by cooling different body areas during red pepper harvest work at WBGT 33 °C. Ind. Health 46, 620-628.

- Chou, C., Tochihara, Y., Kim, T. 2008. Physiological and subjective responses to cooling devices on fire-fighting protective clothing. Eur. J. Appl. Physiol. 104, 369-374.
- Reinertsen, R.E., Farevik, H., Holbo, K., Nesbakken, R., Reian, J., Royset, A., Thi, M.S.L., 2008. Optimising the performance of phase change material in personal protective clothing systems. Int. J. Occup. Saf. Ergon. 14, 43-53.
- 12. Occupational Safety and Health Council of Hong Kong (OSHC), 2012. Invitation to tender of contract study on effectiveness of personal equipment for protecting workers from heat stroke while working in a hot environment, March 2012, 26 pages.
- 13. Huck, J., Kim, Y., 1997. Coveralls for Grass Fire Fighting. Int. J. Cloth. Sci. Tech. 9, 346–359.
- 14. Dejonge, J. O., 1984. The Design Process. In Clothing: The Portable Environment, edited by S. M. Watkins, vii–xi. Ames: Iowa State Press.
- 15. LaBat, K. L., Sokolowski, S. L., 1999. A three-stage design process applied to an industry-university textile product design project. Cloth. Text. Res. J. 7, 11-20.
- 16. Choi, M. S., Ashdown, S. P., 2002. The Design and Testing of Work Clothing for Female Pear Farmers. Cloth. Text. Res. J. 20, 253–263.
- Tan, Y., Crown, E. Capjack, L., 1998. Design and Evaluation of Thermal Protective Flightsuits. Part I: The Design Process and Prototype Development. Cloth. Text. Res. J. 16: 47–55.
- Black, C., Cloud, R. M., 2008. Assessing Functional Clothing Needs of Bicycle Patrol Officers. International Journal of Fashion Design, Technology and Education 1 (1), 35–42.
- 19. Chan, A. P. C., Guo, Y. P., Wong, F. K. W., Li, Y., Sun S., Han, X., 2016. The development of anti-heat stress clothing for construction workers in hot and humid weather. Ergonomics 59, 479-495.
- 20. Hong Kong Observatory, 2017. Number of Very Hot days observed at the Hong Kong Observatory since 1884, exclude 1940-1946. http://www.hko.gov.hk/cis/statistic/vhotday_statistic_e.htm (accessed 10.02.17).
- 21. Lamb, J. M., Kallal, M. J., 1992. A Conceptual Framework for Apparel Design. Cloth. Text. Res. J. 12, 402–447.
- Chan, A. P. C., Song, W., Yang, Y., 2015. Meta-analysis of the Effects of Microclimate Cooling Systems on Human Performance under Thermal Stressful Environments: Potential Applications to Occupational Workers. J. Therm. Biol. 49– 50, 16–32.
- 23. Guo, Y.P., Chan, A. P. C., Wong, F.K.W., Li, Y., Del P., 2016. Factors Determining the Preference for Cooling Vest Across Four Industries in Hong Kong. RISUD Annual International Symposium 2016 (RAIS 2016) – Smart Cities. Hong Kong, 23-24 August 2016.
- 24. ASTM D1776. 2004. Standard Practice for Conditioning and Testing Textiles. West Conshohocken, PA: American Society for Testing and Materials.
- 25. Jeil Trading Co., 2017. Cooling Vest with Cooling Fan. http://www.ec21.com/product-details/Cooling-Vest-with-Cooling-Fan--9413270.html (accessed 10.02.17).

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26. ASTM E96. 2005. Standard Test Methods for Water Vapor Transmission of Materials. West Conshohocken, PA: American Society for Testing and Materials.

- 27. AS/NZS 4399:1996. 1996. Sun Protective Clothing Evaluation and Classification. Sydney: Australian/New Zealand Standard, Joint Technical Committee TX/21.
- American Association of Textile Chemists and Colorists. 2003a. AATCC technical manual, 2002. Water repellency-spray test. Research Triangle Park [NC]: AATCC; 2002. p. 65-7.
- 29. Sharma, Atul, Tyagi, V.V., Chen, C.R., Buddhi, D., 2009. Review on thermal energy storage with phase change materials and applications. Renew. Sust. Energy Rev. 13 (2), 318–345.
- 30. Holmer, I., 2008. How is performance in the heat affected by clothing?. JFBI 1, 7–12.
- 31. CIC (Construction Industry Council). 2011. Specifications for Supply and Delivery of Worker Uniforms for Construction Industry Council. (84) in P/AE/PUR/AGC.
- 32. Li, Y., Mao, A. H., Wang, R. M., Luo, X. N., Wang, Z., Hou, W. B., Zhou, L.Y., Lin, Y. B., 2006. P Smart – A Virtual System for Clothing Thermal Functional Design. Comput Aided Des. 38, 726–739.
- Mao, A. H., Li, Y., Luo, X. N., Wang, R. M., Wang, S. X., 2008. CAD System for Multi-Style Thermal Functional Design of Clothing. Comput Aided Des. 40, 916– 930.
- 34. Gagge, A. P., Stolwijk, J. A. J., Nishi., Y., 1971. An Effective Temperature Scale Based on a Simple Model of Human Physiological Regulatory Response. ASHRAE Transactions 77, 247–257.
- 35. Hensel, H., 1981. Thermo Reception and Temperature Regulation. New York: Academic Press.
- 36. Chan, A. P. C., Yam, M. C. H., Chung, J. W. Y., Yi, W., 2012. Developing a Heat Stress Model for Construction Workers. JFM 10 (1), 59–74.
- 37. Iriki, M., 2003. Textbook of Physiology on Body Temperature. Tokyo: Bunko-do. 9.
- 38. Chan, A.P.C., Yang, Y., Guo, Y.P., Yam, M.C.H., and Song, W.F. 2016. Evaluating the physiological and perceptual responses of wearing a newly designed construction work uniform. Text. Res. J. 86, 659–673.
- 39. Guo, Y. P., Li, Y., Wong, T., Chung, J., Wong, A., Gohel, D., Leung, P., Luximon, A., 2009. Evaluation of Different PPE Ensembles in Terms of Sensation, Usability, Satisfaction and Preference. JFBI 2, 126–136.
- 40. Chan, A. P. C., Yang, Y., Wong, D. P. E., Lam, W. M., Li, Y., 2013. Factors Affecting Horticultural and Cleaning Workers' Preference on Cooling Vests. Build Environ. 66, 181–189.
- 41. Li, Y., 2005. Perceptions of Temperature, Moisture and Comfort in Clothing during Environmental Transients. Ergonomics 48, 234–248.
- 42. Wright, A., Akin, F., 2005. Comfort perception of breathable and nonbreathable diapers. Int. Nonwovens J. 14, 19–22.
- 43. Corcoran, S., 2002. Why some workers boil over wearing cooling garments. Occupational Health and Safety 71, 104-106.
- 44. Webborn, N., Price, M.J., Castle, P., Goosey-Tolfrey, V.L., 2010. Cooling strategies improve intermittent sprint performance in the heat of athletes with tetraplegia. Br. J. Sports Med.44, 455–460.

45. Yi, W., Zhao, Y. J., Chan, A. P. C., Lam, E. W.M, 2017. Optimal cooling intervention for construction workers in a hot and humid environment. Build Environ. 118, 91-100.

- 46. Zhao, Y. J., Yi, W., Chan, A. P. C., Wong, F. K. W., Yam, M. C. H., 2017. Evaluating the physiological and perceptual responses of wearing a newly designed cooling vest for construction workers. Ann Work Expo Health. 2017, 1–19.
- Chan, A. P. C., Yang, Y., Song, W. F., Wong, D. P., 2017. Hybrid cooling vest for cooling between exercise bouts in the heat: effects and practical considerations. Therm. Biol. 63, 1–9.



(A) Anti-heat stress clothing in actual wearing conditions



(C) Newly designed cooling vest (front view)



Two fans

Eight PCM packs



(D) Newly designed cooling vest (back view)

Fig. 1. Newly designed cooling vest for the construction workers.



To license the technology of new cooling vest to the CIC* in Hong Kong, and the CIC will further promote the technology to contractors for site adoption

CIC*: Construction Industry Council.

Fig. 2. Functional design process for new cooling vest for construction workers.





Fig. 3. The interfaces for defining the wear activities (1), environmental conditions (2), human subject (3), garments (4) and computational simulation (5) in S-smart system.





Fig. 4. The predicted temperature and humidity wearing virtual cooling vest.



Fig. 5. The predicted comfortable sensation wearing virtual cooling vest.



Fig. 6. The wind velocity and duration tested in two kinds of fans.

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Fig. 7. Newly designed cooling vest prototype.



Fig. 8. The core temperature (A) and exercise time (B) wearing newly designed cooling vest. NCV: newly designed cooling vest Con: control (wearing the anti-heat stress clothing only)

NS: not significant

****p* < 0.001.

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Table 1 Fabric description, color and mean physical characteristics

5 Fabric code	Description	Color	Fabric	Fabric	Air	Thermal	Water vapor	UV	Abarison-
6	Description	00101	weight	thickness	resistance	conductance	nermeability	protection	15000-
/ 0			(gm/m^2)	(mm)	$\frac{(kPa\cdot S/m)}{(kPa\cdot S/m)}$	(W/(m*K))	$(g/m^2/day)$	factor	Weight
0 Q			(511/111)	(IIIII)			(g/m/duy)	luctor	loss (%)
Coll fabria	(\$)								1033 (70)
ð1	Dolvester taffeta	Grav	0.73	0.06	0.04	0.023	846 19	50+	2 32%
12	Polyester taffeta	Brown	0.75	0.00	0.02	0.023	846 38	50+ 50+	3 73%
13	Nylon taffata	Blue	0.05	0.00	0.02	0.022	878.81	50+	0.20%
1 4 S4	Nylon tancia Dolyester taffeta	Blue	0.00	0.08	0.01	0.020	858 46	50+	0.2970
115 85	Polyester taffeta	Vallow	0.72	0.00	0.03	0.022	800.16	50+ 50+	1.7570
96 977	Togler	I CHOW	0.70	0.00	0.02	0.022	609.10	50+ 5	5.0770
30 49	Tasian	w nite	0.04	0.08	œ	0.024	030.47	5	0.08%
39 40	Tasian	Blue	0.94	0.23	œ	0.033	425.81	50+	0.06%
88 20	l aslan	Gray	1.37	0.32	00	0.033	648.00	50+	2.06%
5 9 21	Nylon taffeta	Green	1.30	0.32	1.18	0.038	1103.62	50+	0.82%
<u>\$10</u>	<u>Nylon taffeta</u>	<u>Gray</u>	<u>0.42</u>	<u>0.07</u>	<u>2.46</u>	<u>0.020</u>	<u>1052.31</u>	<u>50+</u>	<u>0.55%</u>
$\overline{\mathbf{S}}\overline{\mathbf{J}}^{1}$	Nylon taffeta	Green	0.98	0.28	1.10	0.034	1014.30	50+	0.48%
<u>ça</u> cv	<u>Taffeta</u>	<u>Black</u>	0.71	<u>0.12</u>	$\overline{\infty}$	<u>0.035</u>	<u>938.50</u>	<u>50+</u>	<u>1.65%</u>
⊵f ning fabri	c (L)								
26 57	Polyester mesh	Gray	0.53	0.28	0.00	0.029	Miss ²	NA ³	NA
<u>£2</u>	Polyester mesh	Black	<u>1.13</u>	<u>0.14</u>	0.00	<u>0.016</u>	1046.39	NA	<u>NA</u>
50	Polyester mesh	Green	1.65	0.52	0.07	0.038	1095.56	NA	NA
₿ 0	Polyester mesh	Red	1.44	0.42	0.05	0.034	1035.55	NA	NA
B1	Polyester mesh	Blue	1.44	0.44	0.04	0.034	1119.12	NA	NA
BB	Polyester mesh	Gray	1.57	0.34	0.03	0.032	1041.39	NA	NA
£ 3	Polyester mesh	Orange	0.75	0.24	0.00	0.032	885.88	NA	NA
28	Polyester mesh	Black	0.48	0.24	0.00	0.028	1253.48	NA	NA
$\frac{35}{\text{SACV}^4}$	Polyester mesh	Black	<u>0.89</u>	<u>0.29</u>	0.00	0.037	<u>841.09</u>	<u>NA</u>	<u>NA</u>
37	∞^1 : infinity;								

 ∞^{1} : infinity; Miss²: data were missed; NA³: not available due to mesh fabric as lining fabric; CACV⁴: Commercially available cooling vest.

]	Table 2	Functional criteria of compo-	nents in a newly de	esigned cooling vest	
Item PCM	Table 2DescriThe vePCM (Size: VMain (TypicaPhysicPhaseLatentSpecifiThermTherm	Functional criteria of compo- ptions est has eight pockets for PCN (C28) Width 115 mm*Length 120 r components: sodium sulpha al temperature stabilization eal data: change temperature: Solid change temperature: Liqui t heat of fusion: 45 Wh/kg – ic gravity: 1.4 kg/litre nal conductivity: Solid 0.98 pal conductivity: Liquid 0.7	nents in a newly de 4 packs: four on the nm ite, water and addit n span: 27°C-31°C 1 27°C id 31°C - 170 kJ/kg W/m/°K 72 W/m/°K	e chest and four on the ives	back (Figure 1B)
Fan and battery		Fa Di Ra 2.5 W	iameter (cm): 10 iameter (W): 5 feight (g): 95.5	Battery Material: Lithium poly Voltage (V): 7.4 Capacity (mAh): 4400 Input: DC8.4V1A Power: 20WMax Size (cm): 8.6*7.1*2.2 Weight (g): 177	ymer
Shell	Item	Specification		Test Method	<u>Requirement</u>
fabric	1 2	Weight (gsm) Water vapor permeability	70,	ASTM D 3376 ASTM E96	≥ 40 > 550 (g/m ² /day)
	3	UV protection factor (UPF		AS/NZS 4399:1996	>40
	4	Abarison-15000-Weight los	ss percentage (%)	ASTM D4966	\leq 5%
	5	Water repellency and wetta	bility (Spray test)	AATCC standard 22	Grade 5
Clothing ergonomic design	1. 2. 3. 4. 5. 6. 7.	Narrow elastic bands in the elegant and convenient to b Openings located on collar Two air-vents on the back: dissipation Wide and high resilience el out, and enhance safety due Opening zipper on the side cooling and the size adjusta Fans were firmly installed a Washable retroreflective st enhance differentiation deg	e collar and cuff of body activity and cuff of a sleev transfer more hot astic bands in the to the reduction o es of the body: ma ble as if the cloth and f trips with different ree for safety reaso	Ta sleeve: make the clo e: make heat transfer of air and enhance evapor waist: appear neat and t f falling objects in the v akes PCM packs more Tan are one: enhance the patterns on the front a	thing considerably ut ration rate and heat tidy, keep the wind worksites close to body for e safety and back surfaces:

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dry level 4.26 3.27 23.37 4.25 3.25 23.41 During the break I feel comfort level 4.87 3.50 28.13 4.60 3.49 24.12 After the break I feel physical recovery level 4.63 3.76 18.76 4.61 3.63 21.35 Preference of NCV 5.04 4.69 Whether NCV fits 4.89 4.84 the body sizes The dissipation of heat 5.13 4.95 in NCV Note: A '7' was the best possible rating; a '1' was the poorest possible rating. NCV: newly designed cooling vest Mor: morning Aft: afternoon	dry level 4.26 3.27 23.37 4.25 3.25 23.41 During the break I feel comfort level 4.87 3.50 28.13 4.60 3.49 24.12 After the break I feel physical recovery level 4.63 3.76 18.76 4.61 3.63 21.35 Preference of NCV 5.04 4.69 Whether NCV fits 4.89 4.84 the body sizes The dissipation of heat 5.13 4.95 in NCV Note: A '7' was the best possible rating; a '1' was the poorest possible rating. NCV: newly designed cooling vest Mor: morning Aft: afternoon	During the break I feel						
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After the break I feel 4.87 3.50 28.13 4.60 3.49 24.12 After the break I feel 4.63 3.76 18.76 4.61 3.63 21.35 Preference of NCV 5.04 4.69 Whether NCV fits 4.89 4.84 the body sizes 4.95 The dissipation of heat 5.13 4.95 in NCV Note: A '7' was the best possible rating; a '1' was the poorest possible rating. NCV: newly designed cooling vest Mor: morning Aft: afternoon Aft: afternoon	4.87 3.50 28.13 4.60 3.49 24.12 After the break I feel physical recovery level 4.63 3.76 18.76 4.61 3.63 21.35 Preference of NCV 5.04 4.69 Whether NCV fits 4.89 4.84 the body sizes 4.85 4.84 The dissipation of heat 5.13 4.95 in NCV Note: A '7' was the best possible rating; a '1' was the poorest possible rating. NCV: newly designed cooling vest NOC: newly designed cooling vest Mor: morning Aft: afternoon	During the break I feel						
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4.63 3.76 18.76 4.61 3.63 21.35 Preference of NCV 5.04 4.69 Whether NCV fits 4.89 4.84 the body sizes 4.95 The dissipation of heat 5.13 4.95 in NCV Note: A '7' was the best possible rating; a '1' was the poorest possible rating. NCV: newly designed cooling vest Mor: morning Aft: afternoon 4.61	4.63 3.76 18.76 4.61 3.63 21.35 Preference of NCV 5.04 4.69 Whether NCV fits 4.89 4.84 the body sizes 4.95 The dissipation of heat 5.13 4.95 in NCV Note: A '7' was the best possible rating; a '1' was the poorest possible rating. NCV: newly designed cooling vest Mor: morning Aft: afternoon Aft: afternoon	After the break I feel						
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Whether NCV fits 4.89 4.84 the body sizes The dissipation of heat 5.13 4.95 in NCV Note: A '7' was the best possible rating; a '1' was the poorest possible rating. NCV: newly designed cooling vest Mor: morning Aft: afternoon Aft: afternoon	Whether NCV fits 4.89 4.84 the body sizes 4.95 The dissipation of heat 5.13 4.95 in NCV 9 9 Note: A '7' was the best possible rating; a '1' was the poorest possible rating. NCV: newly designed cooling vest Mor: morning Aft: afternoon	Preference of NCV	5.04	5.10	10.70	4.69	5.05	21.55
the body sizes The dissipation of heat 5.13 4.95 in NCV Note: A '7' was the best possible rating; a '1' was the poorest possible rating. NCV: newly designed cooling vest Mor: morning Aft: afternoon	the body sizes The dissipation of heat 5.13 4.95 in NCV Note: A '7' was the best possible rating; a '1' was the poorest possible rating. NCV: newly designed cooling vest Mor: morning Aft: afternoon	Whether NCV fits	4 89			4 84		
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In NCV Note: A '7' was the best possible rating; a '1' was the poorest possible rating. NCV: newly designed cooling vest Mor: morning Aft: afternoon	in NCV Note: A '7' was the best possible rating; a '1' was the poorest possible rating. NCV: newly designed cooling vest Mor: morning Aft: afternoon	The dissipation of heat	5.13			4.95		
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