THE ROLE OF PERSONAL COOLING SYSTEM (PCS) IN COMBATING BODY HEAT STRAIN: A CASE STUDY IN HONG KONG

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The Role of Personal Cooling System (PCS) in Combating Body Heat Strain: A Case Study in Hong Kong

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A thesis submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy

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CERTIFICATE OF ORIGINALITY

I hereby declare that this thesis is my own work and that, to the best of my knowledge and belief, it reproduces no material previously published or written, nor material that has been accepted for the award of any other degree or diploma, except where due acknowledgement has been made in the text.

(Signed)

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(Name of Student)

STATEMENT OF THE CONTRIBUTION AND CERTIFICATE OF ORIGINALITY

This study is originated from and funded by a Research Grants Council (RGC) project, titled "Developing a personal cooling system (PCS) for combating heat stress in the construction industry", of which the author is a team member. The RGC research project focuses on developing a PCS for the construction industry, which includes design, testing and application. The author has extended the work as a part of her PhD study. As the key research personnel of the research team, the author was involved in the whole process of the product development (as shown in Chapter 4), the entire experimentation process of laboratory experiment (as shown in Chapter 5 and 6), and the field survey (as shown in Chapter 7). The author was also involved in data collection and data analysis under the guidance of the principal supervisor and other team members. The author's individual contribution is embodied by the execution and generalization of laboratory experiment and the field study as shown in Chapter 5, 6, and 7. Furthermore, reviewing literature and proposing a cooling intervention for construction workers in Hong Kong is another key contribution of the PhD study as shown in Chapters 2 and 3. Although the author was not involved in some research activities personally, for example, testing of phase change materials (PCMs) and clothing fabrics, the results are reported in Chapter 4 for the integrity of the thesis. The author also declares that this thesis is her own work, and that, to the best of her knowledge and belief, it reproduces no material previously published or written, nor material that has been accepted for the award of any other degree or diploma, except where the acknowledgement has been made in the text.

ABSTRACT

The construction industry features high-level risks on the safety and health of the working population. The safety and health of construction workers should be given with significant attention by the research community and governments. The nature of climatic and urbanised conditions in Hong Kong poses considerable threats to occupational safety and health. Heat stress is a major occupational hazard in Hong Kong's construction industry. During the hot and humid summer season in Hong Kong, construction workers are susceptible to heat stress due to physically strenuous and demanding work activities, high air temperature and relative humidity, and prolonged exposure to sunlight. Various cooling countermeasures [e.g. personal cooling system (PCS), fanning and hand and/or forearm immersion in cold water] have been proposed to relieve heat stress and improve work performance.

PCS, in the form of cooling garment, enables microclimate cooling around the body, thereby promoting heat dissipation. PCS is amongst the most effective cooling methods. Various PCSs have been used in firefighting, hazmat operations, military and sports. However, their application in the construction industry is still in its infancy, and their effects are yet to be evaluated. To bridge this research gap and develop practical solutions, a study was undertaken to engineer and design a tailor-made PCS for construction workers. This PCS is a two-layer cooling vest, specifically designed to wear over the construction uniform. The PCS design comprehensively considers cooling effect, cooling duration, weight, mobility, comfort, aesthetics, visibility and safety of construction workers. This initiative requires further

evaluation on the effectiveness and practicality of this newly designed PCS to protect construction workers from heat-related injuries.

The current study aims to develop a cooling intervention with this newly designed PCS to reduce body heat strain in the construction industry. The main objectives are to present a research framework for cooling intervention development research, examine the effectiveness and applicability of wearing the PCS on alleviating heat strain and formulate recommendations on precautionary measures to safeguard workers' health and safety whilst working in a hot environment. Experimentation, which is a scientific approach that facilitates the discovery and creation of knowledge, is adopted in this study. A series of laboratory tests on thermal manikin and human subjects and field wear trial studies are conducted in sequence to assess the cooling capability, effectiveness and applicability of the newly designed PCS.

Results of the thermal manikin test in the laboratory revealed that the newly designed PCS displays higher cooling power and longer cooling duration than a commercially available cooling vest. An optimal cooling intervention, in which the PCS is used during rest between repeated bouts of work, is determined through human wear trials in the climatic chamber. The findings of the wear trial test in the climatic chamber indicated that the newly designed PCS can significantly attenuate physiological and perceptual strains and improve work performance compared with the control condition (no cooling intervention). The field experiments showed that the heat strain of the steel bar workers wearing the PCS during rest is significantly reduced compared with that of the control condition. Furthermore, field surveys from 143 construction workers across two trades on construction sites revealed that approximately 91% of the workers are satisfied with the newly designed PCS. Most of these workers also provide good subjective evaluation on this PCS.

The current study develops an optimal cooling intervention and presents a fresh perspective to further improve occupational safety and health in construction. This study helps address the research gap caused by the lack of cooling intervention research in construction. The experimentation used in this study is well structured, rigorous and reliable. Moreover, this study is carried out within a multidisciplinary context (e.g. construction management, industrial hygiene, occupational hygiene, textile science, biological science and exercise science) to deal with scientific, theoretical, technical, statistical, sociopolitical and practical issues, thereby promoting the collaboration between academia and industry practitioners.

LIST OF PUBLICATIONS

Journal papers (Published and accepted)

1. Zhao Y., Yi W.*, Chan A.P.C., Wong D.P. (2018) Impacts of cooling intervention on the heat strain attenuation of construction workers. International Journal of Biometeorology, 62, 1625-1634.
2. Yi W., Zhao Y.*, Chan A.P.C., Lam E.W.M. (2017) Optimal cooling intervention for construction workers in a hot and humid environment, Building and Environment, 118, 91-100.
3. Yi W., Zhao Y.*, Chan A.P.C. (2017) Evaluation of the ventilation unit for personal cooling system (PCS), International Journal of Industrial Ergonomics, 58, 62-68.
4. Yi W., Zhao Y.*, Chan A.P.C. (2017) Evaluating the effectiveness of cooling vest in a hot and humid environment, Annals of Work Exposures and Health, 61(4):481-494.
5. Zhao Y., 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, Annals of Work Exposures and Health, 61(7): 883-901.
6. Zhao Y., Yi W.*, Chan A.P.C., Chan D.W.M. (2017). Comparison of heat strain recovery in different anti-heat stress clothing ensembles after work to exhaustion. Journal of Thermal Biology, 69: 311-318.

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CHAPTER 1 INTRODUCTION

1.1 INTRODUCTION

This chapter sets the background, states the research problem, clarifies the aim and objectives, provides the significance and value of the present study, and outlines the research approaches.

1.2 RESEARCH BACKGROUND

1.2.1 Construction safety and health

In most industrialised countries, construction is one of the most significant industries in terms of its contribution to GDP (Lingard and Rowlinson, 2005). The construction industry is labour intensive and recognised as a high hazard industry. This industry has approximately 7% of the world's work force but accounts for 30%–40% of casualties (Sunindijo and Zou, 2012). Construction workers commonly suffer from a high frequency of construction site accidents and injuries, such as falling from high heights or scaffolding; getting hit by a vehicle; getting caught in-between objects or materials; getting electrocuted and having illnesses due to their exposure to dusts, fibers, chemicals, vibration, radiation, noise and temperature extremes (Reese and Eidson, 2006). Academics and practitioners should take initiatives to promote occupational safety and health policies as well as practices in the construction industry. Since the past decades, construction management research has witnessed a growing concern over the issue of safety management system, safety culture and accident prevention (Zhou et al., 2015). In comparison with safety and accident research, the health and well-being of construction workers received less attention from researchers and practitioners (Lingard and Rowlinson, 2005). The management of occupational hygiene in construction is more challenging than in other industries given that the construction industry has temporary worksites, diffused control mechanisms and a complex mix of different activities and trades (Lingard and Rowlinson, 2005). Given the high frequency of occupational health hazards and illnesses in the construction industry, it remained a priority area for research and interventions (Hoonakkera et al., 2005).

1.2.2 Occupational heat stress

Heat stress refers to the *"net heat load to which a worker may be exposed from the combined contributions of metabolic cost of work, environmental factors and clothing requirements"* (ACGIH, 2011). It is dependent on four meteorological parameters, namely, ambient temperature, relative humidity, air velocity and solar radiation, combined with metabolic heat and clothing effect (Chan et al., 2012c; Kjellstrom et al., 2009; Parsons, 2014). Environmental heat load combined with physical work may induce heat stress above the compensable level, which results in productivity loss and increased risk of heat-related incidents, as indicated by the excessively elevated body temperature and cardiovascular strain (Cheung et al., 2000). The risk of heat stress can be further increased by personal protective equipment (PPE), such as a protective ensemble, work uniforms, goggles, helmets and gloves, given that the impermeable nature of PPE can severely impede evaporative heat loss through sweating. Heat strain denotes the physiological and/or psychological consequences of heat stress (Sawka et al., 2003). Body heat strain includes an increase in core temperature, heart rate, and sweat rate

(Parsons, 2014). Fainting, heat exhaustion, or even death from heat stroke occurs when heat strain is not effectively controlled. Heat-induced confusion, irritability and discomfort inhibit workers from concentrating on tasks and from observing safety procedures (Chan and Yi, 2016). Operations that involve high environmental heat, physically demanding activities, or impermeable protective clothing have a high potential for inducing heat stress among exposed workers. Such conditions can be experienced in military and civilian missions and operations, either outdoors or indoors, such as firefighting, mining, steelmaking, food canneries and hazmat operations (Chan and Yi, 2016). When performing outdoor tasks, employees will be directly exposed to sunlight and can easily get heat exhaustion. These are common conditions faced in construction, agriculture and outdoor horticulture and cleaning.

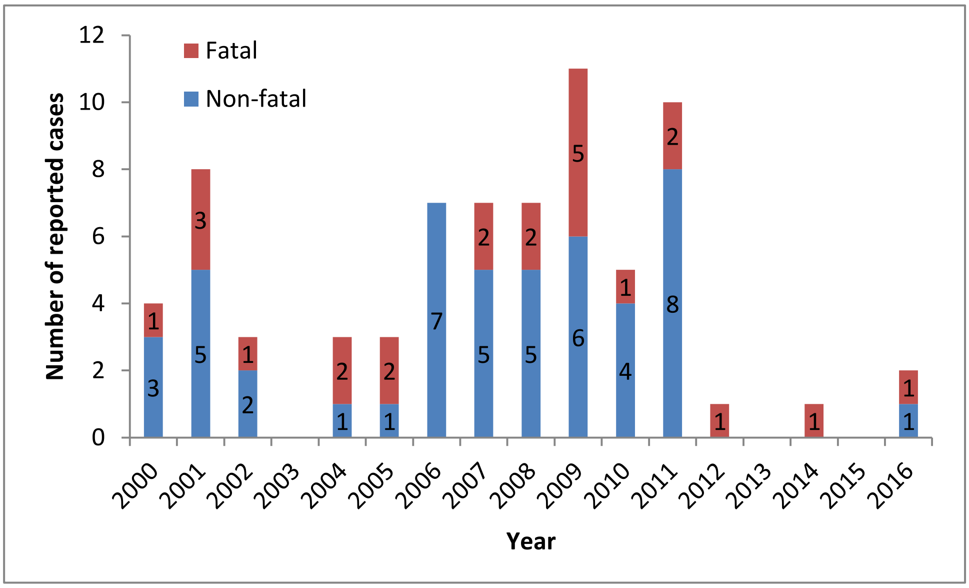
To evaluate heat stress, a series of indices considering the characteristic of the environment, metabolic rate and/or clothing effect have been developed. Heat stress monitor is set up near the workplace to collect microclimatological parameters, including dry bulb temperature, wet bulb temperature, globe temperature, wind speed, and relative humidity (Chan et al., 2012d; Miller and Bates, 2007b; Rowlinson and Jia, 2014). The Wet Bulb Globe Temperature (WGBT) index is a combination of these meteorological parameters. WBGT is the most convenient on-site measurement of thermal stress and can be easily interpreted by a layman (Parsons, 2006). WBGT-based thresholds were established, e.g. the most widely used Reference Value by ISO 7243 (1989) and Threshold Limit Value (TLV) by ACGIH (2013). The WBGT is common and convenient to use in a range of work settings. However, limitations in using this environmental index to assess thermal stress remain debatable (Miller and Bates, 2007b). Work intensity, clothing factor and personal conditions, including body fat ratio, smoking and drinking habit, acclimatisation and hydration status should be further considered (Chan et al., 2012a; Miller and Bates, 2007b; Montazer et al., 2013). In addition to measuring the microclimate (e.g. WBGT) in which the human subjects worked, certain studies simultaneously monitored the physiological heat strains of individuals (Chan et al., 2012c; Chan et al., 2012d; Miller and Bates, 2007b; Rowlinson and Jia, 2014). Core temperature and heart rate were usually measured for signs of heat strain in thermal work environments (Moran et al., 2002).

1.2.3 Heat stress in construction

The construction industry is vulnerable to heat stress given that most physically demanding work is performed outdoors on a floor/roof that is directly exposed to sunlight or in confined places that lacks ventilation. According to a recent survey on occupational heat-related fatalities among US industries, the construction industry has an average yearly heat-related illness deaths of 12 that accounts for the highest percentage (36.7%) of all industry sector heat-related illness deaths (Gubernot et al., 2015). In Japan, the most frequent type of work at the onset of heat stroke was construction (Horie, 2013). In Japan's construction industry, the largest number of fatalities by month in a year occurs in summer, specifically between June and October (OSH Statistics in Japan). The hot weather contributes to the increased rates of accidents and injuries in construction. During summer seasons, worksites, especially in tropical and subtropical areas, experience environmental heat load (combined with high air temperature temperatures, relative humidity and/or solar radiation). Construction workers in tropical and subtropical areas are exposed to a high risk of heat stress.

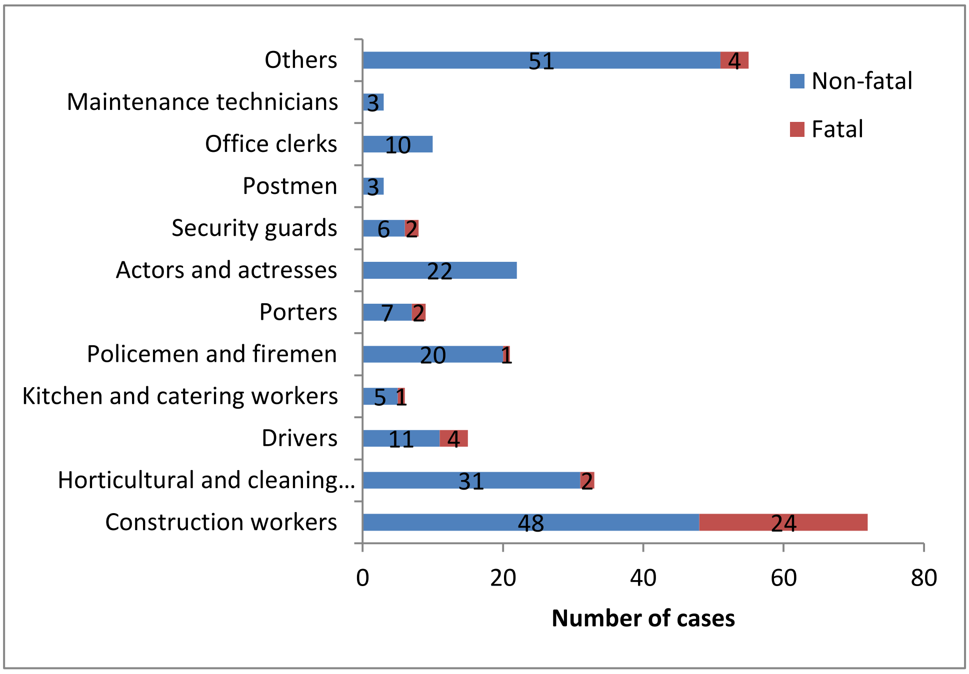
Hong Kong (22°18N, 114°10E), which is located on China's south coast, has a hot and humid subtropical climate in summer. On August 2015, the recorded highest temperature in Hong Kong was up to 36.3 ℃ (Hong Kong Observatory, 2015). Environmental conditions in Hong Kong put individuals at a high risk of heat stress. The construction industry has been recognised as a high-risk industry, having the highest accident and fatality rates among industry sectors over the past decades in Hong Kong (OSH Statistics Bulletin, 2016). During the summer season in Hong Kong, construction workers (including outdoor and indoor workers) are more vulnerable to heat stress than other occupations, as shown by the number of heat-related incidents in construction (Figure 1.1) and the percentage distribution of heat-related incidents across occupations (Figure 1.2).

Figure 1.1 Heat-related incidents in the construction industry in Hong Kong



Source: WiseNews Database. Search methods: Keywords for "construction sites/workers and heat stroke" (in Chinese), Region: Hong Kong (http://libwisenews.wisers.net/wisenews/index.do?new-login=true). A total of 72 cases in the construction industry between 2000 and 2016 were obtained.

Figure 1.2 Heat-related incidents distributed by industries, from 2000 to 2016



Source: WiseNews Database. Search methods: Keywords for "heat stroke" (in Chinese), Region: Hong Kong (http://libwisenews.wisers.net/wisenews/index.do?new-login=true). A total of 257 cases between 2000 and 2016 were obtained.

1.2.4 Precautionary measures for heat stress in construction

Heat stress incidents in the construction industry have attracted the attention of the government, statutory bodies and concerned industries, prompting them to investigate safety and health problems related to working in hot weather conditions (Chan et al., 2016c; Yi and

Chan, 2014a). In most cases, heat stress can be avoided through improving the efficiency of the body's cooling mechanisms (e.g. sweating efficiency) or reducing the level of heat exposure. A series of guidelines and practice notes, including engineering and administrative for controlling occupational heat stress (e.g. appropriate work arrangements, shelters at work or rest places to reduce radiant heat gain, ventilation in indoor working environments, air-conditioned rest rooms, provision of drinking water or sports drinks and heat acclimatisation programs), have been proposed (Department of Health, 2010; HSE, UK, 2011; US Department of Labour, 2010).

1.2.4.1 Administrative control

Administrative control relies on information, instruction, training, shift designs, procedures and enforcement (NIOSH, 2009). This control includes establishing procedures for the acclimatisation of workers; arranging intermittent recovery/rest periods in-between heat exposures; allowing individuals to control over work, such as self-pacing and extra breaks if requested; providing adequate cool and fresh drinking water; training workers and supervisors to recognise early symptoms of heat disorders and seek timely medical help; and increasing the workforce to allow workers to operate at a low metabolic rate (work intensity) (OSHA, 1999).

Acclimatisation refers to the body's physiological adaption to heat. Acclimatised individuals are more tolerant to heat strains (ACGIH, 2009). Acclimatisation can be achieved through a graded exposure to heat over a period of 3–7 days (Rowlinson et al., 2014). An acclimatisation program should be offered on the basis of individual profiles. Workers' initial level of physical fitness and the total heat stress experienced can influence the level of acclimatisation they achieve. NIOSH (1986) has specified acclimatisation schedules for new workers and workers who had previous experience with the job. Acclimatisation declines to complete loss after workers are not exposed to the same level of heat stress for one or two weeks (ACGIH, 2009). Compared with other industries, the construction industry is characterised as high mobility.

Hydration status affects one's ability to tolerate heat stress. Hypohydration increases thermal and cardiovascular strain and decreases work tolerance time in a hot environment (Sawka and Pandolf, 1990). Regular drinking can maintain adequate levels of hydration and prevent hypohydration during work. Bates et al. (2010) and Miller and Bates (2007a) examined the level of hydration of construction workers in Abu Dhabi and Australia. They suggested to maintain adequate hydration status under hot conditions. As for certain tasks that must be conducted immediately and continuously, such as concreting, workers are unable to take a drink during work. Proper hydration prior to the work shift is, hence, imperative (Bates and Schneider, 2008).

Work arrangements are documented in regulations and guidelines (US Department of Labour, 2011; CIC Hong Kong, 2013). For instance, work activities should be rescheduled to cool places or periods in the daytime, and rotation or regular breaks should be arranged to reduce workers' exposure to the thermal environment. Intermittent rest periods between bouts of work can be effective in reducing the risk of heat stress (Yi and Chan, 2014b). ACGIH (2013) and ISO (7243, 1989) established the threshold limit value (TLV) of WBGT for work at a range of intensities (light, moderate, heavy and very heavy); workers are subject to a rest when the workplace WBGT exceeds the threshold. Based on required sweat rate, thermal work limit (TWL) was developed (Brake, 2002; Brake and Bates, 2002). It took into account of the effect of air movement which was ignored in WBGT. Chan et al. (2012b) examined a TWL heat-stress model for rebar workers to predict the maximum work duration under different thermal loads. Rowlinson and Jia (2014) applied the predicted heat strain model [ISO 7933 (2004)] to produce duration-based thresholds (e.g. maximal allowable exposure time) in a hot environment. Concerning humans' physiological responses, Moran et al. (1998) developed the physiological strain index (PSI), which was based on core temperature and heart rate records to estimate thermal strain during exercise. Chan et al. (2012c, 2012d) used PSI as a yardstick to determine the optimal recovery duration after a period of work to exhaustion for rebar workers. The findings from Chan et al. (2012c, 2012d) have been adopted in the Hong Kong Construction Industry Council (CIC) Guidelines on "Site Safety Measures for Working in Hot Weather" released in April 2013. An additional 15-minute rest period was introduced for construction workers during hot summer season (from May to September every year).

1.2.4.2 Engineering control

Engineering control relates to a physical barrier, safeguard, or device (NIOSH, 2016). Typical engineering controls in construction include ventilation, fans, air conditioning and shelters

(Jia et al., 2016). The provision or availability of those engineering controls varies across the sizes of construction projects (Rowlinson and Jia, 2015).

Ventilation is used to introduce the outside air into a confined space. Ventilation works well when the outside climate is relatively cool. Certain construction works are performed in a confined space, such as painting, decorating, MEP (mechanical electrical plumbing) and HAVC (heat, air ventilation and cooling) fitting. Diluting hot air with outside cool air by ventilation system will help in achieving desired psychrometric (dehumidification and thermal comfort) conditions in a confined space (Vedavarz et al., 2007).

Fanning delivered at the work site increases air velocity, promoting convective and evaporative heat transfer from the body to the environment (Selkirk et al., 2004). Industrial fans can be localised nearby the worksite to provide continuous cooling effect during work. This method cannot be used when the air temperature is higher than 35 ℃ given that the high speed hot air will irritate workers' skin (Wolfe, 2003). Improvements made on fan cooling involve using ice water in the fan's container. Meanwhile, using multiple fans with ice water in a confined space can result in additional rises in ambient vapour pressure, which will compromise the evaporation heat dissipation (Selkirk et al., 2004).

Gaining access to air conditioning could significantly reduce excess heat-related illnesses (Semenza et al., 1996). However, air conditioning is impractical for the outdoor work. Air-conditioning rest rooms can be built nearby the construction sites, which will allow workers to take a rest and recovery from heat stress. This method is probably the most effective one in cooling down body temperature but costs too much to install and operate.

Temporary shelters are widely used at work or rest places of construction sites. They shield outdoor workers from radiant heat exposures. Although the heat-relief benefit of shelters is inferior to that of air conditioning rooms, the build-up of shelters at all sites can be considerably cheap and easy.

1.2.4.3 Personal protective clothes and equipment

When administrative and engineering controls are infeasible or ineffective, personal protective clothes could be used. Anti-heat stress clothing ensembles are used to protect workers from heat-related injuries and hazards. Chan et al. (2016a, 2016b) developed a work uniform with superior air permeability and excellent moisture management capacity for construction workers and reported its effectiveness in alleviating heat strains through laboratory experiments and field wear trials. The summer work uniform is viewed as passive cooling clothing, which relies on natural air movement between the body surface and the clothing to facilitate evaporative heat dissipation (Selkirk et al., 2004). Whereas, cooling garment utilises cooling sources (e.g. cooling packs and ventilation fans) to increase conductive, convective and evaporative heat dissipation (Zhao et al., 2017a). OSHA recommended the use of auxiliary body cooling garments, such as ice vest, and water- and air- cooled garments to prevent from heat stress. The Hong Kong Occupational Safety and Health Council (OSHC), in collaboration with the local government, launched the “Cooling

Vest Promotion Pilot Scheme” in 2013 and tested the effectiveness of commercially available cooling vests in several outdoor and indoor industries (including the construction industry). Questionnaire surveys were conducted to compare the acceptability and practicality of several commercially available cooling vests (Chan et al., 2013). The shortcomings of the commercially available cooling vests were identified (Chan et al., 2016c). The development of a tailor-made personal cooling system (PCS) for the construction industry is inconsiderably explored.

1.3 RESEARCH PROBLEM

Construction workers are exposed to a high risk of heat stress. To help alleviate body heat strain and ensure work performance, cooling intervention is proposed for the construction industry in the present study. The design of a proper cooling intervention in construction should consider the practical conditions of the workplaces. Fanning enhanced convective and evaporative heat dissipation from the body through increasing the air flow of microenvironments (Barwood et al., 2009a). Industries blowers should be connected to a heavy motor and supplied by constant electricity to ensure sufficient air ventilation around the body and maintain steady air velocity (Hostler et al., 2010). However, the installation of blowers at construction sites is occasionally impossible because of elevated platform, limited space, uneven ground and lack of electricity. A large reservoir with water at a low temperature (10–20 ℃) is required for cold water immersion, which generally immersed extremities (e.g. forearm and/or hand immersion) to reduce body temperatures (McEntire et al., 2013). However, the cold water immersion of the large groups of workers is usually problematic given that cold water delivery and storage may be impractical in construction sites. Cold water ingestion is a convenient and cheap cooling method that is particularly useful when electrical equipment is unavailable or in cases of difficult transportation (Jones et al., 2012). However, limited evidence indicated the effectiveness of cold water drink in reducing heat strains (warm water drink is generally used as the control condition to maintain a similar hydration level) (Bongers et al., 2014; Jones et al., 2012). PCS, in the form of cooling garment, was used to remove body heat from the wearer (Chan et al., 2017). PCS is portable and wearable and does not require external power source or pre-installation. Furthermore, meta-analysis studies corroborated that the PCS had a moderate-to-large cooling effect, which was comparable with cold water immersion and fanning (Bongers et al., 2014; Chan et al., 2015). Therefore, this garment type has a high potential to be well accepted and applied in the construction industry.

PCSs have been applied in various occupations, particularly for athletes (Luomala et al., 2012), firefighters (Bennett et al., 1995; Hostler et al., 2010; Kenny et al., 2011), soldiers (DeGroot et al., 2013) and hazmat personnel (Carter et al., 2007; House et al., 2003).

PCSs provide microclimate cooling around the body and can be used continuously during the entire work period. The three types of PCSs have been examined in previous studies, including air cooling garments (ACGs), liquid cooling garments (LCGs) and phase change garments (PCGs) (Mokhtari Yazdi and Sheikhzadeh, 2014). Air and liquid cooling garments are connected to external cooling devices and circulate cooled air or liquid around human body (Chan et al., 2016c). PCGs use the precooled phase change materials (PCMs), e.g. inorganic salt, ice and paraffin wax, to absorb heat and act as a heat sink (Mondal, 2008). PCM, classified as latent heat storage material, can absorb and release heat at a roughly constant temperature (i.e. melting temperature) as it goes through solid–liquid transitions (Shim et al., 2001). When the ambient temperature is higher than the melting temperature, PCM absorbs heat energy as it goes from a solid state to a liquid state, producing a temporary cooling effect (Shim et al., 2001). After reviewing the characteristics of different PCSs, potential PCS for the construction industry was selected as reference prototype for the engineer and design of the cooling sources and fabrics in the new PCS.

Although existing studies and meta-analyses have designed and evaluated the effectiveness and applicability of PCSs for athletes, firefighters, soldiers and hazmat personnel, little attention has been paid to construction workers who are susceptible to heat stress (Chinevere et al., 2008; Kenny et al., 2011; McLellan et al., 1999; Muir et al., 1999; Song and Wang, 2016).

1.4 RESEARCH AIM AND OBJECTIVES

This research aims to develop a cooling intervention with a tailor-made PCS to protect construction workers from heat-related injuries while working in a thermal environment. A tailor-made PCS is engineered and designed for the construction industry. Then, this research attempts to examine the effectiveness and applicability of the newly designed PCS by a series of laboratory experiments and field wear trials. Hence, the objectives of this research are as follows.

Objective 1: To review different PCSs for combating occupational heat stress and improving work performance.

Objective 2: To engineer and design a tailor-made PCS for the construction industry.

Objective 3: To assess the cooling capability of the newly developed PCS on a sweating thermal manikin.

Objective 4: To evaluate the effectiveness of the cooling intervention with the newly developed PCS in reducing heat stress by human wear trials in the laboratory.

Objective 5: To examine the applicability of the cooling intervention with the newly developed PCS by human wear trials in real work settings.

As depicted in Figure 1.3, the study begins by reviewing the literature on current PCSs designed to combat occupational heat stress (Objective 1). After gaining an understanding of different PCSs, a tailor-made PCS was engineered and designed (Objective 2). In order to evaluate the effectiveness and applicability of the newly designed PCS, sweating thermal manikin (Objective 3), wear trials in the laboratory (Objective 4) and wear trials in the field

(Objective 5) were conducted in sequence in accordance with a three-level evaluation system (Figure 1.4). In this “triangle” evaluation system in Figure 1.4, the wide base represents a number of simple tests using a heat transfer apparatus (e.g. sweating manikin) (Parsons, 2014). Controlled wear tests on human subjects in the climatic chamber measured the physiological variables and subjective perceptual responses. Human subjects were asked to wear PCSs and perform physical work under controlled environment conditions. The triangle’s narrow peak refers to field wear trials. Construction workers were asked to wear PCSs under daily working conditions, including a wide range of work activities and climates. The field wear trials provide realistic and comprehensive evaluation; however, they require large resources and are difficult to control. The evaluation of PCSs from a lower level to a higher level can reduce cost and avoid unnecessary testing (Parsons, 2014).

Figure 1.3 Relationships between objectives

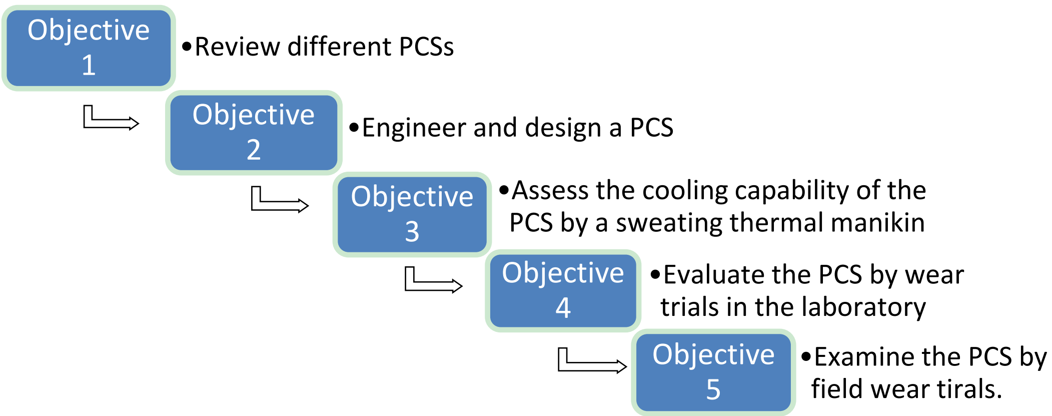
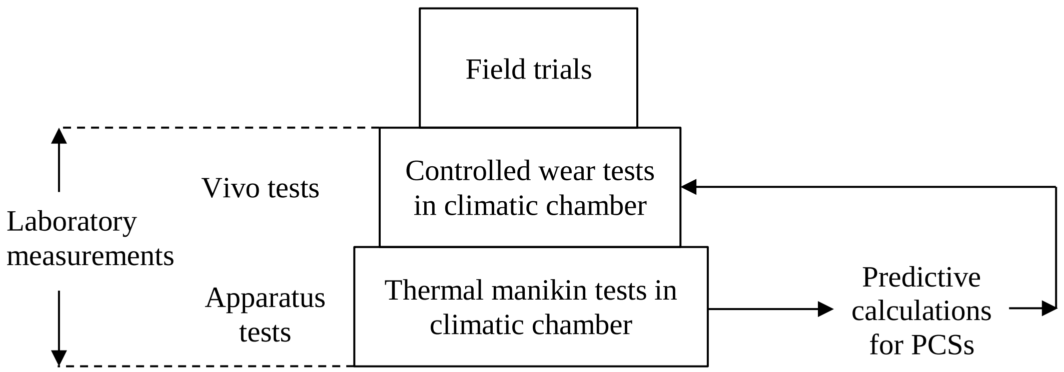


Figure 1.4 A three-level evaluation system of PCS performance



Adapted from Umbach (1988)

1.5 SIGNIFICANCE AND VALUE

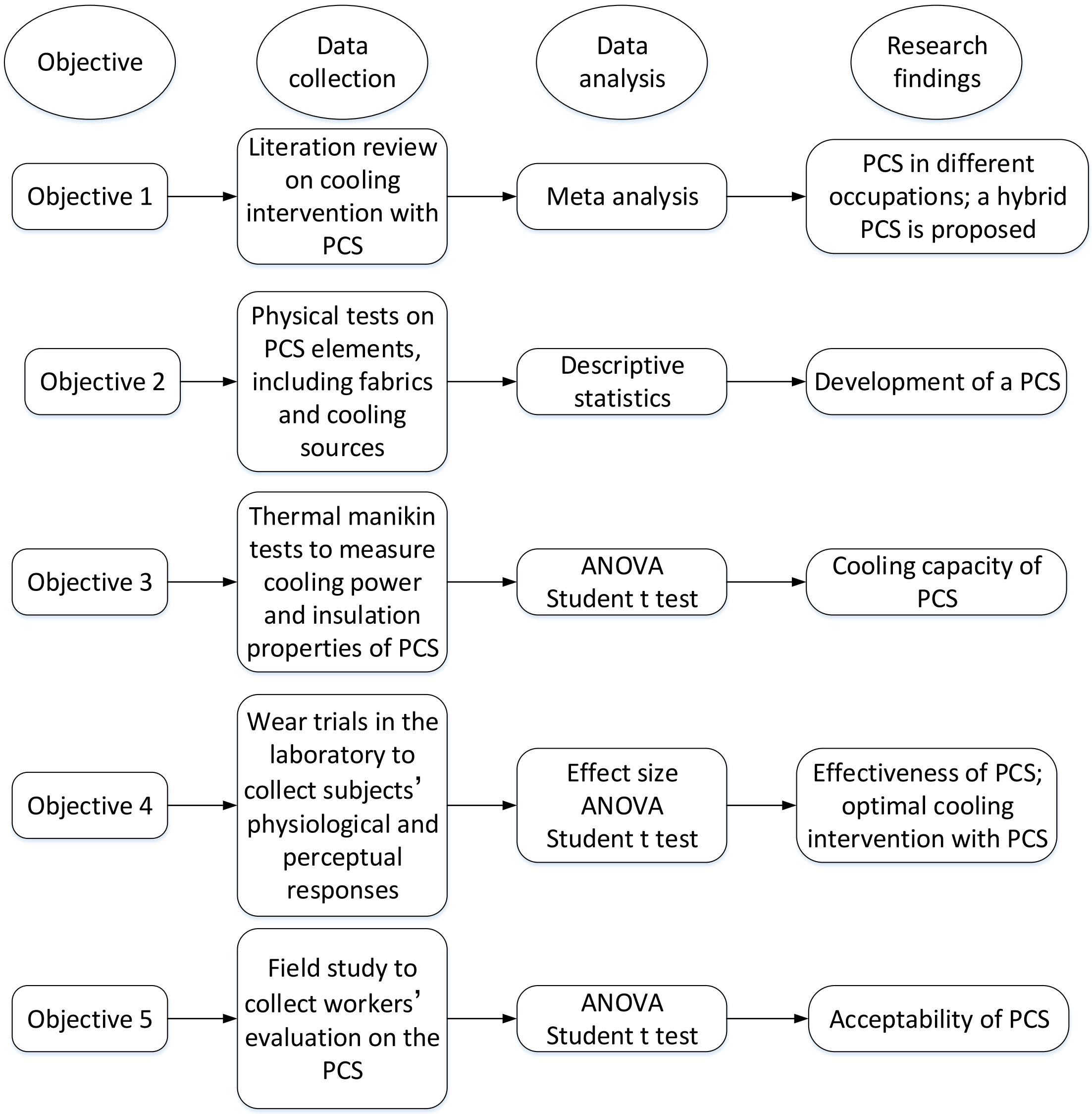
Construction work is tough and physically demanding. Construction workers should perform outdoor work and sometimes in a confined space with poor ventilation. Working under these settings during summer exposes them to a high risk of heat-induced incidents, such as heat stroke, which has already led to several injuries and deaths (Gubernot et al., 2015; Rowlinson et al., 2014). PCS is used to alleviate body heat strains and has been widely used in sports, emergency and military settings. However, its application in the construction industry is still in its infancy, and its effects are yet to be evaluated. The overall objective is to develop a cooling intervention with the newly developed PCS that will reduce heat stress on construction workers. This will be of tremendous value in improving labour productivity and safeguarding construction workers' safety and health. Although this study applies specifically to the construction industry, the same methodology could be extended to other occupations which require routine exposure to extreme temperature conditions, such as horticulture and outdoor cleaning, metal refining, forestry, agricultural, kitchen and catering, and airport apron and ramp handling, after considering their unique job features and characteristics.

1.6 RESEARCH APPROACH

This study involves major research stages, namely, literature review, PCS engineering and design, cooling power measurements and performance assessment by human wear trials under laboratory and field settings.

The research project commenced in January 2014. Followed by comprehensive literature review, fabric selection, cooling sources engineering and clothing design, a new pattern of the PCS was devised in the middle of 2015. Ten sets of PCSs were manufactured by the end of June 2015. From July to September 2015, sweating thermal manikin tests were conducted in a climatic chamber to compare the cooling power of the PCSs. In early 2016, human wear trials were conducted in a climatic chamber to examine the effectiveness of the PCS in reducing body heat strains in a hot and humid environment. An optimal cooling intervention with the newly designed PCS was, thus, determined through the wear tests in the laboratory. Design improvements on the PCS were made according to the results of the manikin tests and the human wear trials in the laboratory. Subsequently, 100 sets of PCSs were manufactured by the end of June 2016. Field studies were conducted on construction sites to evaluate the applicability of the PCS in the summer of 2016. Figure 1.5 illustrates the overall flow chart of this study.

Figure 1.5 Research flow of the research



CHAPTER 1 INTRODUCTION provides an introduction of the research study. It covers the background, research motivations, research aim and objectives, and the scope and significance of the research. The research approach and the structure of the thesis are also outlined.

CHAPTER 2 LITERATURE REVIEW presents a systematic literature review on PCSs that are designed to combat occupational heat stress. The effectiveness of cooling intervention with PCSs is compared quantitatively by meta-analysis. Then, a PCS with hybrid and portable cooling sources is proposed for the Hong Kong construction industry.

CHAPTER 3 RESEARCH METHODOLOGY describes and explains the research design and research strategies formulated to achieve the five objectives of this study. A sequential mixed-methods research methodology that includes qualitative and quantitative research strategies is adopted.

CHAPTERS 4 DEVELOPMENT OF PCS engineers and designs a tailor-made PCS in six stages as follows: making a request, exploring the design situation, perceiving the problem structure, selecting the fabric, engineering of the cooling source, and developing the prototype.

CHAPTER 5 COOLING CAPACITY OF PCS assesses the cooling capability of the PCS on a sweating thermal manikin. Sweating thermal manikin tests are conducted to determine and compare the cooling power of the newly developed PCS with the commercially available one.

CHAPTER 6 OPTIMAL COOLING INTERVENTION WITH PCS examines the effectiveness of the newly developed PCS by human wear trials in the laboratory. An optimal cooling intervention is, thus, determined in the experiments. The experiments are conducted in a climatic chamber, which simulates the hot and humid environment during summer in Hong Kong.

CHAPTER 7 APPLICABILITY OF PCS examines the applicability of the cooling intervention with the newly developed PCS by human wear trials in real work settings.

CHAPTER 8 CONCLUSIONS AND RECOMMENDATIONS provides an overview of the research findings and highlights the contributions, significance and limitations of this study.

1.7 SUMMARY

Heat stress impairs the health and well-being of construction workers as shown by the alarming heat-induced casualties in the construction industry. Prolonged physically demanding activities in a hot ambient environment, e.g. under direct sunlight or in a confined place that lacks ventilation, expose workers to a high risk of heat stress. The local government has set a series of guidelines and notes for preventing heat stress. Among these precautionary measures, PCS gained an increasing concern. PCS has been widely used in sports, firefighting, military, and hazmat operations. However, its application in construction is still in its infancy, and its effectiveness and applicability are yet to be evaluated. This study attempts to present an overall research framework for conducting a cooling intervention with the PCS that will be verified through a case study—the role of PCS—that is expected to provide a fresh insight into cooling intervention studies in the construction industry.

The objectives of this study include reviewing current PCSs for combating occupational heat stress, developing a tailor-made PCS for the construction industry, assessing the cooling capability of the newly developed PCS, evaluating the effectiveness of the cooling intervention with the newly developed PCS in reducing heat stress and examining the applicability of the cooling intervention with the newly developed PCS in real work settings.

CHAPTER 2 LITERATURE REVIEW[1]

2.1 INTRODUCTION

Literature review systematically identified the literature related to cooling intervention with personal cooling system (PCS) for combating occupational heat stress. Meta-analysis was conducted to quantitatively synthesise findings from peer-reviewed randomised controlled trials (RCTs) that deal with the effects of PCSs on work performance.

2.2 PERSONAL COOLING SYSTEM (PCS)

PCS is a form-fitting garment used to remove body heat from the wearer (Chan et al., 2017). PCS is portable and wearable and does not require external power source or pre-installation. PCSs provide microclimate cooling around the body and can be used continuously during the entire work period. PCSs have been applied in various occupations, particularly for athletes (Luomala et al., 2012), firefighters (Bennett et al., 1995; Hostler et al., 2010; Kenny et al., 2011), soldiers (DeGroot et al., 2013) and hazmat personnel (Carter et al., 2007; House et al., 2003). The three basic types of PCSs are air cooling garments (ACGs), liquid cooling garments (LCGs) and phase change garments (PCGs) (Mokhtari Yazdi and Sheikhzadeh, 2014). Hybrid cooling garments (HCGs) combine two or more of the aforementioned cooling techniques (Chan et al., 2015). PCG combined with air ventilation and LCG combined with

[1] Presented in a paper under review: Yi W., Zhao Y.*, Chan A.P.C. (2017). Continuous and intermittent cooling for improving work tolerance in civilian and military sectors: A systematic review and meta-analysis.

air ventilation are two common types of HCGs (Kim et al., 2011; Lu et al., 2015; Song et al., 2016). The characteristics of different PCSs are shown in Table 2.1.

Table 2.1 Characteristics of different PCSs

PCS	Components	Merits	Drawbacks	Application
ACG (cold air)	Two-layer garment, an external compressor and cooling agent	High cooling power and long cooling duration based on the external compressor	Restricted and tethered system	Suitable for conditions in which workers do not move a lot, such as mounted combat (on a vehicle) and hazmat operations
ACG (ambient air)	Two-layer garment, ventilation fans embedded in the garment	Long cooling duration based on the battery-powered fans	Limited cooling power when the ambient environment is hot and humid	Suitable for moderate thermal environment
LCG	Two-layer garment, tubes embedded in the garment, a battery-powered pump, a tank containing a liquid coolant and a heat exchanger (e.g., water reservoir)	High cooling power and long cooling duration based on the external heat exchanger	Restricted and tethered system	Hazmat operations, firefighting, piloting in a small and hot cockpit, and bicycling (a heat exchanger is compacted and located on the bicycle)

PCS	Components	Merits	Drawbacks	Application
PCG	Two-layer garment, cooling packs inserted in the garment	Portable and easy system	Short cooling duration	Suitable for outdoor work, sports, firefighting, and military activities
HCG	LCG + air ventilation	High cooling power and long cooling duration	Hybrid cooling sources should be well engineered and designed to acquire a higher cooling power than a single cooling source, restricted and tethered system	Suitable for conditions in which workers do not move a lot
	PCG + air ventilation	Long cooling duration, portable and easy system	Hybrid cooling sources should be well engineered and designed to acquire a higher cooling power than a single cooling source	Suitable for outdoor work

ACG blows cold, dry air surrounding the body, thereby improving convective heat dissipation and enhancing evaporation of sweat secreted on the skin surface. ACG usually has two layers, an inner layer cloth characterised as air permeable and an outer layer cloth characterised as impermeable. Thus, forced air circulates between two layers and onto the skin surface through the inner layer, whilst the outer layer prevents air from escaping to the environment. The cold, dry air is supplied by an external compressor and cooling agent (heat exchanger) connected to the garment. The cooling power of ACG can be influenced by air flow rate and inlet temperature (McLellan, 2007). The higher the air flow rate and the lower inlet temperature, the higher the cooling power. When the external compressor is removed, ACG works by directly ventilating ambient air around the body. A low air temperature and relative humidity in the local environment can improve the effectiveness of ACG. ACG (supplied with cold air) has tethered system and is suitable for conditions in which workers do not move a lot, such as mounted combat (on a vehicle) and some hazmat operations (Bishop et al., 1991; McLellan et al., 1999; Pimental et al., 1987; Vallerand et al., 1991). ACG (supplied with ambient air) is suitable for moderate thermal environments. Chinevere et al. (2008) demonstrated the effectiveness of ACG in reducing heat stress for marching soldiers under 30 ℃ air temperature and 50% relative humidity.

LCG operates by circulating cooled water through tubes embedded in the garment. LCG consists of a three-layer system with tubes sandwiched between two fabric layers (Cao et al., 2006). The distribution, diameter, length and wall thickness of the tubing properties in LCG are optimised to enhance system efficiency (Burton, 1966; Shvartz, 1972; Shvartz et al., 1974). A battery-powered pump, a tank containing a liquid coolant and a heat exchanger (e.g., water reservoir) are required for supplying continuous flow of temperature-controlled liquid to LCG (Burton and Collier, 1964; Shvartz, 1970). The contact pressure and uniformity of LCG on the body influence the efficiency of conductive heat transfer (London, 1969; Nunneley, 1970). Liquid flow rate and inlet temperature are two other factors that affect the heat extraction (Burton, 1969). LCG restricts body movements because of external connections with a heat exchanger. LCG is usually used for hazmat operations, firefighting, piloting in a small and hot cockpit, and bicycling (a heat exchanger is compacted and located on the bicycle) (Bishop et al., 1991; Cadarette et al., 2003; Caldwell et al., 2012; Vallerand et al., 1991).

PCG use phase change materials (PCMs) (e.g. inorganic salt, ice and paraffin wax) to absorb heat from the body. PCM is classified as latent heat storage material, which can absorb and release heat at a roughly constant temperature (i.e. melting temperature) as it goes through solid–liquid transitions (Shim et al., 2001). When the ambient temperature is higher than the melting temperature, PCM absorbs heat energy as it goes from a solid state to a liquid state, producing a temporary cooling effect (Shim et al., 2001). The PCM packs (average dimension: 5–15 cm) were inserted in the garment to enhance the conductive cooling effect. Many factors, including the temperature gradient between the PCM melting temperature and skin temperature, the covering area of PCM, the amount of PCM, and the PCM latent heat capacities, have an impact on the cooling efficiency of PCG (Gao et al., 2010, 2011; Reinertsen et al., 2008). PCG is portable and can be widely used for outdoor work, sports, firefighting, and military activities (Bennett et al., 1995; Luomala et al., 2012; Muir et al., 1999; Zhang et al., 2010). However, the cooling duration of PCG is always short based on the cooling effect provided by PCMs as they undergo solid–liquid transitions.

In recent years, HCG is developed based on two or more of the aforementioned cooling techniques (Chan et al., 2015). The design of HCG aims to combine the advantages of different cooling techniques, thereby improving cooling efficiency and thermal comfort (Kim et al., 2011; Lu et al., 2015; Song et al., 2016). A typical example is PCG combined with ventilation air (Lu et al., 2015). PCG is portable and has wide ranging applications (Mokhtari Yazdi and Sheikhzadeh, 2014). However, solid PCM packs in the clothing increase the clothing insulation, thereby impeding sweat evaporation and making the skin sticky and wet (Lu et al., 2015). When circulating air (by ventilation fans) is added to PCG, evaporative and convective heat dissipation is enhanced, thereby largely improving body wetness sensation. Research on the applications of HCG is limited (Chan et al., 2015). Selecting and combining cooling techniques is essential to develop a tailor-made HCG for a specific industry, and such a design should meet the requirements of ergonomics and high cooling efficiency.

Previous studies have designed and implemented cooling intervention with PCS for various occupations, including sports, firefighting, hazmat operations and military activities (Bennett et al., 1995; Carter et al., 2007; DeGroot et al., 2013; Hostler et al., 2010; House et al., 2003; Kenny et al., 2011; Luomala et al., 2012). The design of a cooling intervention considers the characteristics of occupations, the types of PCSs as well as intervened time and length.

Through a series of wear trial tests, the effectiveness of the cooling intervention was examined by comparing the results of the cooling group with those of the control group. Measurements for evaluation typically include core body temperature, heart rate, skin temperature, subjective ratings of perceived exertion and thermal sensation. Most studies used total work time (tolerance time) to assess the effectiveness of the cooling intervention with PCS on work performance. In this chapter, previous studies that examined cooling intervention with PCS were systematically reviewed and quantitatively analysed by meta-analysis.

2.3 METHODOLOGY

2.3.1 Search strategy and study identification

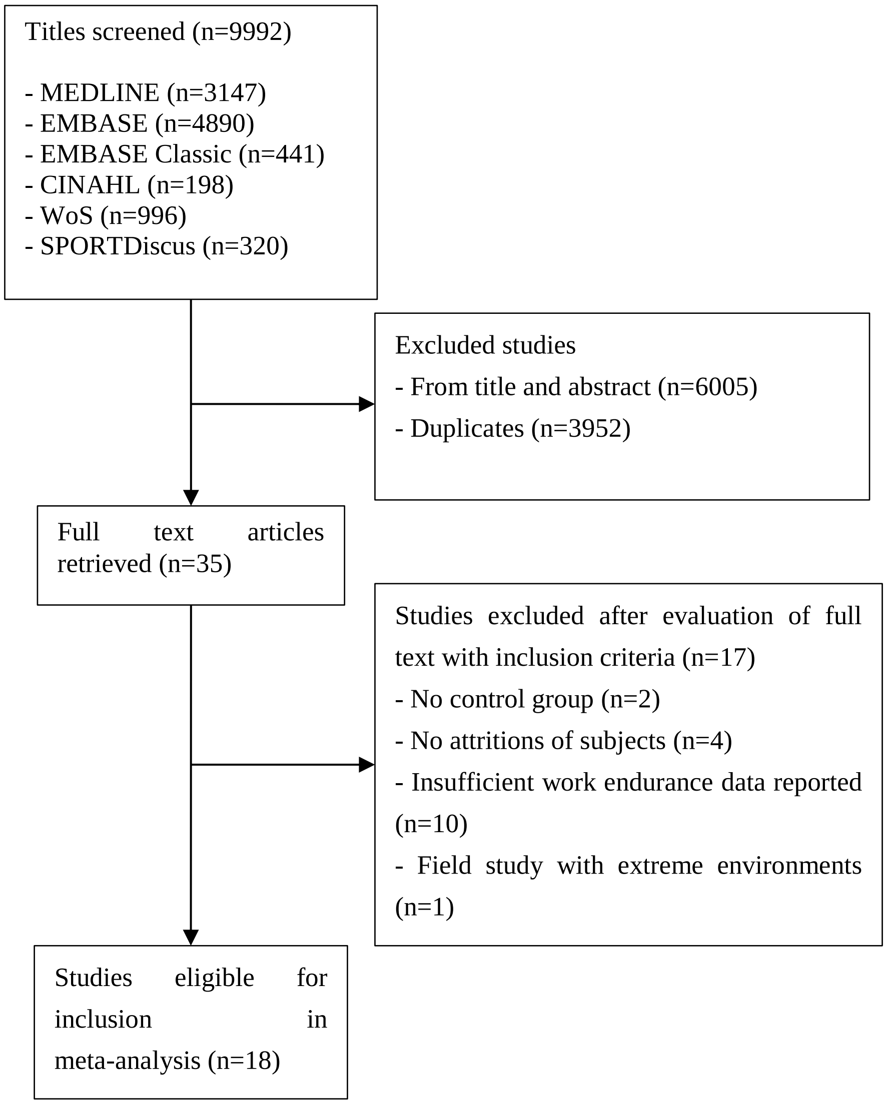
The following databases were searched: MEDLINE (Ovid Web, 1946 to 2016), EMBASE (Ovid Web, 1980 to 2016), EMBASE Classic (Ovid Web, 1947 to 1979), CINAHL (EBSCOhost, 1982 to 2016), Web of Science (1899 to 2016) and SPORTDiscus (EBSCOhost, 1830 to 2016). Keywords adopted in the search strategy and the search results are shown in Appendix 1 Table 1. The search keywords were used in varying combination by Boolean logic (AND) or (OR) and the results were further limited to English language. Review articles and reference lists were also retrieved to ensure relevant studies had been involved.

The main bodies of the selected articles were reviewed. Studies included in the quantitative analysis are those that met the following criteria: (i) studies that tested PCSs for different occupations, including construction, iron and steel manufacturing, mining, oil and gas well operations, glass factories, horticulture, cleaning, catering, agricultural activity, firefighting, hazmat operations, and military; (ii) PCSs was administered during whole heat exposure or during recovery stages (i.e. continuous and intermittent cooling); (iii) randomised crossover experimental design, that is, the existence of a control condition, and participants acting as their own controls; and (iv) studies that reported work tolerance parameters (e.g. time to exhaustion).

Reviews, case studies, textbooks, unpublished studies, non-full texts, non-peer reviewed publications, and articles not written in English were excluded in the meta-analysis. In addition, studies were excluded when they met one or more of the following criteria: (i) studies that used non-human subjects, such as animal subjects, thermal manikin, and skin model, and participants with pathological conditions that make them susceptibility to heat stress, such as multiple sclerosis (White et al., 2000) and spinal cord injury (Price, 2006); (ii) investigation of post-exercise cooling only for reducing heat strain, without following exercise performance test; and (iii) no attritions of subjects and all subjects succeeded in completing the trial.

Online article records were imported to EndNote X7 (Thomson Reuters, Philadelphia, PA, USA). In total, 9992 literature were gathered. After deleting some duplicates due to the cross-referenced literature, a total of 6005 literature were identified. Each title and abstract was assessed by two reviewers using an inclusion/exclusion criteria checklist. When information included in the title and abstract was insufficient to determine, the full text were reviewed. Any disagreements about the inclusion of a study were settled by a consensus meeting. Figure 2.1 shows a flow chart of our literature search and selection.

Figure 2.1 Flow chart of literature identification and study selection



2.3.2 Methodological quality assessment

Quality assessment of randomised controlled trials (RCTs) is a common step in a systematic review (Maher et al., 2003). Low-quality studies exhibit biased estimates of treatment effectiveness (Maher et al., 2003). Thus, Physiotherapy Evidence Database (PEDro) scale, which is a valid measure of the methodological quality of clinical trials, was introduced to assess methodological quality (de Morton, 2009). An additional criterion, namely, “sample size calculation”, which was recommended by a previous systematic review, was included in the quality assessment but did not contribute to the PEDro score. Studies were considered high-quality if PEDro scores were higher than 6 (Jones et al., 2012).

2.3.3 Statistical analysis and data synthesis

Standardised mean differences (SMDs) (with 95% CIs) were estimated by using Hedges’ (adjusted) g for continuous outcomes across all included studies for comparison between results. The standardised mean difference refers to the size of the intervention effect (difference in mean outcome between groups) in each study relative to variability (standard deviation of outcome among participants) observed in that study (Cochrane Handbook). The use of Hedge’s adjusted g can overcome the drawbacks of small sample sizes (Hedges, 1985). Hedges’ adjusted g is defined as

$$\text{adjusted g} = \frac{M_E - M_C}{SD_{pooled}}\left(1 - \frac{3}{4(n_E + n_C) - 9}\right) \tag{2.1}$$

where M_E and M_C are the experimental and control group sample mean, respectively. SD_{pooled} is the pooled standard deviation of the two groups,

$$SD_{pooled} = \sqrt{\frac{(n_E - 1)(SD_E)^2 + (n_C - 1)(SD_C)^2}{n_E + n_C - 2}} \tag{2.2}$$

and n_E and n_C are the experimental and control group sample sizes, respectively; SD_E and SD_C are the experimental and control group standard deviations, respectively. Data were pooled and synthesised using Cochrane Collaboration’s software RevMan for Windows version 5.3.4.

If the data provided by the original literature were inadequate (e.g. no standard deviations) such that effect size calculations could not be completed, emails were sent to the corresponding author of the study for the required data. The effect size was interpreted based on Cohen’s scale: ≥ 0.8 = large effect, 0.50 to 0.79 = moderate effect, 0.20 to 0.49 = small effect, 0 to 0.19 = negligible effect. Negative effects of cooling intervention were indicated by a minus sign. Heterogeneity was examined by using Higgins’ I^2 statistic with a significance level set at p-value < 0.10 (Cochran’s Q test), which estimates the percentage of variation among studies (Higgins and Thompson, 2002; Higgins et al., 2003). An I^2 value below 40%, between 40% and 75%, and above 75% suggests negligible heterogeneity, moderate heterogeneity and considerable heterogeneity respectively. The publication bias was assessed by Begg’s funnel plot asymmetry and Egger’s linear regression test, in which $p < 0.05$ was considered significant. The Begg’s method plots the effect size against sample size of all included studies. Egger’s test quantifies the bias by the funnel plot, which calculates the values of the effect sizes and their deviation, instead of ranks (Borenstein, 2005). Begg’s and Egger’s test were conducted in Stata version 12.

The physiological parameters, including core temperature (T_c), mean skin temperature ($\overline{T_{sk}}$), and heart rate (HR), were extracted from the included studies. The change rates of ΔT_c, $\Delta\overline{T_{sk}}$, and ΔHR were estimated by subtracting the initial value from the end-point value divided by the heat exposure duration for each included study. The change rates of T_c, $\overline{T_{sk}}$ and HR between the cooling and control condition were examined by student’s paired t-test. The differences in change rates of the physiological parameters between the control and cooling condition were calculated ($\Delta T_{c\_control}$ – $\Delta T_{c\_cooling}$, $\Delta\overline{T_{sk}}_{\_control}$ – $\Delta\overline{T_{sk}}_{\_cooling}$, $\Delta HR_{\_control}$ – $\Delta HR_{\_cooling}$). The exercise performance enhancement (EPE) was calculated by percentage change in exercise duration between the cooling and the control condition, i.e., (Duration$_{_cooling}$ – Duration$_{_control}$)/Duration$_{_control}$ × 100%. Correlations between the differences in change rates of physiological parameters and the EPE were estimated, and the level of significance was set at $p < 0.05$.

2.4 OVERVIEW OF STUDIES

A total of 18 articles that met the inclusion criteria were identified for the statistical analysis. Several studies that examined various cooling interventions were involved more than once, thus resulting in 27 pairs of comparison between cooling and control condition. A total of 305 subjects were included in these studies. The average sample size of participants was 9, ranging from 4 to 14. Investigation protocol for each involved study is shown in Appendix 1 Table 2. 13 studies adopted work–rest pattern in their exercise protocol, while 5 studies designed continuous treadmill exercise without rest period. The work ensembles worn during heat exposure include general work uniform, nuclear, biological, chemical (NBC) protective suit, firefighting garment, and the body armor. 7 studies designed cooling intervention for civilian settings, including 2 studies for firefighters (Bennett et al., 1995; Kim et al., 2011), 3 studies for civilian hazmat personnel (Caldwell et al., 2012; Kenny et al., 2011; Muir et al., 1999), and 2 studies for industrial workers (Chan et al., 2017; Zhang et al., 2010). 11 studies for military settings, including 6 studies for army hazmat team (Bishop et al., 1991; Cadarette et al., 2001; Cadarette et al., 2003; McLellan et al., 1999; Muza et al., 1988; Pimental et al., 1987), 1 study for aircrew defense personnel (Vallerand et al., 1991), and 4 studies for marching soldiers (Amorim et al., 2010; Barwood et al., 2009b; Chinevere et al., 2008; Ciuha et al., 2016).

The results of Egger's test ($p = 0.02$) and Begg's test ($p = 0.01$) indicated the presence of significant publication bias. The reason might be that we only used peer-reviewed studies, while dissertations, technical reports and others were not reviewed. High statistical heterogeneity exists across studies, suggesting the subgroup analysis. Heterogeneity for different continuous and intermittent cooling techniques was acceptable, ranging from 0% to 50% ($p > 0.05$).

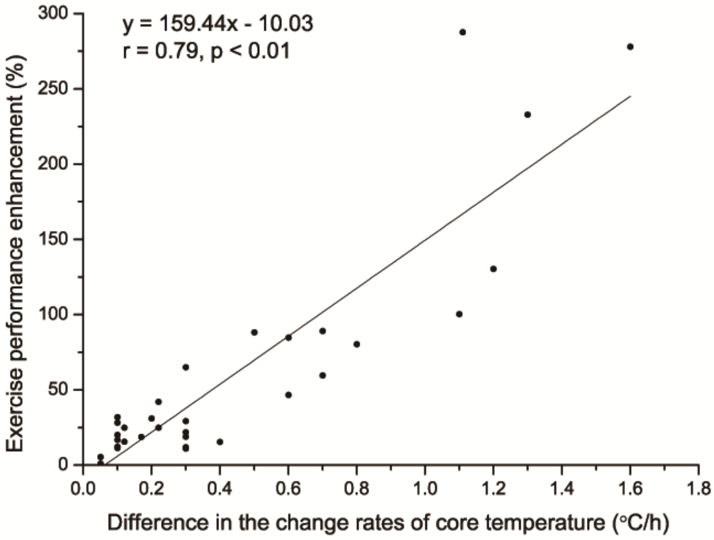
Quality assessment of included studies show that 8 studies attained a PEDro score of 6/10, and 10 studies attained a PEDro score of 5/10 (Appendix 1 Table 3). Sample size calculation was found in one study (Chinevere et al., 2008).

2.5 COOLING EFFECTS ON PHYSIOLOGICAL RESPONSE

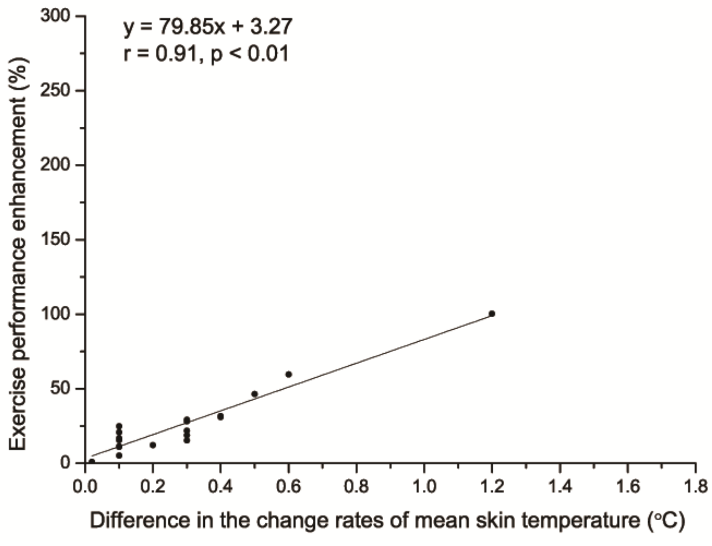
T_c, $\overline{T_{sk}}$ and HR during the control and cooling conditions in each study were extracted and the change rate in these physiological parameters was calculated. The change rates of T_c (0.94 ± 0.03 ℃/h), $\overline{T_{sk}}$ (1.03 ± 0.08 ℃/h) and HR (55 ± 9 bpm/h) were significantly lower in the cooling condition than those of the control condition (1.52 ± 0.05 ℃/h, $p < 0.01$; 2.07 ± 0.06 ℃/h, $p < 0.05$; 72 ± 10 bpm/h, $p < 0.01$). Correlations were found between the differences in change rates of physiological parameters ($\Delta T_{c\_control} - \Delta T_{c\_cooling}$, $\Delta\overline{T_{sk}}\_{control} - \Delta\overline{T_{sk}}\_{cooling}$, $\Delta HR\_{control} - \Delta HR\_{cooling}$) and EPE (all p values < 0.05) (Figure 2.2).

Figure 2.2 Correlations between exercise performance enhancement (%) and differences in change rates of (a) core temperature (℃ /h), (b) mean skin temperature (℃ /h), and (c) heart rate (bpm/h)

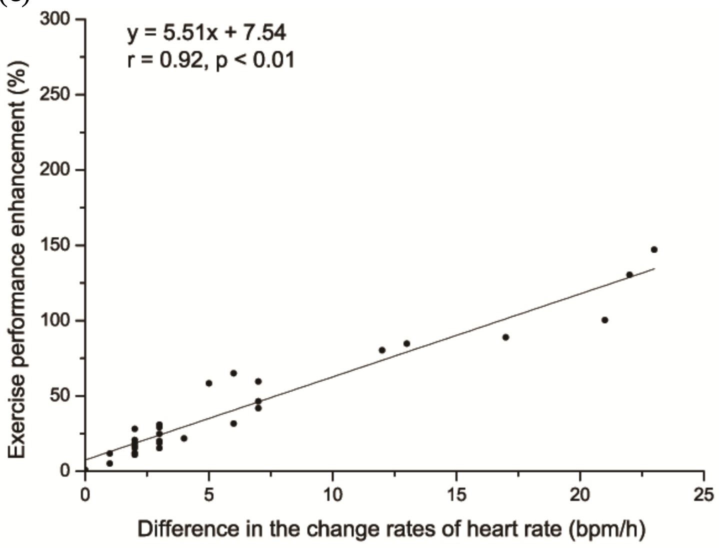
(a)



(b)



(c)



NOTE: Pearson's correlation coefficient, significance assumed at $p < 0.05$

During physical activities, the high rate of metabolic heat generation can exceed the heat dissipation, which then leads to continued rise in body heat storage, posing a risk of heat stress. This scenario can be further aggravated by impermeable protective clothing, which impedes evaporative heat transfer through sweat (Cheung et al., 2000). Previous research revealed that fatigue or exhaustion under heat stress is associated with thermoregulatory and/or circulatory failure, specifically, the attainment of a critically high core temperature and/or maximal heart rate (Cheung and McLellan, 1998; Sawka et al., 1992; Yi et al., 2017a). The change of skin temperature during exercise can be an indicator of thermal behavioural responses in humans (Schlader et al., 2011; Yi et al., 2017a). The current findings show that skin temperature in the control condition is consistently higher than that in the cooling garment condition. The high skin temperature may further contribute to the early stop of exercise in the control condition. The results of this study show a positive correlation ($p < 0.05$) between the change rates of physiological parameters and the EPE. This reinforces the findings in Chan et al. (2015), wherein they stated that the PCS is effective in improving work endurance by attenuating body core temperature and heart rate.

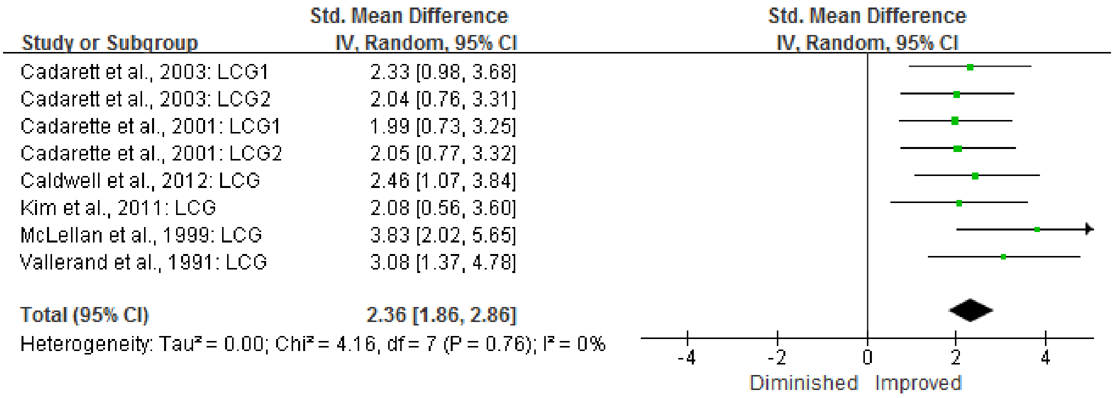
2.6 EFFECTIVENESS OF DIFFERENT PCS

Various PCSs, including LCG, ACG supplied with cooled air (ACG-C), ACG supplied with ambient air (ACG-A) and PCG were adopted throughout the whole heat exposure to combat heat stress and improve work duration. 8 pairs of comparison validated that LCG was effective in improving work tolerance compared to a control condition (SMD: 2.36, 95% CI: 1.86 to 2.86; EPE: + 76.76%) (Figure 2.3a). No heterogeneity was observed within these LCG studies (I^2 = 0%, p = 0.76). 5 pairs of comparison assessed the effectiveness of ACG-C, and the results demonstrated a large effect (SMD: 5.22, 95% CI: 3.25 to 7.19; EPE: + 170.06%) with a moderate heterogeneity between studies (I^2 = 47%, p = 0.11) (Figure 2.3b). 4 pairs of comparison evaluated the effectiveness of ACG-A in improving subsequent work performance, indicating an average EPE of + 36.32% (SMD: 0.87, 95% CI: 0.29 to 1.45) with no heterogeneity between studies (I^2 = 0%, p = 0.77) (Figure 2.3c). 5 pairs of comparison validated that PCG was effective in improving work tolerance compared to a control condition (SMD: 1.68, 95% CI: 1.08 to 2.22; EPE: + 32.92%) with large heterogeneity between studies (I^2 = 29%, p = 0.23) (Figure 2.3d). 1 pair of comparison indicated that HCG produced a large effect on improving subsequent work endurance (SMD: 3.46, 95% CI: 1.42 to 5.49; EPE: + 59.68%) (Figure 2.3e).

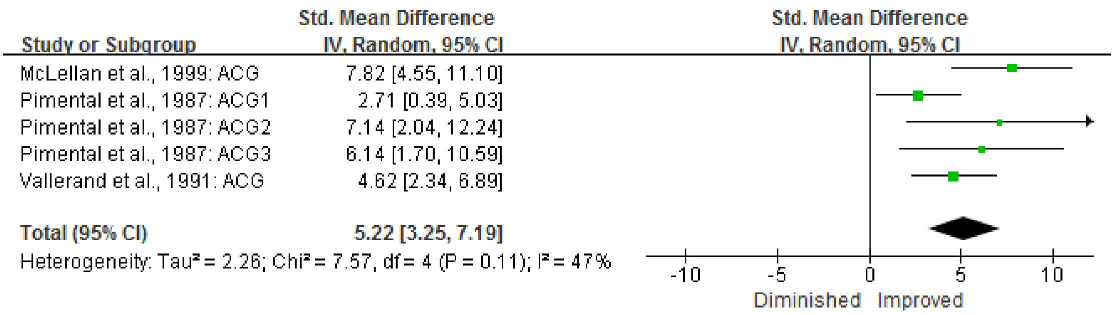
LCG, ACG-C, ACG-A, and HCG were utilised as an intermittent cooling intervention during rest period. There were 5 pairs of comparison of PCSs during recovery, exhibiting a large effect in improving subsequent work endurance (SMD: 1.81, 95% CI: 1.23 to 2.38; EPE: + 45.03%) with a moderate heterogeneity between studies (I^2 = 40%, p = 0.15) (Figure 2.3f).

Figure 2.3 Forest plot of PCSs effects on work performance

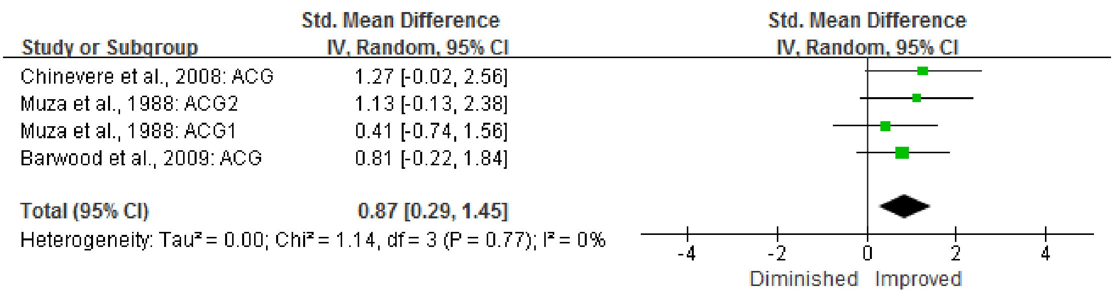
(a) Continuous cooling_Liquid cooling garment (LCG)



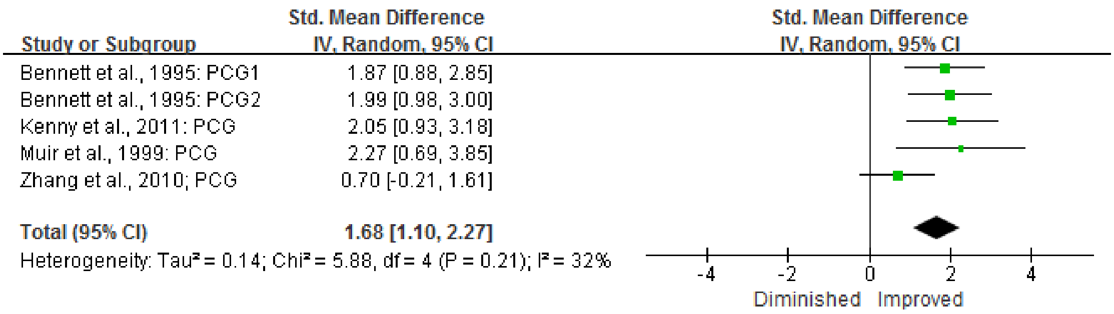
(b) Continuous cooling_Air cooling garment supplied with cooled air (ACG_C)



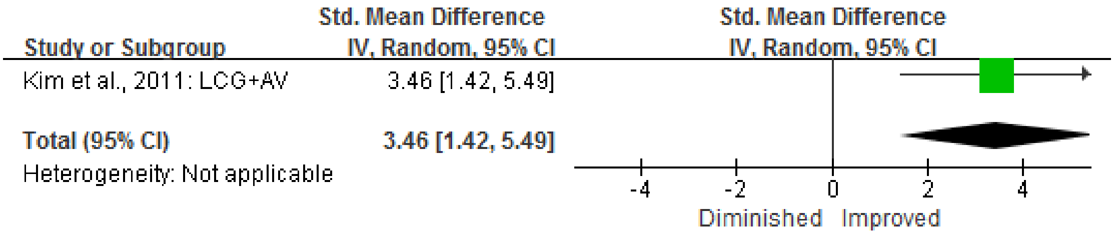
(c) Continuous cooling_Air cooling garment supplied with ambient air (ACG_A)



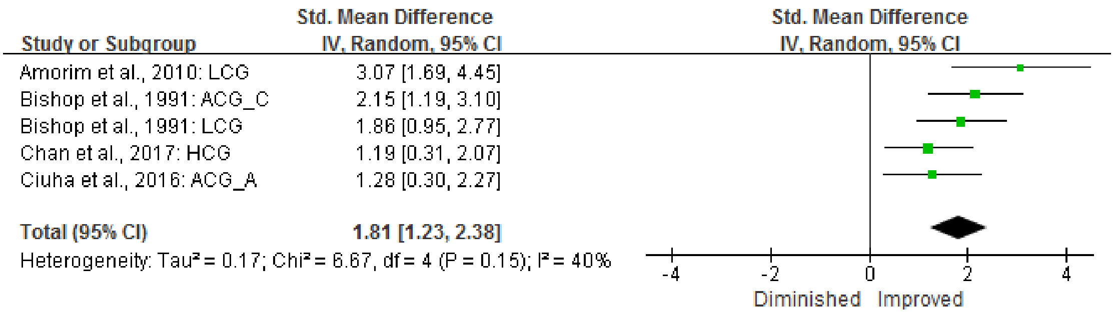
(d) Continuous cooling_Phase change garment (PCG)



(e) Continuous cooling_Hybrid cooling garment (HCG)



(f) Intermittent cooling



Different PCSs have been used as a continuous or intermittent cooling intervention. The use of ACG-C is the most effective, followed by HCG, LCG, PCG, and ACG-A. The reason for the higher cooling capacity achieved by ACG-C might be the cooled air ventilation is conducive to enhancing evaporative heat dissipation and reducing the moisture accumulation on the skin/clothing. The cooling effect of LCG and PCG mainly relies on the circulated cooling liquid and cooling packs, respectively. Heat strain attenuation by thermal conductivity of the circulated cooling liquid/cooling packs around the body might cause condensation problem, which would impair wearers' wetness and comfort sensation.

HCG combined two or more of the aforementioned cooling techniques (Chan et al., 2015; Pandolf, 1995). Taking the advantages of air ventilation that increases evaporative heat transfer and cooled liquid/PCMs that enhance conductive heat dissipation, a variety of HCGs (e.g. LCG with air ventilation and PCG with air ventilation) were developed. Current evidence showed that the EPE of HCG (LCG with air ventilation) and HCG (PCG with air ventilation) was +59.68% and +100.45%, respectively, which was higher than that of ACG-A (+ 36.32%) and PCG (+32.92%). Since only two studies on HCG were included in this meta-analysis, further work with more randomised controlled trials on assessing HCGs is envisaged to be examined.

ACG-A also exhibited significant effectiveness in enhancing work endurance, although relatively low compared to other PCSs. It was noted that the effect size of ACG-A (suppled air temperature at 35–40 ℃) is much lower than that of ACG-C (supplied air temperature at 12–27 ℃), which reinforced the theoretical model that inlet air temperature is an important factor affecting the heat absorbing capacity of an ACG (Mokhtari Yazdi and Sheikhzadeh, 2014). In addition, air velocity was demonstrated to influence the cooling capacity of ACG. It can be seen in Figure 2.3c that ACG with inlet air flow rate at 18 cubic feet per minute (cfm) had a larger effect on improving work endurance compared with that of ACG at 10 cfm (Muza et al., 1988).

Different work–rest patterns were adopted in the experimental protocol, e.g. a 50 min treadmill walking followed by a 40 min rest (Amorim et al., 2010) and a 15 min treadmill running followed by a 10 min rest (Kim et al., 2011). Intermittent cooling with PCSs was implemented during recovery between bouts of work. Large effect on work performance was observed in intermittent cooling intervention with PCS.

2.7 INDUSTRIAL APPLICATION

The application of cooling intervention with PCSs in occupational settings considers the cooling efficiency, thermal comfort, safety and ergonomic factors of weight, mobility and convenience. Thermal comfort is associated with the heat balance of the body and the absence of uncomfortable hot due to sweating or uncomfortable cold due to vasoconstriction and low skin temperatures (Parsons, 2014). The PCS design considers the sufficient cooling power and the acceptable thermal comfort. Research found that the wearer feels discomfort when the coolant inlet temperature is below 10 ℃ (Speckman et al., 1988). An ice vest (melting temperature at 0 ℃) may also cause torso erythema when insufficient insulation is worn between the skin and the cooling packs (House et al., 2013). Reflective strips are attached, and flame-retardant fabric is used for safety in industrial settings (Chan et al., 2016b). The burden induced by PCSs may lead to increased metabolic production, thereby aggregating body thermal strain and impairing work performance (Lu et al., 2015; Wang et al., 2013). Body movement and/or mobility restriction can cause physiological (e.g. musculoskeletal pain) and psychological discomfort (Akbar-Khanzadeh et al., 1995; Chan et al., 2015).

Different PCSs have been adopted in different occupations by considering the type of task, exposure level of heat stress and the required protective clothing.

Amongst the cooling garments, LCGs and ACGs (with cooled air) exhibit high performance in alleviating heat stress and extending exercise performance (measured by the effect size of endurance time) in laboratory experiments. However, both LCGs and ACGs are heavy. They also require external connections to the coolant supplier or compressor, which may restrict user mobility and compromise the general cooling benefits. PCGs provide cooling through the insertion of the precooled PCMs in the garment. This process requires no external connections (high portability), and it is easy to operate. Certain PCMs provide cooling in a limited duration compared with “infinite” cooling source (e.g. LCGs with external heat sink). Large amount of PCMs can extend the effective cooling duration. Nevertheless, the added weight increases the human metabolic rate/physical work load. The environment for construction workers is difficult because of various practices associated to heat, such as activities on the floor/roof, which expose workers to direct sunlight, and activities in a confined place with poor ventilation. LCGs and ACGs consist of a complex and bulky system. These garments are not always suitable for construction workplaces because of many factors, including elevated platform, limited space and lack of electricity. The use of PCG is also limited in the construction industry because of its limited cooling duration. On the basis of literature review and comparison of different commercial PCS products, this research project aims to design a hybrid PCS for construction workers. PCS is designed based on characteristics of the construction industry, e.g. work activity (forceful pulling and heavy lifting), work shift (work-rest schedule), and complex working environment including elevated platforms, uneven grounds and confined spaces. Therefore, cooling duration, cooling power, thermal comfort, ergonomics and mobility of the PCS are considered. The hybrid PCS will combine PCM cooling and air cooling by using PCM packs and ventilation fans. This PCS should be portable (no external connection to coolant or compressor requirement) and lightweight and able to provide consistent cooling for approximately 7 h. Given the limited previous research on hybrid cooling garment, further work is required to examine the effectiveness and applicability of this PCS.

2.8 SUMMARY

This chapter systematically reviews selected papers related to cooling intervention with PCSs. The meta-analysis reveals the effectiveness of different PCSs on work endurance. The evaluation of cooling intervention considers the characteristics of different occupations, including the design of exercise protocol (exercise type, duration and intensity), meteorological condition and clothing ensemble. The literature review identifies the research gap and provides a basis for developing the research framework of the present study.

CHAPTER 3 RESEARCH METHODOLOGY

3.1 INTRODUCTION

This chapter presents the research design and strategies to achieve the five objectives of this study. A comprehensive review on major research methods employed in this study is reported.

3.2 RESEARCH DESIGN

3.2.1 Intervention research

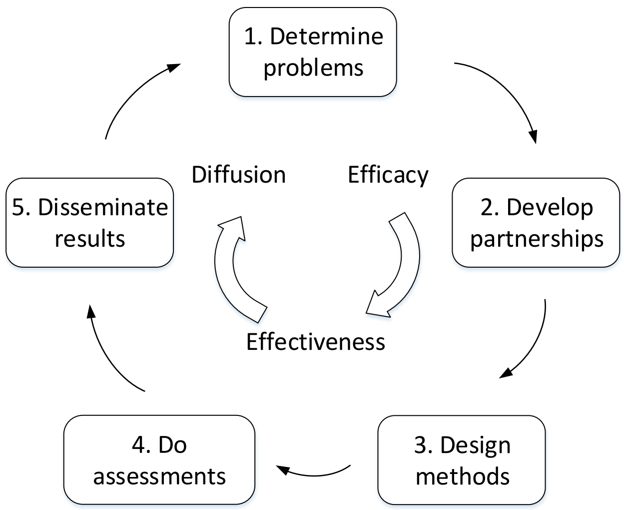
Intervention research determines the cause–effect relationships between an intervention and an outcome (Melnyk and Morrison-Beedy, 2012). Intervention research in the occupational health area gained an increasing attention over the past 30 years (Kristensen, 2005). Occupational intervention research examines the effects of planned activities in the workplace to improve workers' health and well-being, increase motivation, job satisfaction and productivity, alleviate morbidity and mortality and reduce absence or turnover (Kristensen, 2005). The present study developed a cooling intervention with personal cooling system (PCS) and examined its effectiveness in improving occupational health and safety (e.g. alleviating workers' body heat strain) in the construction industry. In addition to evaluating the utility of the intervention to produce the desired effect or unintended outcomes, disseminating convincing evidences to implement the intervention in the workplace is an important part of the intervention research (Goldenhar et al., 2001). Intervention research enables close cooperation between researchers and practitioners.

Intervention research includes three phases, namely, development, implementation and effectiveness (Goldenhar et al., 2001). First, an intervention that has scientific basis and satisfies the needs of the practitioners is developed. Second, the procedures of implementing an intervention are systematically outlined. Finally, the effectiveness of an intervention is evaluated. The three phases are interdependent and require an interdisciplinary research team to conduct the agenda (Goldenhar et al., 2001).

3.2.2 Tasks in intervention research

A well-structured research framework with scientific rigor and practical concerns has been proposed to carry out an occupational intervention research (Figure 3.1) (Yang and Chan, 2017). The efficacy–effectiveness–diffusion transition cycle was introduced by Camp (2001). The efficacy of an intervention refers to the degree to which it produces an effect under ideal conditions, while the effectiveness of an intervention is the degree to which it produces an effect under realistic workplace conditions (Shannon et al., 1999). Once proven effective, an intervention should be diffused, which will make the intervention accessible to wide population. In the efficacy–effectiveness–diffusion transition cycle, five research tasks are fulfilled, namely, determine problems, develop partnerships, design methods, do assessments and disseminate results (Goldenhar et al., 2001).

Figure 3.1 The 5-D model for conducting intervention research



Adapted from Yang and Chan (2017)

(1) Determine problems

Background information is collected to help determine the problem and its history, the range of intervention methods and the evaluation settings. Several questions need to be solved in this task, including the evaluation history of an intervention, already known intervention options and application, quality of the already collected data, and specific aspects of effectiveness or implementation that should be evaluated (Goldenhar et al., 2001). A literature review was conducted to identify previous cooling interventions with PCS to reduce heat strain and improve work performance, examine the research methods used in the intervention research and access the effectiveness of these cooling interventions (see Chapter 2). Hypothesis was subsequently made based on past research, which needs to be confirmed in the current study.

(2) Develop partnerships

Collaboration between researchers and workplaces is required in occupational intervention research (Kristensen, 2005). Stakeholders from the industry, government agencies and academia are involved in the process. A multidisciplinary team is better equipped to deal with various theoretical, technical, scientific, practical and socio-political factors during the intervention research phases (Goldenhar et al., 2001). The research team in the present study possesses expertise and experience in occupational safety and health, industrial hygiene, materials science, textile science, biological and exercise science and other relevant disciplines. Extensive professional and research experience from team members in these fields is useful in enriching and enhancing research capability.

(3) Design methods

Previous studies have documented the methodologies used in intervention research (Shannon et al., 1999). Intervention research designs can generally be categorised as experimental, quasi-experimental and nonexperimental. In experimental design, subjects are assigned randomly to either experimental or control conditions, thus comprising two (or more) groups. The randomisation ensures that subjects are assigned to the conditions in an unbiased manner, thereby improving the internal validity of the intervention research. Due to practical, ethical, legal, financial and/or political constraints, the experimental design is sometimes not feasible (Shannon et al., 1999). In such case, ‘lesser’ design options (i.e. quasi- or non-experimental) would be used (Shannon et al., 1999). Quasi-experimental design refers to non-randomly assigned experimental and control groups (Goldenhar and Schulte, 1994). Non-experimental design refers to the experimental group only (Goldenhar and Schulte, 1994).

Randomised controlled trials (RCTs) are the basic methodological paradigm in intervention research (Kristensen, 2005). Randomisation is performed for avoiding confounding and selection bias. The control group is adopted to distinguish *"between change and effect (the effect refers to the difference between what happened in the intervention group and what would have happened without the intervention)"* (Kristensen, 2005). Blinding and placebo treatment are necessary in RCT for biomedical research to reduce information bias. RCT is generally carried out in the laboratory under highly controlled conditions. However, RCTs can be difficult to conduct in some occupational settings (e.g. occupational safety interventions) because of practical, ethical technical and/or financial factors (Shannon et al., 1999).

The evaluation of intervention implementation usually includes survey (e.g. field questionnaire survey), case study, qualitative (e.g. collection of subjective ratings from participants) and quantitative (e.g. measure of core body temperature during the experiment) research methods. The effectiveness evaluation should consider both internal validity (i.e. whether the intervention made a difference) and external validity (i.e. generalisation of results).

In the present study, participants are randomly assigned to either experimental (cooling) or control conditions to examine the effectiveness of the cooling intervention. Both quantitative (including body temperature and heart rate) and qualitative (including subjective ratings of perceived exertion and thermal sensation) data are collected during the experiment. The influence of extraneous variables (unwanted sources of variation) is controlled to ensure the causal inference between the independent and the dependent variables and attain internal validity.

(4) Do assessments

Comparisons are typically made between pre- and post-intervention conditions or between experimental and control groups (Shannon et al., 1999). Descriptive statistics (e.g. percentage, frequency, mean, standard deviation and effect size) and appropriate analytic techniques [e.g. analysis of variance (ANOVA) and paired t-test] are conducted to examine whether the proposed intervention makes a difference as expected. ANOVA is used to compare multiple group differences, whereas paired t-test is used to compare two groups. When evaluating the differential effect of an intervention across several groups, specific comparison (e.g. Tukey test) is conducted after determining that the overall (multiple) group effect exists (multiple group effect is assessed by ANOVA).

(5) Disseminate results

This task is the crucial closing of the intervention research loop (shown in Figure 3.1) (Goldenhar et al., 2001). Research results are disseminated to intervention participants intuitively and in easy-to-understand manner. Moreover, dissemination of research findings to relevant nonparticipants (e.g. safety and health professionals, stakeholders, producers of intervention products and government agencies) is essential (Goldenhar et al., 2001). Key features in disseminating research findings include engineering (whether the intervention works as expected), infrastructure (whether there is an infrastructure that supports the widespread of the new knowledge), price (whether the price allows the widespread of the new knowledge) and standards (whether standards are adopted and/or required for the dissemination of the knowledge) (Goldenhar et al., 2001).

3.3 RESEARCH PROCESS

The research methods and process employed to achieve each of the research objectives are presented in Figure 1.3. Throughout the research process, data collected through literature review, laboratory experiments and field studies were analysed and consolidated.

The purpose of this study is to develop a cooling intervention with the newly designed PCS for combating heat stress in the construction industry. Table 3.1 shows the five specific research objectives and the corresponding research methods.

Table 3.1 Research objectives and corresponding methods

No.	Research Objectives	Research Methods
1	Review different PCSs for combating occupational heat stress	Literature review
2	Engineer and design a tailor-made PCS	Physical testing of fabrics and cooling sources
3	Assess the cooling capability of the newly developed PCS	Sweating thermal manikin measurements
4	Evaluate the effectiveness of the newly developed PCS in reducing heat stress	Human wear trials in the laboratory
5	Examine the applicability of the newly developed PCS in the construction industry	Field wear trials

3.4 OVERVIEW OF RESEARCH METHODS

This study aims to develop a cooling intervention with PCS for the construction industry. Literature review was conducted in Objective 1 to lay the foundation of this study. Then, a series of physical testing of the PCS elements were carried out in Objective 2 to engineer and design a tailor-made PCS. Sweating thermal manikin was used in Objective 3 to measure and compare the thermal properties (including cooling power, thermal insulation, and evaporative resistance) of the PCS. Subsequently, a cooling intervention with the newly developed PCS was implemented and examined in Objective 4 and 5 (i.e. human wear trials in climatic chamber and construction field). RCTs were adopted to examine the effectiveness of the cooling intervention with the newly developed PCS. Questionnaire survey was further carried out, which focused on assessing the applicability of the proposed cooling intervention.

3.4.1 Physical testing of PCS elements

A series of physical testing of the PCS elements (including fabrics and cooling sources) were carried out. First, fabrics for the inner and outer layers of the PCS were tested and selected. The fabrics were tested considering the weight, thickness, heat/moisture transporting properties and UV protection. The air resistance, water vapour permeability and radiation properties of the fabrics were tested by KES-F8-API (Kato Tech Co., Ltd., Kyoto, Japan), test dish and electric balance (GF-2000, A&D, Japan) and CRAY 300 Conc UV-visible spectrophotometer (Agilent Technologies, Inc., USA), respectively (photos of the instrument are provided in Appendix 7). Then, the cooling sources involving a pair of ventilation unit and phase change materials (PCMs) packs were identified by comparing and testing several commercially available products. Ventilation units were tested considering weight, air velocity and work duration. PCM packs were tested considering weight, melting temperature and heat of fusion. An electronic balance (GF-2000, A&D, Japan) and a hot wire anemometer (RS327-0640, Tecpel, Taiwan) were used to measure the weight and air flow rate of the ventilation unit, respectively (see photos in Appendix 7). A Differential Scanning Calorimeter (DSC) (DSC822e, Mettler Toledo, USA) was used to test the melting temperature and heat of fusion of the PCMs (see photos in Appendix 7).

3.4.2 Sweating thermal manikin measurements

The thermal manikin is developed to simulate the heat transfer between humans and the thermal environment (Foda and Sirén, 2012). A human-shaped thermal manikin can measure conductive, convective and radiative heat losses over its skin surface (Holmér, 2004). When sweating is simulated on the thermal manikin, heat exchange by evaporation can be further measured (Holmér, 2004). The thermal manikin has been widely used to evaluate clothing insulation and the effect of thermal environments on the body. The current thermal manikin generally consists of more than 30 independently regulated segments (e.g. face, head, right hand, left hand, shoulders, upper chest, stomach and mid back) (Holmér, 2004). During operation, the manikin's segmental heat loss and surface temperature are measured and recorded (Wang et al., 2014). The overall body heat loss can be estimated by summing up the surface area-weighted segmental heat loss. The method of thermal manikin measurements is quick and easily standardised and repeatable (Holmér, 2004).

Sweating thermal manikin measurements were conducted in an isothermal condition $T_{manikin}=T_a=T_r$ (air temperature T_a equals the manikin temperature $T_{manikin}$; both values are equal to the radiant temperature T_r) in a climatic chamber. Under the isothermal condition, no dry heat exchange (i.e. radiative, conductive and convective heat losses are all equal to zero) occurred between the manikin surface and the environment (Wang et al., 2011).

A heated sweating thermal manikin, Newton (Measurement Technology Northwest, Seattle, WA, USA) (Figure 3.2), was used in this study. The manikin consisted of 34 individually controlled zones. Its segmental surface temperature could be individually controlled and each segmental heat loss could also be recorded by the ThermDAC® software (Lu et al., 2015). This study used the constant temperature mode, and the surface temperature of all segments was set to 34.0 ℃ to assess the cooling effect of the PCS in the so-called isothermal condition ($T_{manikin} = T_a = T_r$) (Lu et al., 2015). The total surface area (i.e., all) of the manikin is 1.697 m^2. A torso fabric skin (100% nylon knitted) that tightly fitted the Newton was employed to simulate torso sweating. It was pre-wetted by using tap water to simulate the sweat-saturated skin (Wang et al., 2012; Wang et al., 2011; Zhao et al., 2013a). In the current study, the sweating rate was set to 1,200 ml/hr m^2 to simulate the human body during heavy sweating. The water flow was heated up to 34.0 ℃.

Figure 3.2 The sweating thermal manikin in a climatic chamber

3.4.3 Wear trials in the laboratory

3.4.3.1 Sample size

The sample size is the number of subjects recruited in the tests. Four factors are included to estimate sample size: (1) the significant level (i.e. α, type I error), (2) statistical power (i.e. $1 - \beta$, the ability to detect a statistically significant difference when a specified difference between the groups in reality exists, and β is type II error), (3) the minimal difference between the treatment groups that the experimenter wishes to detect, and (4) the variability of the measurements, expressed as the standard deviation (SD) (Noordzij et al., 2010). Formula for a continuous outcome and equal sample sizes in both treatment groups is developed as follow, Equation (3.1) (Chow et al., 2007): (desirable significant level α and power = $1-\beta$, set as 0.05 and 0.80 for a two-tailed statistical analysis)

$$\mathrm{n}=\frac{2\left[\left(\mu_{1-\frac{\alpha}{2}}+\mu_{1-\beta}\right)^{2}\sigma^{2}\right]}{\delta^{2}} \tag{3.1}$$

where n is the sample size in each of the group, σ is the standard deviation of outcome measure, δ is the difference between the means in the two treatment groups; the $\mu_{1-\alpha/2}$ value is given for the desired significance criterion, the $\mu_{1-\beta}$ value is given for the desired statistical power. The standard deviation and difference between the means in measured variables were obtained from our pilot study.

3.4.3.2 Experimental design and analysis

RCTs were used in the laboratory experiment. A repeated-measures experimental design, in which one group of subjects is tested under all conditions and each subject served as his/her own control, was adopted. It ensures the highest possible degree of equivalence across treatment conditions because subjects are perfectly matched with themselves (Portney and Watkins, 2015). Tests were conducted in a balanced random order. Each participant completed a set of treatment trials (cooling and control) separated by a few days (Arngrimsson et al., 2004). What’s more, all trial tests were performed at the same time of the day for each subject to minimize the effects of the circadian rhythm on the body core temperature and heart rate (Luomala et al., 2012).

3.4.4 Field wear trials

To further evaluate the applicability of the PCS, construction workers will be invited to wear the newly designed PCS during their regular working activities on a number of occasions and in different workplaces. On August 2016, a total of 14 visits to construction sites were made. Both on-site questionnaire survey and field experiment were conducted during the visits. The questionnaire survey aims to examine the applicability of the PCS by collecting participants' subjective ratings and their preference to the newly developed PCS. The purpose of the field experiment is to further examine the effectiveness of the cooling intervention with the newly designed PCS in reducing heat strain in real-world setting.

3.4.4.1 On-site questionnaire survey

Each survey consists of two wear trials in counterbalanced order, one with cooling intervention and one without cooling intervention. To minimise systematic errors, workers participating in the wear trials were randomly assigned to two groups, in which one group of workers wore the PCS during rest (COOL) and the other group did not wear the PCS (CON) in the first wear trial. In the second wear trial, the COOL and CON conditions were reversed among workers. Before the wear trials, the participants were briefed of the survey procedures and objectives. Participants were asked to fill in a questionnaire immediately after each wear trial to collect their subjective ratings on the PCS. The questionnaire includes questions regarding cooling capacity, comfort, suitability, acceptability and safety of the PCS.

The required sample size for the questionnaire survey was determined as shown in Equation (3.2) (Watson, 2001):

$$\mathrm{n} = \frac{\left[\frac{P(1-P)}{\frac{A^2}{Z^2}+\frac{P(1-P)}{N}}\right]}{R} \tag{3.2}$$

where n is the required sample size, N = 215 is the number of people in the population, P = 0.5 is the estimated variance in population, Z = 1.96 assumes a 95% confidence level, A = 6% is the desired precision of results and R = 0.85 is the estimated response rate. Therefore, n = 140.

3.4.4.2 Field experiment

Rebar workers were recruited in the field experiment. The sample size of the field experiment was determined according to Equation (3.1). Each subject participated in two trials, i.e. with PCS (COOL) and without PCS (CON). Each trial lasted for one working day, from 9:00 am to 4:00 pm, eliminating a 1-h lunch break at noon (12:00 noon to 1:00 pm). Prior to each test, the participants were asked to wear the assigned work uniform and equip with a heart rate belt with its monitor (Polar WearLink®, Finland). At the beginning of the test, the participants rested for 30 min to stabilise their heart rate. In this period, they were briefed about the procedures and objectives of the test and requested to sign the consent form. The participants performed their usual daily work at the sites, from 9:00 am to 12:00 noon in the morning, with a 15-min rest session from 10:15 am to 10:30 am. Daily work resumes from 1:00 pm to 4:00 pm in the afternoon, with a 30 min-rest session from 3:00 pm to 3:30 pm. During the rest session, workers in the COOL wore the PCS. Their ear temperature, heart rate, rating of perceived exertion (RPE) and thermal sensation were recorded every 5 min.

3.5 SUMMARY

This chapter describes and explains the research methodology adopted in this study. Qualitative and quantitative research methods are employed to achieve the five research objectives. First, systematic literature review and meta-analysis are conducted to examine different PCSs in combating occupational heat stress. Second, physical testing is conducted for the development of a tailor-made PCS for construction workers. Third, a sweating thermal manikin test is employed to assess and compare the cooling capability of the PCS. Fourth, human wear trials in the laboratory are conducted to examine the effectiveness of the PCS in terms of thermo-physiological and perceptual parameters. Fifth, field wear trials are conducted to further examine the applicability of the PCS in the construction industry.

CHAPTER 4 DEVELOPMENT OF PCS

4.1 INTRODUCTION

This chapter focuses on the development of personal cooling system (PCS) for the construction industry. PCS development includes six stages as follows: making a request, exploring the design situation, perceiving the problem structure, selecting the fabric, engineering of the cooling source, and developing the prototype.

4.2 REQUEST MADE

In this stagey, request has been made to introduce PCS into construction worksites where workers are exposed to heat stress. Heat stress is a cause of preventable deaths, and it is a major hazard in construction in Hong Kong, particularly during hot and humid summer season (Chan et al., 2016c). Cooling garments/suits work by providing a cooler microclimate around the body. They are among the most effective methods for reducing heat strain, increasing comfort and productivity and enhancing safe work conditions (Hasegawa et al., 2005; Webster et al., 2005). Various PCSs have been engineered for athletes, soldiers, firefighters and hazmat personnel. However, construction workers who are susceptible to heat stress have not been the focus of research. During the summer of 2013, the Hong Kong Occupational Safety and Health Council (OSHC) launched the “Cooling Vest Promotion Pilot Scheme” and tested the effectiveness of commercially available cooling vests in construction, kitchen and catering, outdoor cleaning and horticulture and airport apron service industries.

Workers are unwilling to wear the commercially available cooling vest because of many reasons, as follows: easily stained colours, heavy weight, short cooling time, inflexibility (e.g. poses hazard around moving equipment) and lack of industry-specific design (e.g. lack of reflective strips) (Chan et al., 2016c), thereby inducing the request to develop a tailor-made PCS for the construction industry.

4.3 DESIGN SITUATION EXPLORED

Design situation has been examined by analysing the characteristics of construction work and interviewing frontline workers and managers to identify user requirement.

Construction work is physically strenuous and demanding (Chan et al., 2012c; Chan et al., 2012d; Yi and Chan, 2013). The construction work is complex and includes standing, squatting and bending postures. Besides the cooling effect, the PCS design for the construction industry should consider weight, mobility, overall comfort, aesthetics, visibility and interference with work.

Most construction tasks are performed outdoors, thereby exposing workers to direct sunlight. The PCS cloth should be UV resistant to protect workers against the UV rays of the sun.

4.4 PROBLEM STRUCTURE PERCEIVED

A questionnaire survey was conducted to identify the practicability of existing PCSs in the construction industry (Chan et al., 2016c).

To examine the effectiveness of various types of PCS, OSHC tested a number of commercially available PCSs that are commonly used in Hong Kong (OSHC, Hong Kong, 2013). PCG (e.g. ice vest) is often the most usable cooling technique because of its simple mechanism, untethered system and unpowered nature based on the literature review (Chan et al., 2015). Considering the cost, quality, availability and popularity, two kinds of commercial PCGs (Vest CA and CB) were identified for evaluation in the "Cooling Vest Promotion Pilot Scheme" launched by the Hong Kong Labour Department in cooperation with the OSHC. Vest CA incorporated 12 packs of frozen gel, whereas Vest CB incorporated three packs of frozen gel and a pair of ventilation fans. The first round of field studies was carried out during the summer of 2012 in four industries, namely construction, kitchen and catering, outdoor cleaning and horticulture and airport apron service (Chan et al., 2013). The questionnaire survey was administered immediately after each wear trial. The questionnaire included 11 subjective attributes (rated by scales 1–7) towards the tested cooling vests (Table 4.1). The results showed that most workers preferred Vest CB in terms of thermal comfort, usability, tactile comfort and fabric hand (feel). The second round of field studies was carried out during the summer of 2013. In the "Cooling Vest Promotion Pilot Scheme", about 1,500 sets of Vest CB were distributed to the aforementioned four industries. A questionnaire was developed to further evaluate Vest CB (Table 4.2) (Chan et al., 2016c). Top ten shortcomings were identified: *"(1) easily staining colour; (2) short cooling time; (3) heavy weight; (4) inflexibility (i.e. it presents a hazard around moving equipment); (5) a lack of industry-specific design (i.e. a lack of reflective strips); (6) easily fragile fabric; (7) thick* *fabric with poor permeability; (8) difficult to clean; (9) inconvenient to recharge/replace batteries during working time; and (10) inconvenient to replace gel pack during working time"* (Chan et al., 2016c).

Table 4.1 Survey questionnaire on the commercially available cooling vests (Vest CA and CB)

Item No.	Subjective rating	Scales
(1)	Hot–Cold	1–7
(2)	Wet–Dry	1–7
(3)	Heavy–Light	1–7
(4)	Restricted–Flexible	1–7
(5)	Nondurable–Durable	1–7
(6)	Uncomfortable– Comfortable	1–7
(7)	Inconvenient–Convenient	1–7
(8)	Unacceptable–Acceptable	1–7
(9)	Ugly/strange–Smart	1–7
(10)	Ineffective–Effective	1–7
(11)	Unsatisfactory–Satisfactory	1–7

Adapted from Chan et al. (2016c)

Table 4.2 Survey questionnaire on Vest CB

Item No.	Question	Scales
(1)	Easily staining colour	1–7
(2)	Singular colour	1–7
(3)	Small and tight	1–7
(4)	Loose size	1–7
(5)	Singular size	1–7
(6)	The fan is noisy	1–7
(7)	The position of fan is inappropriate	1–7
(8)	The fan is easily broken	1–7

Item No.	Question	Scales
(9)	The fan easily drops out	1–7
(10)	Easily fragile gel pack	1–7
(11)	Uneven distribution of gel pack	1–7
(12)	Small quantities of gel pack	1–7
(13)	Small size of gel pack	1–7
(14)	Thick fabric and poor permeability	1–7
(15)	Easily fragile fabric	1–7
(16)	Inflammable fabric	1–7
(17)	Heavy weight	1–7
(18)	Unfashionable appearance	1–7
(19)	Cooling time is short	1–7
(20)	Cooling effect is only partial	1–7
(21)	Cooling power is weak	1–7
(22)	Excessive cold	1–7
(23)	Inflexibility (that presents a hazard around moving parts)	1–7
(24)	Long time to freeze gel pack	1–7
(25)	Inconvenient to recharge/replace batteries during work time	1–7
(26)	Inconvenient to replace gel pack during work time	1–7
(27)	Easy to catch a cold	1–7
(28)	Expensive	1–7
(29)	A lack of industry-specific (e.g., a lack of reflective strips, require a cooling vest with long sleeves design/waterproof fabric)	1–7
(30)	Difficult to clean (due to fans)	1–7
(31)	Difficult to dismantle fans	1–7
(32)	Require cleaning service/cleaner for the cooling vests	1–7
(33)	Difficult to maintain	1–7
(34)	Difficult to store	1–7
(35)	Require refrigerating facilities (for gel pack freezing) nearby the workplace	1–7

Adapted from Chan et al. (2016c)

4.5 FABRIC SELECTED

The newly designed PCS is a two-layer cooling vest, specifically designed to wear over the construction uniform that was previously designed by our research team (Figure 4.1). This two-layer cooling vest design was determined based on the following process:

(1) In the "Cooling Vest Promotion Pilot Scheme", several commercially cooling vests were tested and the two-layer cooling vest was preferred by construction workers.

(2) Shortcomings of the commercially available two-layer cooling vest were further identified in the scheme.

(3) The commercially available two-layer cooling vest was used as reference prototype for the current design.

(4) The current design improved the commercially available two-layer cooling vest in terms of fabrics, cooling sources, thermal comfort, safety, aesthetics and ergonomics.

Figure 4.1 The newly designed PCS (two-layer cooling vest) worn over the construction uniform (from left to right: front view, back view)

The PCS consists of two layers, i.e. the inner layer made of polyester meshed fabric and the outer layer made of nylon taffeta. The two-layer design in the new cooling vest was adopted from the commercially available cooling Vest CB. The inner layer cloth should have high air permeability, permitting air go through to the skin surface, whereas the outer layer cloth should be highly air resistant, preventing the air from escaping to the environment, thereby facilitating air ventilation around the body (Weber, 1999). The fabrics should be thin and light to improve the system bulkiness and weight. The fabrics should have anti-abrasive and anti-static properties. Commercially available samples (that have the above features, have a well sense of fabric hand and tactile comfort) were primarily selected from the market by textile experts in the research group. Therefore, 9 types of mesh spacer fabrics for the inner layer and 12 types of nylon taffeta fabrics for the outer layer were identified to test for the thermal properties (air permeability and water vapour permeability) and mechanical properties (UPF rating, anti-static and anti-abrasion) (Table 4.3). These fabric properties were examined according to some well-recognised international standards (i.e., International Standard Organization, American Society for Testing and Materials).

A total of 21 commercially available fabrics (9 polyester meshed fabrics for the inner layer and 12 nylon taffeta fabrics for the outer layer) were identified and tested to select the optimal fabrics for the new PCS. The properties of fabrics, including thickness, air permeability and water vapour permeability (WVP), were used as critical indicators for assessing the thermal comfort of a clothed body. Furthermore, UV protection, anti-abrasion and anti-static properties were considered for the outer layer fabrics. Table 4.3 shows the properties of the fabrics for the inner and outer layers. For inner layer, the lower the fabric weight, fabric thickness and air resistance the better. The higher the WVP the better. The values in each property of inner layer were equally divided into 3 groups and scored from 1 to 3 accordingly (Table 4.4). For outer layer, the lower the fabric weight and fabric thickness the better. The higher the air resistance and WVP the better. The values in each property of outer layer were equally divided into 4 groups and scored from 1 to 4 accordingly (Table 4.4). The total score of each fabric were calculated (Table 4.4). Consequently, fabrics I2 and O10 were chosen for the inner and outer layers, respectively (based on Table 4.4, the higher the total score the better). The thin and light fabric improves the system bulk and weight; it can be easily blown up by the fan, thereby accelerating air convection between the skin and vest (McLellan, 2007).

WVP is tested to determine the rate of water vapour diffusion through the textiles, expressed in grams per square meter hour pascal. The high WVP of our vest fabric enhances water vapour transport and thus help with sweat evaporation (Chan et al., 2016b). The outer layer has UPF ~50+, blocking 98% of UVA and UVB, which is categorised as “excellent” sun protection (JAS/NZS 4399:1996) with high potential for outdoor use. Considering the concerns regarding durability and safety during construction, fabrics with anti-abrasion and anti-static properties were selected for the outer layer.

Table 4.3 Fabric physical characteristics

Fabric code	Fibre content	Fabric weight (g/cm^2)[a]	Fabric thickness (mm)[a]	Air resistance (kPa S/m)[a]	Water vapour permeability (g/m^2/day)[a]	UPF[a]	Anti-abrasion (20000 spins-weight loss, %)[a]	Anti-static (surface resistivity, ohms/square)[a]
				Inner layer (I)				
I1	100% polyester	0.75	0.24	0	885.88	-	-	-
I2*		0.48	0.24	0	1253.48	-	-	-
I3		0.53	0.28	0	1145.56	-	-	-
I4		0.89	0.29	0	841.09	-	-	-
I5		1.12	0.14	0	1046.39	-	-	-
I6		1.65	0.52	0.07	1095.56	-	-	-
I7		1.44	0.42	0.05	1035.55	-	-	-
I8		1.43	0.44	0.05	1119.12	-	-	-
I9		1.57	0.34	0.03	1041.39	-	-	-
				Out layer (O)				
O1	100% nylon	0.73	0.06	0.04	846.19	50+	2.32	0.53×10^{14}
O2		0.65	0.06	0.02	846.38	50+	3.23	0.27×10^{14}
O3		0.60	0.08	0.01	828.81	50+	0.29	1.38×10^{14}
O4		0.72	0.06	0.03	858.46	50+	1.75	6.29×10^{14}
O5		0.70	0.06	0.02	809.16	50+	3.07	1.89×10^{14}
O6		0.64	0.08	∞	656.47	5	0.68	0.70×10^{14}
O7		0.94	0.23	∞	425.81	50+	0.06	1.59×10^{14}
O8		1.37	0.32	∞	648.00	50+	2.06	0.01×10^{14}
O9		1.29	0.32	1.18	1103.62	50+	0.82	0.41×10^{14}

Fabric code	Fibre content	Fabric weight (g/cm^2)[a]	Fabric thickness (mm)[a]	Air resistance (kPa S/m)[a]	Water vapour permeability (g/m^2/day)[a]	UPF[a]	Anti-abrasion (20000 spins-weight loss, %)[a]	Anti-static (surface resistivity, ohms/square)[a]
O10*		0.42	0.07	2.46	1052.31	50+	0.55	3.72×10^{14}
O11		0.98	0.28	1.10	1014.30	50+	0.48	0.82×10^{14}
O12		0.71	0.12	∞	938.50	50+	1.65	0.18×10^{14}

Note: I, inner layer; O, outer layer; *The finally selected fabrics; [a] Average value on five fabric samples.

Table 4.4 Total score of each fabric

Fabric code	Total score	Fabric weight (g/cm^2)[a]	Fabric thickness (mm)[a]	Air resistance (kPa S/m)[a]	Water vapour permeability (g/m^2/day)[a]	UPF[a]	Anti-abrasion (20000 spins-weight loss, %)[a]	Anti-static (surface resistivity, ohms/square)[a]
				Inner layer (I)				
I1	7	3	3	√	1	-	-	-
I2*	9*	3	3	√	3	-	-	-
I3	8	3	2	√	3	-	-	-
I4	5	2	2	√	1	-	-	-
I5	7	2	3	√	2	-	-	-
I6	4	1	1	√	2	-	-	-
I7	4	1	1	√	2	-	-	-
I8	5	1	1	√	3	-	-	-
I9	3	1	1	√	1	-	-	-
				Out layer (O)				
O1	11	3	4	1	3	√	√	√
O2	12	4	4	1	3	√	√	√
O3	12	4	4	1	3	√	√	√
O4	11	3	4	1	3	√	√	√
O5	11	3	4	1	3	√	√	√
O6	14	4	4	4	2	NA	√	√
O7	9	2	2	4	1	√	√	√
O8	8	1	1	4	2	√	√	√
O9	10	1	1	4	4	√	√	√
O10*	16*	4	4	4	4	√	√	√
O11	11	2	1	4	4	√	√	√
O12	15	3	4	4	4	√	√	√

Note: For inner layer, *fabric weight* 0.48~0.87 scored 3, 0.88~1.26 scored 2 and 1.27~1.65 scored 1; *fabric thickness* 0.24~0.26 scored 3, 0.27~0.39 scored 2, 0.40~0.52 scored 1; all values in *air resistance* are qualified; *water vapour permeability* 841.09~978.55 scored 1, 978.56~1116.02 scored 2, 1116.03~1253.48 scored 3. For outer layer, *fabric weight* 0.42~0.65 scored 4, 0.66~0.89 scored 3, 0.90~1.13 scored 2, 1.14~1.37 scored 1; *fabric thickness* 0.06~0.12 scored 4, 0.13~0.19 scored 3, 0.20~0.25 scored 2, 0.26~0.32 scored 1; *air resistance* < 1 poor air resistance scored 1, 1~∞ good air resistance scored 4; *water vapour permeability* 425.81~595.26 scored 1, 595.27~764.71 scored 2, 764.72~934.16 scored 3, 934.17~1103.62 scored 4; all *UPF rating* are qualified except O6; all *anti-abrasion* and *anti-static* values are qualified.

4.6 COOLING SOURCE ENGINEERED

Hybrid cooling is used for the newly designed PCS, which includes ventilation fans and phase change material (PCM) packs. The effectiveness of the newly designed hybrid PCS mainly depends on the combined cooling source, i.e. PCMs and air cooling system (Song and Wang, 2016). Hybrid cooling sources with ventilation fans and PCMs were selected because of many reasons, including the following. (1) The PCMs help with conductive cooling. Solid PCM packs in the clothing increase the clothing insulation, thereby impeding sweat evaporation and making the skin sticky and wet. (2) The circulating air by the ventilation fans around the body enhances evaporative and convective heat dissipation; however, the ventilated air can be inefficient or even harmful to the skin when the ambient air temperature is very high (over 35 ℃). (3) Combining PCMs and ventilation fans in the PCS helps improve wetness sensation because of the circulated air around the body and ensure cooling efficiency since the PCMs improve conductive heat transfer and cool down the ventilated air. Commercially available products were tested for selecting the PCM with appropriate melting temperature and large heat of fusion and customising ventilation fans with high air flow rate, light weight and long work duration.

4.6.1 Phase change material (PCM) packs

PCM (e.g. ice, inorganic salt and paraffin wax), classified as latent heat storage material, can absorb and release heat at a roughly constant temperature (i.e. melting temperature) as it goes through solid–liquid transitions (Shim et al., 2001). When the ambient temperature is higher than the melting temperature, PCM absorbs heat energy as it goes from a solid state to a liquid state, producing a temporary cooling effect (Shim et al., 2001). The PCM packs were chosen in the PCS to enhance conductive heat dissipation. Indicated by PCM's transition from solid to liquid, the conductive cooling effect can sustain 1–3 hours based on the amount of the PCM packs, surface area of the PCM packs and temperature gradient between the PCM's melting temperature and ambient environment's temperature. Commercially available PCM packs with melting temperature of 10 ℃–30 ℃ were compared. Heat of fusion of PCM packs was measured by the differential scanning calorimetry (DSC822e, Mettler Toledo, USA). Differential scanning calorimetry was used to measure heat flow during the phase transitions of PCM, resulting in a curve of heat flux versus temperature.

The PCM packs adopted have melting temperature of 28 ℃ and latent heat of fusion of 131 J/g (Table 4.5). The PCMs absorb heat when the ambient temperature is higher than their melting temperature. The studies by Gao et al. (2010, 2011) on both manikin and humans found that PCM with melting temperature of 24 ℃ –28 ℃ have strong cooling effect. According to the sweating thermal manikin test, the cooling power of the cooling vest with PCM 28 is comparable with that of the cooling vest with PCM 24 (65.8 ± 5.6 W/m^2 versus 64.5 ± 6.1 W/m^2, $p > 0.05$). Besides, the latent heat of fusion of PCM 28 is higher than that of PCM 24 (131 J/g versus 105 J/g). Therefore, PCMs with melting temperature of 28 ℃ were utilised in the newly designed PCS. The PCMs with 28 ℃ melting temperature provide much milder cooling than the ice packs. An ice vest causes significant decreases in skin temperature, thereby inducing skin vasoconstriction (Bogerd et al., 2010; Cotter et al., 2001). The vasoconstriction can slow down skin blood flow, thereby decreasing the heat transfer between the body and the ice vest (Cheuvront et al., 2003). In addition, PCM at 28 ℃ can be solidified at room temperature with air-conditioning (20 ℃ –25 ℃), which relieves the need of freezing the ice pads (or other PCMs with low melting temperature) in a freezer to turn them back to solid state and hence easier to maintain and implement on site.

Considering the distribution of sweat gland, eight PCM packs were evenly placed on the chest and back region of the body, which covers 960 cm^2. Large mass and latent heat of PCMs improve the cooling duration, whereas high temperature gradient and large coverage area increase cooling rate (Gao et al., 2010).

Table 4.5 Thermo-physical properties of the phase change materials (PCMs) used in the cooling vests

PCM	Main component	Melting temperature (℃)	Onset temperature (℃)	Endset temperature (℃)	Latent heat of fusion (J/g)	Weight (g)	Total latent heat available (kJ)	Total covering area (cm^2)
PCM28	Sodium sulphate	28	29.22	36.18	131	880 (110×8)	115.28	960 (120×8)
PCM24	Sodium sulphate	24	25.50	34.45	105	880 (110×8)	92.40	960 (120×8)
ICE	Ice	0	2.95	11.72	334	420 (140×3)	140.28	300 (100×3)

4.6.2 Ventilation unit[2]

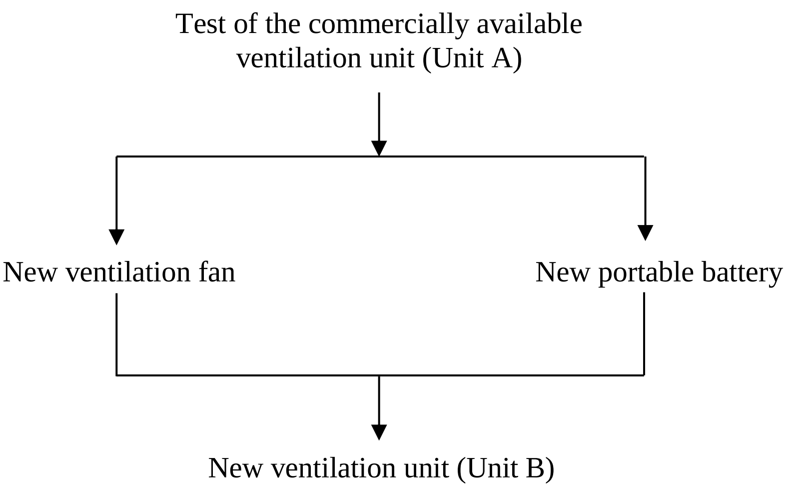
Ventilation fans in the PCS circulated air around the body, thus facilitating convective and evaporative heat transfer. The ventilation fans can be powered by portable battery pack and are expected to work for about 7 hours with a fully charged battery (Yi et al., 2017b). The ventilation unit consists of a pair of ventilation fans and a battery pack (Figure 4.2). The evaluation of a ventilation unit for PCS was conducted following the steps illustrated in Figure 4.3. The air flow rate of the commercially available ventilation unit (Unit A) was measured with a hot wire anemometer, and its work duration was also recorded. To achieve

[2] Presented in a published paper: Yi, W., Zhao, Y., Chan, A.P.C. (2017b). Evaluation of the ventilation unit for personal cooling system (PCS). International Journal of Industrial Ergonomics, 58, 62-68.

higher performance, a unit with newly customised fan and battery was proposed, i.e. Unit B. The air flow rate of Unit B was measured and compared with that of Unit A.

Figure 4.2 Ventilation unit (a pair of fans and a battery pack)

Figure 4.3 Overall framework of evaluating the ventilation unit for PCS



The parameters of ventilation fans for both Unit A (Fan A) and Unit B (Fan B) are shown in Table 4.6. Fan B is a little heavier than Fan A. The number of blade in Fan B (9) is more than that in Fan A (5). The rated power of each fan is 2.5W, and diameter of each fan blade is 10 cm. In Unit A, the fans are powered by AA battery. In Unit B, the fans are powered by 7.4V rechargeable lithium–polymer (Li-Po) battery. The fans are connected to the battery by a Y-type cable. Two kinds of AA batteries are available, i.e., 1.5 V alkaline AA battery with 2122 mAh capacity [Gold Peak Industries (Holdings) Limited] and 1.2 V rechargeable nickel–metal hydride (NiMH) AA battery with 1300 mAh capacity [Gold Peak Industries (Holdings) Limited] (Table 4.7). The 7.4V Li-Po battery has three capacities, i.e., 3000, 3800, and 4400 mAh (BAK Battery Co., Ltd) (Table 4.7). All the batteries were fully recharged just before each test.

Table 4.6 Parameters of ventilation fans

Item	Appearance	Supplier	Rated power (W)	Diameter of blade (cm)	No. of blade	Weight (g)
Fan A		IB Co., Ltd.	2.5	10	5	87
Fan B		Jinghai Co., Ltd.	2.5	10	9	98

Table 4.7 Parameters of battery

	Capacity (mAh)	Weight (g)	Voltage (V)
Unit A/4 pieces of alkaline AA battery	2122	95.33	6
Unit A/4 pieces of rechargeable NiMH AA battery	1300	87.63	4.8
Unit B/ Li-Po rechargeable battery	3000	103.07	7.4
Unit B/ Li-Po rechargeable battery	3800	138.64	7.4
Unit B/ Li-Po rechargeable battery	4400	153.86	7.4

The air flow rate of the Unit A and B was tested and compared. A total of six test scenarios are listed in Table 4.8. The first five scenarios were tested at full output power. In Unit A, Fan A was powered by 6 V 2122 mAh alkaline AA battery and 4.8V 1300mAh rechargeable NiMH AA battery, respectively. The four pieces of AA batteries were connected in series to provide 6 V and 4.8 V voltages, respectively. In Unit B, Fan B was powered by 7.4 V rechargeable Li-Po batteries with different capacity (3000 mAh, 3800 mAh and 4400 mAh). A controllable switch was used to compare fan performance powered by the same battery but under different output powers. In the last scenario, with the use of the controllable switch, Unit B_7.4 V 4400 mAh was adjusted to work at 60% output power (see Table 4.8, Scenario 6).

Table 4.8 Test scenarios

No.	Item	Description
1	Unit A_6 V 2122 mAh	Fan A powered by 6 V 2122 mAh alkaline AA battery
2	Unit A_4.8 V 1300 mAh	Fan A powered by 4.8 V 1300 mAh NiMH rechargeable AA battery
3	Unit B_7.4 V 3000 mAh	Fan B powered by 7.4 V 3000 mAh Li-Po battery
4	Unit B_7.4 V 3800 mAh	Fan B powered by 7.4 V 3800 mAh Li-Po battery
5	Unit B_7.4 V 4400 mAh	Fan B powered by 7.4 V 4400 mAh Li-Po battery
6	Unit B_7.4 V 4400 mAh (60% output)	Fan B powered by 7.4 V 3000 mAh Li-Po battery at 60% output power

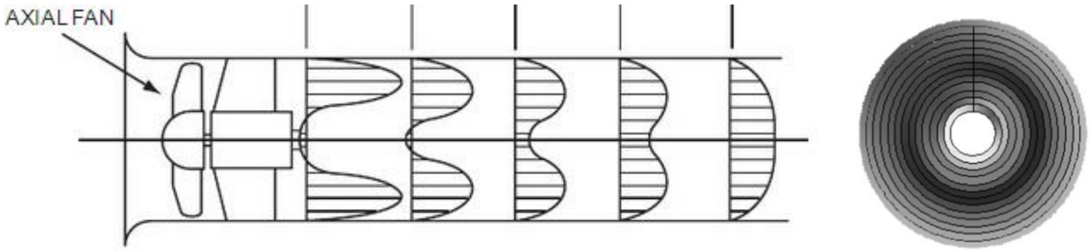
A hot wire anemometer was used (RS327-0640, Taiwan) to measure the air flow rate of the fan. The fan was connected tightly to a duct to make the air flow parallel through the duct. The hot wire probe was then inserted into the duct (10 cm in front of the axial fan) to measure the air flow rate. Figure 4.4a shows the changes in velocity profiles at various distances from the axial-flow fan outlets (AMCA, 2007). The airflow velocity is inconsistently distributed along the circular cross section. In Figure 4.4b, the darker the shade, the higher the airflow velocity (IEC, 1986; Zhao et al., 2012). The hot wire measured the airflow every 1 cm from the edge to the center of the circle, which was divided into five circle rings. The volumetric air flow rate can be calculated by the following formula:

$$Q = \sum v_i \cdot A_i \quad (4.1)$$

where v_i is the airflow velocity in each circle ring, and A_i is area of the circle ring corresponding to v_i. Air velocity was measured every 30 min until the battery was exhausted. The overall work duration was recorded.

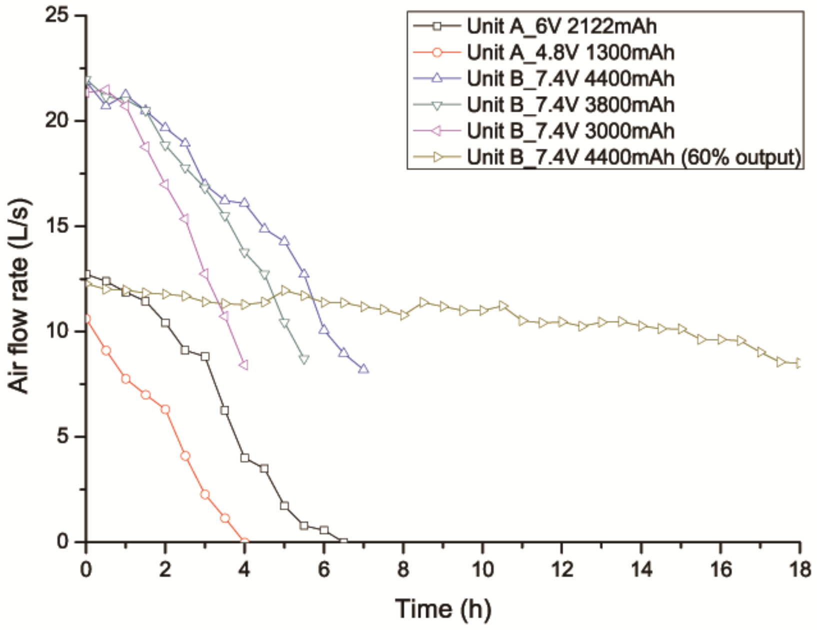
Figure 4.4 (a) Velocity profile in a straight length of outlet duct (adapted from AMCA 201-02, R2007, pp.5); (b) Airflow distribution on the circular cross section (adapted from Zhao et al. (2012), pp.291)

(a) (b)



Unit A was powered by 6 V 2122 mAh alkaline AA battery and 4.8 V 1300 mAh NiMH rechargeable AA battery, which worked for 6.22 and 3.75 h, respectively. The air flow rate was measured every 30 min. The fan operated at a flow rate of over 5 L/s only before second and third hours (Figure 4.5). The airflow of the fan powered by the AA battery subsequently decreased gradually to zero. Throughout this entire period, the air flow rate ranged from 13 L/s to 0 L/s for Unit A_6 V 2122 mAh and from 11 L/s to 0L/s for Unit A_4.8 V 1300 mAh. The total volume of air flow, calculated by the integral of air flow rate over time, was 1.69×10^5 L for Unit A_6 V 2122 mAh and 0.87×10^5 L for Unit A_4.8 V 1300 mAh.

Figure 4.5 Air flow rate and work duration of the Unit A and Unit B



Unit B was powered by 4400, 3800, and 3000 mAh Li-Po batteries, which could work for 7.05, 5.87 and 4.03 h, respectively. The air flow rate was measured every 30 min, as shown in Figure 4.5. The fan stopped working abruptly because the embedded protection circuit module in the Li-Po battery pack ensured overcharge/discharge, over-current and short-circuit protection. When the battery discharged to approximately 4 V, the circuit was cut off to stop the fan. Before the end point, the fan could maintain an air flow rate of 8–22 L/s. Under the same voltage, i.e. 7.4V, the axial fan operated longer when powered by a battery with a larger capacity. The total volume of air flow over work time was 2.64×10^5 L, 3.59×10^5 L and 4.34×10^5 L for Unit B_7.4 V 3000 mAh, Unit B_7.4 V 3800 mAh and Unit B_7.4 V 4400 mAh, respectively, which are higher than that of Unit A powered by AA battery. When the output power of the 7.4V 4400 mAh battery was reduced to 60%, i.e. the overall capacity remained the same whereas the output voltage was adjusted to 4.5 V by a controllable switch, the fan worked for 18 h at a lower air flow rate of 8–12 L/s (Figure 4.5).

4.7 PROTOTYPE DEVELOPED[3]

A tailor-made PCS for the construction industry was developed (Figure 4.6). The principal rules of design were listed as follows:

(1) Strong cooling power;
(2) Long cooling duration;
(3) Achieving thermal comfort;
(4) Mobility, weight and compact design (without any external connections);
(5) Wearing comfort (perfect fit to wear over the construction uniform, without interfering with work);
(6) Excellent UV protection;
(7) Fit-design;
(8) Visibility and safety;
(9) Aesthetics;
(10) Ergonomics.

These rules are summarized based on literature review and previous "Cooling Vest Promotion Pilot Scheme" field study on construction sites. The rules of design are strongly correlated with the design and engineer of cooling sources and fabrics as presented in the

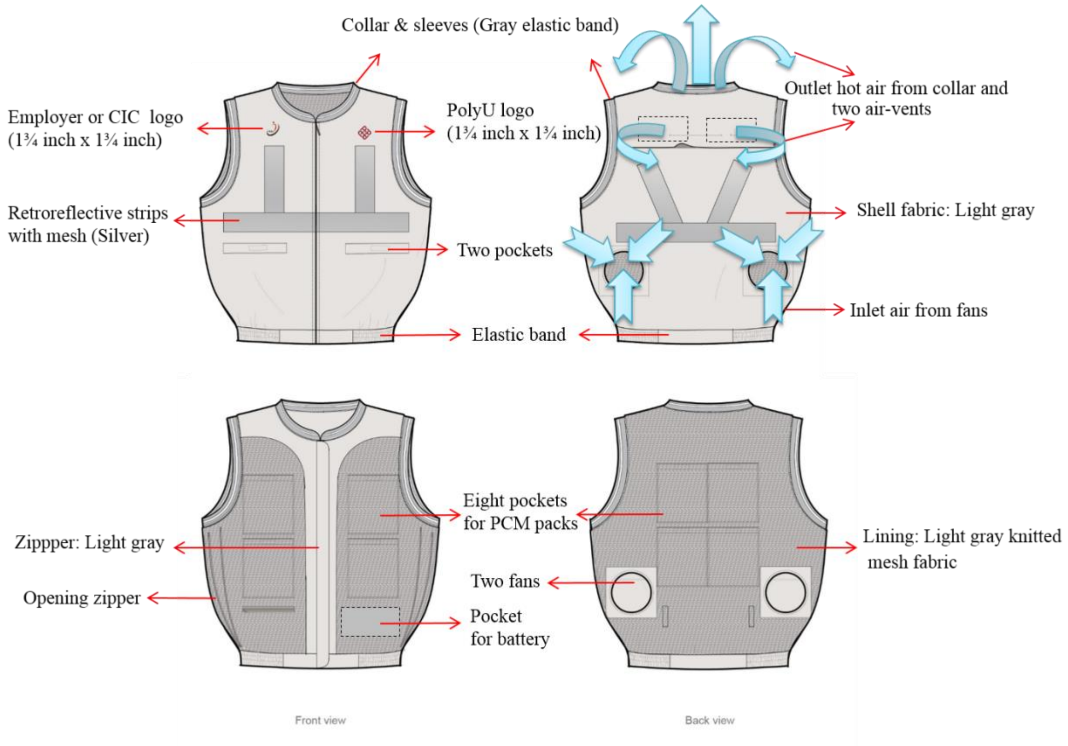
[3] Presented in a published paper: Zhao, Y., Yi, W., Chan, A. P., Wong, F. K., & Yam, M. C. (2017b). Evaluating the physiological and perceptual responses of wearing a newly designed cooling vest for construction workers. Annals of Work Exposures and Health, 61(7), 883-901.

aforementioned sections 4.5 and 4.6. Some rules are conflicting with each other whereas others are supplementary. For example, (1) strong cooling power and (2) long cooling duration are balanced with (3) thermal comfort and (4) weight. To achieve strong cooling power and long cooling duration, heavy cooling sources are needed (e.g. large amount cooling packs and high volume battery). However, the total weight was controlled below 1.5 kg by selecting proper amount and type of PCM packs and customizing lightweight battery with required volume. The use of PCM packs with low melting temperature (e.g. ice packs) can provide strong cooling power. However, the ice packs may irritate the skin and provide negative thermal comfort sensation. After comparison and test, PCM with 28℃ melting temperature was selected. Rules (5), (6), (7), (8), (9) and (10) are supplementary factors that can be combined with each other in the design of PCS.

This two-layer cooling vest incorporated a pair of ventilation fan and eight PCM packs. The total mass of the cooling vest is 1.26 kg (including a pair of fans and eight PCM packs).The eight PCM packs are evenly placed (four at the chest and four at the back region considering the distribution of sweat gland) in the newly designed PCS. The PCM packs cover an area of 960 cm^2. To enhance air circulation, the ventilation fans are fixed at the lower back with two openings at the upper back of PCS (Figure 4.7a) (Zhao et al., 2017b). The air gap between the skin surface and inner layer of the new vest is from 55 mm at the lower back region to 10 mm at the upper back region (Figure 4.7b shows the 2D geometry) (Zhao et al., 2017b). The air gap was determined through the following steps. First, the two measuring points were marked on the middle of the lower back and upper back of the cooling vest (non-solid circle in Figure

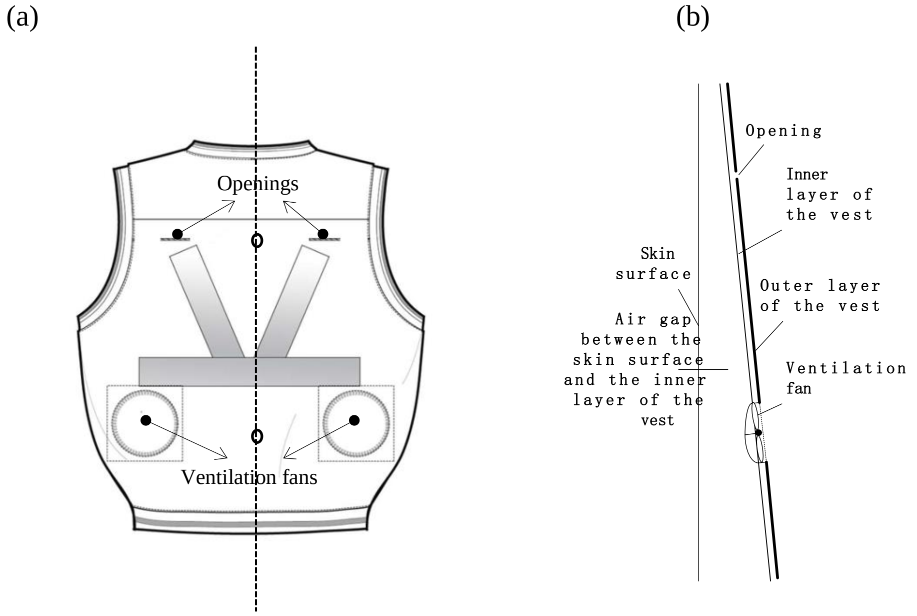
4.7a). The cooling vest was worn on a male manikin, and the ventilation fan was turned on (with PCM packs). Then, a long needle was inserted into the marked point, and the distance between the outer layer of the vest and the manikin surface in contact with the needle was recorded. This step was repeated five times, and the average distance value was used. This value minus 7 mm (the thickness of the vest with PCM packs) is the air gap between the skin surface and the inner layer. A larger gap thickness between the skin and textile garment can enhance convective and evaporative heat transfer along the skin surface. At the upper back, the much smaller air gap ensures close contact between the PCM packs and the skin surface to increase conductive cooling.

Figure 4.6 The newly designed PCS (two-layer cooling vest) incorporating PCM packs and ventilation fans



Adapted from Chan et al. (2017)

Figure 4.7 (a) Cooling vest with small ventilation fans and openings at the back (b) 2D model for the air gap between the skin surface and vest



The new PCS design considers the cooling effect, weight, mobility, comfort, aesthetics, visibility and safety of construction workers. For instance, different front and back designs were adopted to improve on-site visibility and safety. For wearing comfort and mobility, a loose-fit and compact (cooling sources are compacted without any external connections) design was adopted to avoid entanglement with the moving parts of machines.

4.8 SUMMARY

This chapter presents the development of a tailor-made PCS for the construction industry. The development of such a PCS includes six stages, as follows: (1) request made, (2) design situation explored, (3) problem structure perceived, (4) fabric selected, (5) cooling source engineered and (6) prototype developed. The newly developed PCS is a two-layer cooling vest specifically designed to be worn over the construction uniform that was previously designed by our research team. The newly designed PCS has hybrid cooling feature, which includes ventilation fans and PCM packs. The PCS design comprehensively considers the cooling effect, cooling duration, weight, mobility, comfort, aesthetics, visibility and safety of construction workers.

CHAPTER 5 COOLING CAPACITY OF PCS[4]

5.1 INTRODUCTION

In this chapter, the cooling power of the personal cooling system (PCS) was measured and compared by a sweating thermal manikin in the climate chamber. The PCS incorporates hybrid cooling sources, namely, ventilation fans and phase change materials (PCMs). Four test scenarios were included: fan off with no PCMs (Fan-off), fan on with no PCMs (Fan-on), fan off with completely solidified PCMs (PCM + Fan-off), and fan on with completely solidified PCMs (PCM + Fan-on).

5.2 MATERIALS AND METHOD

5.2.1 Cooling vest

Two types of PCSs are compared in this chapter, namely, the commercially available ICEBANK cooling vest (Vest CB) and the other is the newly developed cooling vest (Vest B) (Yi et al., 2017c). The appearance of Vests CB and B is shown in Figure 5.1. The tested cooling vests are in the same size and both cooling vests include hybrid cooling sources, i.e., a pair of ventilation fans and cooling packs.

[4] Presented in a published paper: Yi, W., Zhao, Y., Chan, A.P.C. (2017c). Evaluating the effectiveness of cooling vest in a hot and humid environment. Annals of Work Exposures and Health, 61(4), 481-494.

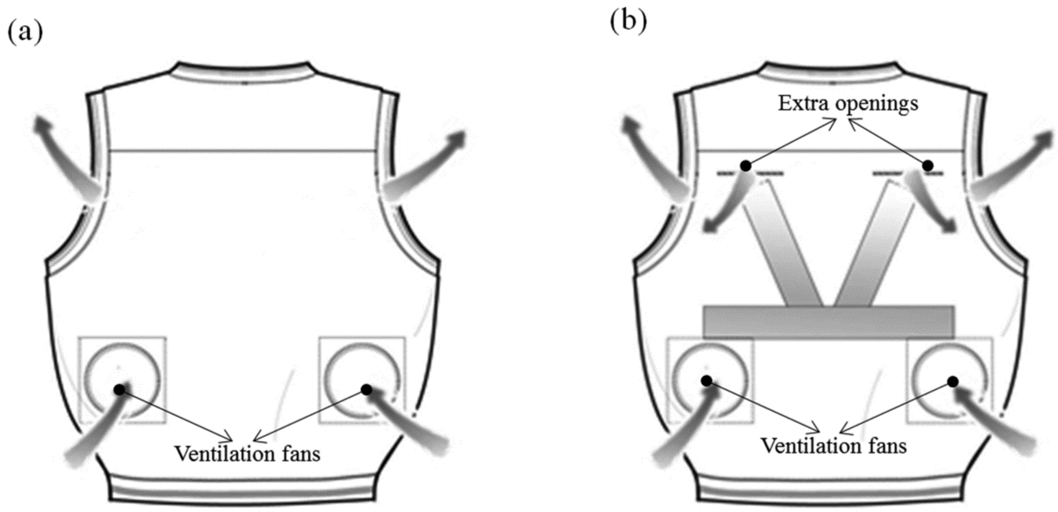
Figure 5.1 Appearance of the two types of cooling vest: (A) Vest CB, (B) Vest B

(A) Vest CB

(B) Vest B

The ventilation fans are at the lower back of the cooling vest. The two vests have normal openings at the cuffs and collar. Vest B has extra openings at the upper back to enable extra channels for air outlet. Figure 5.2 shows the pathway of air flow in the cooling vests.

Figure 5.2 (a) Air flow in Vest CB; (b) Air flow in Vest B



The cloth properties of Vests CB and B are listed in Table 5.1. The outer layer of both vests is made of nylon taffeta and the inner layer is made of mesh spacer fabric. The cloth of Vest B is lighter than that of Vest CB. The outer layer cloth shows high air resistance, which facilitates air ventilation around the body. The cloth of Vest B display higher water vapour permeability than that of Vest CB, which benefits sweat evaporation.

Table 5.1 Cloth properties of the cooling vests

	Vest CB			Vest B		
	Inner layer	Outer layer	Reflective strip	Inner layer	Outer layer	Reflective strip
Fiber content	100% polyester	nylon taffeta	NA	100% polyester	nylon taffeta	100% polyester
Thickness (mm)[a]	0.29	0.12	NA	0.24	0.07	
Weight (g/100 cm^2)[a]	0.89	0.71	NA	0.48	0.42	2.08
Air resistance (kPa s/m)[a]	0	∞	NA	0	2.46	0.03
Water vapour permeability (g/m^2/day)[a]	841.09	938.50	NA	1253.48	1052.31	-
UPF[a]	-	40	NA	-	50+	-
Anti-abrasion (20000 spins-weight loss, %)[a]	-	0.48%	NA	-	0.55%	-

[a] Average value on five fabric samples.

Vest B includes eight PCM packs, whereas, Vest CB incorporates three ice packs. The thermo-physical properties of the cooling packs in the two vests are shown in Table 5.2. The cooling packs in Vest B have less latent heat than those in Vest CB; whereas, the cooling packs in Vest B cover greater body area than those in Vest CB. Prior to each test, the cooling packs were kept at the refrigerator (−10 ℃) for over 4 hours to solidify and reuse.

The air velocity of the fan in Vest B has four levels, and the maximum air flow rate is around 20 L/s when powered by a 7.4 V lithium polymer battery. The velocity of the fan in Vest CB has two levels, and the maximum flow rate is around 12 L/s when powered by a 6 V alkaline battery (Table 5.3). Prior to each test, the batteries were fully recharged.

Table 5.2 Thermo-physical properties of the phase change materials (PCMs) used in the two cooling vests

Cooling pack	Melting temperature	Latent heat of fusion	Weight	Total latent heat available	Total covering area
Ice	0 ℃	336.94J/g	139g×3=417g	140.50 kJ	100cm^2 ×3=300cm^2
PCM28	28 ℃	131.43J/g	110g×8=880g	115.66 kJ	120cm^2×8=960cm^2

Table 5.3 Properties of ventilation unit in the two cooling vests

		Vest CB	Vest B
Fan	Diameter (mm)	100	100
	Rated power (W)	2.5	2.5
	Weight (g)	86.51	95.52
Battery	Material	Alkaline	Lithium polymer
	Voltage (V)	6	7.4
	Capacity (mAh)	2122	4400
	Size (mm)	19 × 64 × 80	22 × 71 × 86
	Weight (g)	138.61	176.88
		Fan A	Fan B
Air flow rate	Level 1	8 L/s	8 L/s
	Level 2	12 L/s	12 L/s
	Level 3	NA	16 L/s
	Level 4	NA	20 L/s

The cooling vest is designed to wear over the construction uniform (consists of a polo shirt and a pair of long pants) designed in our previous study (Figure 5.3). This construction uniform shows superior performance in thermal-moisture properties and improving the wearers' comfort as compared to the Construction Industry Council (CIC) uniform, which is commonly worn by construction workers in Hong Kong (Chan et al., 2016a). A single set of cotton briefs were worn under the construction uniform.

Figure 5.3 The whole manikin clothing system

Front view Rear view

5.2.2 Test protocol

The cooling vest tested in this study includes two types of cooling sources, namely, ventilation fans and cooling packs. A total of six combination scenarios of cooling packs and fans were tested according to standard ASTM F2370 and ASTM F2371 (Table 5.4). A heated sweating thermal manikin, Newton (Measurement Technology Northwest, Seattle, WA, USA), was used in this study. A torso fabric skin (100% nylon knitted) that tightly fitted the Newton was used to simulate torso sweating. The sweating rate was set to 1,200 ml/hr m^2 in the current study to simulate the heavy sweating of human body. The air temperature in the climate chamber was set at 34 ℃ equal to the manikin surface temperature. This process ensures that no dry heat loss will occur from the manikin to the ambient environment. Air velocity was set to 0.4 ± 0.1 m/s. Relative humidity in the chamber was maintained at 60%, which was the average value collected in the construction field in Hong Kong during the summer from July 2011 to August 2011 (Wong et al., 2014). Segmental heat losses under each scenario were recorded at 1-min interval. Each test scenario was repeated thrice on the thermal manikin and average values were used for data analysis.

Moreover, the thermal insulation of different clothing scenarios was determined by using a thermal manikin (dry, without sweating skin) under the environment of 19.5 ℃, 50 ± 5% RH, and 0.4 ± 0.1m/s. The manikin surface temperature was maintained at 34 ℃. Tests were carried out according to procedures in ASTM F1291-10 and ISO 15831-2004.

Table 5.4 Test scenarios

Item	Description
CU	Construction Uniform
Vest CB (Icepack + Fan-on)	Construction Uniform + ICEBANK Vest (three ice packs + Fan-on)
Vest CB (Fan-on)	Construction Uniform + ICEBANK Vest (Fan-on)

Item	Description
Vest CB (Icepack)	Construction Uniform + ICEBANK Vest (three ice packs)
Vest B (PCM28 + Fan-on)	Construction Uniform + NEW Vest (eight PCM28 packs + Fan-on)
Vest B (Fan-on)	Construction Uniform + NEW Vest (Fan-on)
Vest B (PCM28)	Construction Uniform + NEW Vest (eight PCM28 packs)

NOTE: The air flow rate of Fan-on in Vest CB is 12 L/s and that of Fan-on in Vest B is 20 L/s.

5.2.3 Calculation and analysis

The cooling power of the torso region was calculated to quantify the cooling capability of the cooling vests. Torso heat loss Q in W/m^2 referred to the area weighted by the six covered zones, namely, upper chest, shoulders, stomach, mid-back, waist, and lower back. The baseline test was performed without the cooling source (or the cooling source is turned off). The cooling capability test was conducted with the cooling source (or the cooling source is turned on). The cooling power in Fan-on and PCM + Fan-on scenarios was calculated by deducting the mean steady-state heat loss in Fan-off and completely melted PCM (mPCM) + Fan-off (i.e., the baseline condition) from the total recorded heat losses in Fan-on and PCM + Fan-on, respectively. The thermal insulation I_t in ℃ m^2/W and evaporative resistance R_{et} in kPa m^2/W of different clothing scenarios was further calculated by dry and evaporative heat loss, respectively.

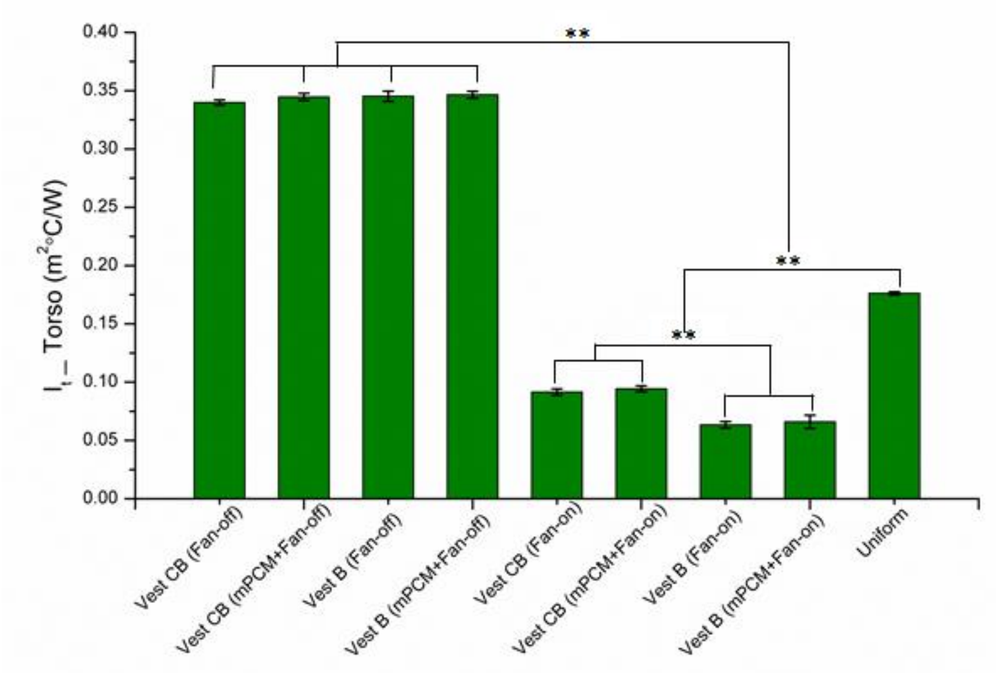
Then, one way analysis of variance (ANOVA) was performance to analyse the significant difference in clothing scenarios according to torso cooling. Bonferroni’s post hoc test was further used to assess the difference between clothing scenarios (Lu et al., 2015). SPSS version 16.0 (SPSS, Chicago, IL, USA) was used in the analysis. The significance level was $p < 0.05$.

5.3 RESULTS

5.3.1 Thermal insulation and evaporative resistance

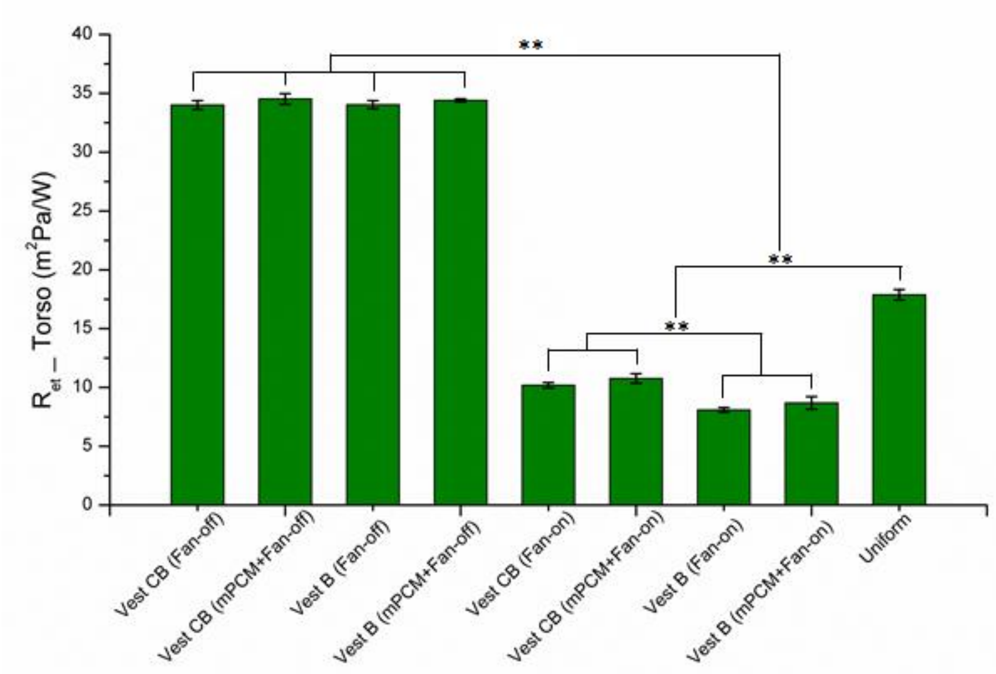
Thermal insulation (I_t) and evaporative resistance (R_{et}) of the tested clothing scenarios are shown in Figure 5.4 and Figure 5.5, respectively. The cooling vest covered the torso region of the sweating thermal manikin. Results showed that the use of completely melted PCMs in the vest did not significantly influence the I_t and R_{et} of the torso region. When the fan was turned off, the added vest significantly increased the I_t and R_{et} of the torso compared to those of the construction uniform scenario ($p < 0.01$). The Fan-on condition improved the heat loss of the thermal manikin and significantly reduced the I_t and R_{et} of the vest compared with those of the construction uniform ($p < 0.01$). In the Fan-on condition, the I_t and R_{et} of Vest CB are significantly higher than those of Vest B ($p < 0.01$).

Figure 5.4 Thermal insulations of It_Torso in different scenarios



(mPCM, completely melted PCMs; *, $p < 0.05$; **, $p < 0.01$)

Figure 5.5 Evaporative resistances of Ret_Torso in different scenarios



(mPCM, completely melted PCMs; *, $p < 0.05$; **, $p < 0.01$)

5.3.2 Cooling capacity of different clothing combinations

The ventilation fans and cooling packs provided hybrid cooling effect. Heat loss of the torso was observed and compared among the six clothing scenarios (Figure 5.6). Accordingly, the cooling power was determined by deducting the baseline cooling power (Figure 5.7). Overall, the cooling power of Vest CB is significantly lower than that of Vest B. The ventilation fan provided constant and stable cooling during the entire test period (180 min). The cooling power of Vest B with fan on (no PCM) is approximately 67 W, which is higher than the approximately 51 W of Vest CB (fan on, no PCM). The use of PCMs increases heat loss during the initial stage (before PCMs completely melted). The eight PCM28 packs in Vest B (PCM28 + Fan-off) showed a cooling effect for approximately 60 min, arriving to 22 W at the initial point. In comparison, the three icepacks in Vest CB (Icepack + Fan-off) provided an initial cooling effect of 10 W, which then gradually decreased to 0 W at the end of the test.

Figure 5.6 Heat loss_Torso in different test scenarios

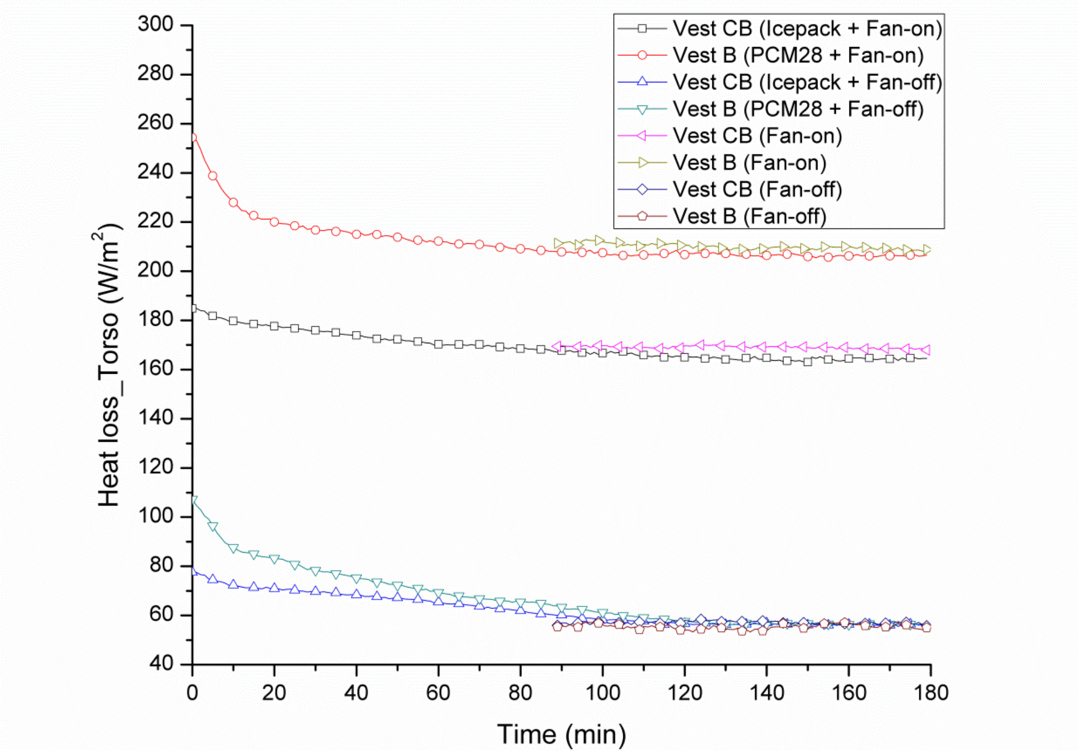
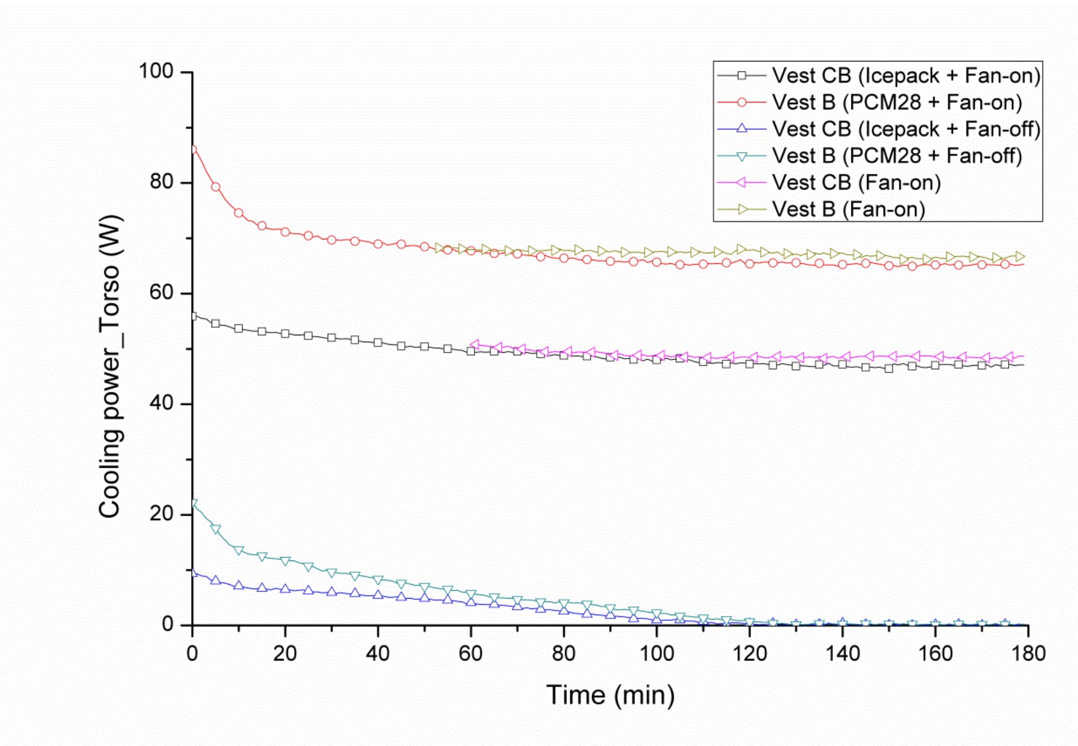


Figure 5.7 Cooling power_Torso in different test scenarios



5.4 DISCUSSION

5.4.1 Efficiency of the hybrid cooling vest

The cooling power of different clothing scenarios were measured and compared inside the environmental chamber under 34 ℃ temperature, 60% RH, and 0.4 m/s air velocity, which simulated a mean weather condition of construction sites in Hong Kong during summer (recorded in July to September 2010–2011) (Wong et al., 2014). The cooling vests used in the present study are effective in such a hot and humid environment. Results show that Vest B (newly designed cooling vest) has significantly higher cooling power than Vest CB (commercially available cooling vest). In the Fan-on + PCM condition, before the PCM is completely melted, the vest provided two types of cooling sources, namely, PCM and ventilation fan, thereby improving both conductive and evaporative heat transfer. Another study by Kim et al. (2011) applied hybrid cooling in human trials where they combined liquid cooling garments (LCGs) with ventilation air; they determined that the hybrid cooling garment significantly reduced heat strain and improved exercise performance in a hot environment (35 ℃, 50% RH). This hybrid cooling garment (LCG/PCM enhances conductive heat transfer and ventilation fan enhances evaporative heat transfer) is quite similar to air cooling garments (ACGs) with cooled inlet air, which is connected to an external cooling device, thus promoting the circulation of the cooled air around the body. Previous studies on human tests demonstrated that ACGs with cooled inlet air at certain considerably low flow rates, such as 12 ℃ at 9.17 L/s (McLellan et al., 1999), 13 ℃ at 4.67 L/s (Vallerand et al., 1991), and 20 ℃ to 27 ℃ at 7.075 L/s (Pimental et al., 1987), have significantly reduced heat strain and substantially enhanced the subjects' heat tolerance. ACGs with cooled air can still be effective in extremely hot environment, such as 49 ℃ and 20% RH (Pimental et al., 1987), 40 ℃ and 30% RH (McLellan et al., 1999), and 37 ℃ and 50% RH (Vallerand et al., 1991).

5.4.2 Cooling efficiency of ventilation fan

The ventilation fans in the vest blew the ambient air on the skin and increased the torso heat loss compared to those in the Fan-off condition. The ventilation fan increases the air velocity around the torso, which alters the evaporative heat transfer coefficient (Candas et al., 1979; Zhao et al., 2013b). Thus, evaporative cooling is enhanced because of the increased evaporative heat transfer coefficient (Zhao et al., 2013b). Under 34 ℃, 60% RH, Vest B had a 275% increase in torso heat loss compared to that of the Fan-off condition; Vest CB had a 200% increase in torso heat loss. These results are comparable to previous manikin test studies. The air velocity of the ventilation fan is 20 L/s in Vest B and 12 L/s in Vest CB. Zhao et al. (2013b) determined that the short-sleeved air jacket had an increase of 205% heat loss in the torso region in comparison with that of the Fan-off condition in a 34 ℃, 60% RH environment. Lu et al. (2015) used the ventilation unit on a long-sleeved jacket and determined a 160% increase of heat loss in the upper body region in a hot and humid condition (34 ℃, 75% RH). They also determined a considerable increase of 184% heat loss in a hot and dry condition (34 ℃, 28% RH). The air velocity of the fans in the studies of Zhao et al. (2013b) and Lu et al. (2015) was at 12 L/s. The high cooling efficiency of the ventilation fan in a hot and dry environment is driven by the considerably large water vapour pressure gradient between the wet fabric skin and the ambient (Lu et al., 2015; Zhao et al., 2013b). Based on Xu and

Gonzalez's (2011) model, the cooling capacity of an air ventilation garment on a sweating thermal manikin decreases as the ambient air temperature or relative humidity increases.

The cooling power measured on the thermal manikin is regarded as a physical property, and its actual effectiveness in reducing heat strain from the human body is further evaluated in physiological studies (Xu and Gonzalez, 2011). Researchers have demonstrated the cooling effectiveness of the ACG ventilating ambient air around the body with different air flow rates under hot environments, such as, 6.2 L/s under 45 ℃, 10% RH (Barwood et al., 2009b); approximately 6 L/s under 40 ℃, 20% RH, 30 ℃, 50% RH, and 35 ℃, 75% RH (Chinevere et al., 2008); and 5.7 L/s under 32 ℃, 40% RH. The ACGs airflow rate and ambient environment can have an effect on the cooling capacity (Xu and Gonzalez, 2011).

5.4.3 Cooling efficiency of PCM

The PCM inserted in the vests enabled an additional cooling mechanism through conductive heat transfer (Zhao et al., 2013a). The melting temperature of PCMs is lower than the skin temperature, thus the temperature gradient between them enhanced the heat loss from the body. Generally, a minimum of 6 ℃ temperature gradient is required when the PCM vests are used in a hot environment (Gao et al., 2010). The initial cooling power provided by the PCMs of Vest B seems higher than that of Vest CB; the cooling duration is almost similar between the two vests. The PCM28 in Vest B had a larger covering area and more mass amount but less latent heat and higher melting temperature than those of the icepacks in Vest CB. Reinertsen et al. (2008) demonstrated that the distribution and number of PCM packs can determine the heat strain alleviation of similar PCM vests. Hence, *"the higher the temperature gradient, the greater the cooling area and the higher cooling rate"* (Gao et al., 2010). The mass and latent heat of capacities of PCMs mainly influence the duration of the cooling effect (Gao et al., 2010). The PCMs in Vest B are different from the icepack in Vest CB in terms of comprehensive factors, including vest design and the number and distribution of PCM packs.

Under a different environment, the PCM vest exhibits a different performance in reducing heat stress. When applied in a dry or moderately dry environment, the cooling effect of the PCM vests is not significant, because the evaporative heat loss in the baseline situation could have played an effective role (Lu et al., 2015; Zhao et al., 2013b). The cooling efficiency of PCMs is better in a hot and humid environment than in a hot and dry one (Lu et al., 2015). This finding is the opposite of the cooling effect of the ventilation fan garment, which exhibits better performance in a relatively dry environment (Lu et al., 2015; Xu and Gonzalez, 2011). Thus, the hybrid vest, which is a combination of PCMs and ventilation fans, is a better alternative for use in a range of conditions.

5.4.4 Industrial applications

In this study, cooling power was calculated by comparing the manikin heat loss in the Fan-on (with/without PCMs) and Fan-off (with/without completely melted PCMs) conditions. However, this result cannot be thought of equivalent to that in human tests (Xu and Gonzalez, 2011). The extra weight added by the cooling garment increases metabolic heat production, which may compensate the cooling effect. Wang et al. (2013) reported that the 6.5 kg additional weight of protective clothing (e.g., firefighting clothing) raised the human metabolic rate by approximately 20 W/m^2. The total weight of the cooling vest (including 8 PCM packs and 1 ventilation unit) developed in the present study is 1.26 kg, which resulted in an estimated increase of 3.88 W/m^2 metabolic rate (assuming the relationship between the added clothing weight and human metabolic rate is linear, that is, 6.98 W for an average man of 1.8 m^2 surface area) (Lu et al., 2015). Meanwhile, the cooling power of Vest B in the Fan-on and Fan-on + PCM conditions tested in this study was approximately 67 W and 86 to 67 W, respectively, thereby exhibiting high cooling performance during the entire 3 hours. Given that construction workers are generally required to complete intensive construction work in a hot outdoor environment, a cooling vest designed with the cooling power considerably higher than the increased metabolic rate that its weight brings can be easier for the user to accept (Lu et al., 2015).

Apart from the added weight, insulation parameter including the evaporative and thermal resistance of the overall clothing is another factor that should be considered when the cooling vest is applied in practical situations. The added clothing layer of the vest increased both evaporative and thermal resistance compared to those of the construction uniform (t-shirt + pair of pants) only. When the fan is turned on, this situation is significantly improved, that is, the evaporative resistance from 34 m^{2}Pa/W in the Fan-off condition to 12 m^{2}Pa/W in the Fan-on condition is considerably lower than that of the construction uniform condition (16 m^{2}Pa/W). The cooling vest in this study exhibited high performance in terms of cooling power and insulation on the sweating manikin. However, further comparison of human responses with and without the cooling vest is necessary to determine its actual cooling effectiveness.

5.5 SUMMARY

This chapter compares the cooling performance of the newly developed cooling vest with that of a commercially available cooling vest on the sweating thermal manikin. The hybrid cooling vest includes PCM packs and a pair of ventilation fans compacted in the vest without any external connection. Without cooling sources (no PCM and the fan was turned off), the newly designed vest has similar insulation performance in the torso region (i.e., thermal insulation and evaporative resistance) with the commercially available vest (approximately 0.36 m^2 ℃ /W thermal insulation and 34 m^2Pa/W evaporative resistance). In the Fan-on condition, the insulation parameter of the newly designed vest is significantly lower than that of the commercial one ($p < 0.01$). In the PCM + Fan-on condition, the vest provides two cooling sources, exhibiting 86 W to 67 W cooling power in the newly designed vest and 56 W to 49 W cooling power in the commercial one.

Overall, the sweating manikin tests in this chapter show that the newly designed cooling vest exhibits better cooling power than the commercial one. Human wear trials in the laboratory and real work settings should be conducted (shown in the following chapters) to comprehensively evaluate the newly designed cooling vest and promote its application in the construction industry.

CHAPTER 6 OPTIMAL COOLING INTERVENTION WITH PCS[5]

6.1 INTRODUCTION

This chapter examines the effectiveness of the newly designed personal cooling system (PCS) (i.e. a hybrid cooling vest) in alleviating physiological and perceptual strains in a climatic chamber that is set to 37 ℃ air temperature and 60% relative humidity to simulate a typical summer working environment of construction sites in Hong Kong. Human wear trials were performed with a work–rest protocol inside the climate chamber. Physiological and perceptual responses of human subjects were measured. The effectiveness of the cooling intervention with the newly designed cooling vest during work and/or rest period (VEST) was compared with that of the control condition without any cooling (CON).

6.2 PARTICIPANTS AND PROTOCOL I

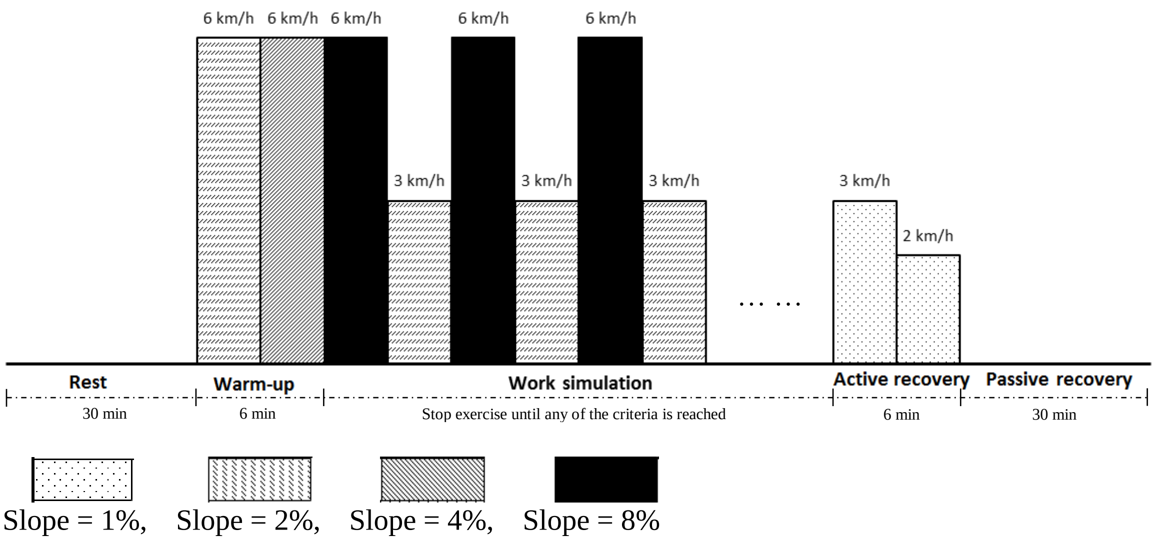
Protocol I was first proposed with the hypotheses that (1) PCS could reduce heat strain during exercise, (2) PCS could reduce heat strain during recovery, and (3) PCS could enhance work performance (prolong exercise duration). A total of ten healthy male university students participated in Protocol I (mean ± SD: age 23 ± 3.51 years; height 169 ± 4.63 cm; body mass 60 ± 7.55 kg; BMI 21.12 ± 2.17; resting heart rate 73 ± 5 beats/min). They have no history of diagnosed major health problem including diabetes, hypertension, cardiovascular disease,

[5] Presented in a published paper: Yi, W., Zhao, Y., Chan, A.P.C., Lam, E.W.M. (2017d). Optimal cooling intervention for construction workers in a hot and humid environment. Building and Environment, 118, 91-100.

neurological problem, and regular medication intake. All participants took exercises two or three times per week and were thought of physically active. They were asked to refrain from any medication/drug, smoking, caffeinated products or alcohol use, and doing intense exercises for at least 4 hours prior to each test. Participants were briefed on the study protocol. They signed a consent form approved by the University's Human Subjects Ethics Sub-committee. They were informed to avoid any smoking, medication/drug, alcohol use or caffeinated products, and intensive exercises for at least 24 h before each test.

Each participant undertook two experimental trials on separate days spaced at around one week (7 to 9 days), at the same time in the afternoon (to avoid circadian variation) (Price et al., 2009). Trials were conducted in a counter-balanced order and consisted of a repeated measures design in which subjects served as their own controls. Trials included VEST and CON, and were conducted in an environmental chamber. The whole protocol included 30 min pre-exercise rest, exercise (a period of 48 min intermittent jogging/walking), and post-exercise recovery (6 min active recovery and 30 min passive recovery) (Figure 6.1). In VEST, the cooling vest was used throughout the entire exercise and recovery periods. While in CON condition, no cooling vest was applied. Intermittent running was designed since construction work is largely intermittent in nature (Rappaport et al., 2003). Exercise intensities were designed based on the oxygen consumption of rebar workers captured in construction sites during hot summer in our previous studies, which ranged from 3.17 to 30.8 ml/min/kg and averaged 13.5 ± 4.9 ml/min/kg (Chan et al., 2012c). The 6 km/h with 8% slope corresponds to the estimated oxygen consumption of 30.7 ml/min/kg; 3 km/h with 2% slope corresponds to the estimated oxygen consumption of 10.3 ml/min/kg (ACSM, 2013). During exercise, participants stopped the exercise and progressed to recovery when any of the following circumstances occurred: (i) T_c reached 38.5 ℃; (ii) HR reached 95% of the age-predicted maximum HR (age-predicted maximum HR = 220 – age); (iii) participant requested to stop (due to difficulty in breathing, feeling very hot, or exhaustion); or (iv) they completed the 48 min intermittent jogging/walking. Rehydration with warm water (37 ℃; 3 ml/kg × body weight) was in the first 5 min of the passive recovery. In VEST condition, participants wore the cooling vest during exercise and recovery periods. While in CON condition, no cooling was applied. Considering the cooling duration of the cooling vest, phase change material (PCM) packs were replaced before the start of passive recovery.

Figure 6.1 Protocol I of the experiment



Participants were asked to swallow an ingestible capsule (CorTemp™, HQInc., USA) with warm water 4–6 hours before their arrival to avoid the confounding impacts of food and drink (Wilkinson et al., 2008) and ensure a more stable core temperature (Byrne and Lim, 2007). The participants were informed that this silicone coated capsule would measure their T_c and pass harmlessly through the body after 24−36 hours normally. Before delivered to the participants, each capsule was calibrated against a thermometer with an accuracy of $\pm(0.15+(0.002\times T))$℃ (Lutron®, Taiwan) in a water cup at temperatures ranging from 30 ℃ to 42 ℃ to ensure its accuracy and functionality (Edwards and Clark, 2006).

At the beginning of the experiment session, the participant was briefed on the protocol of the experiment and signed a consent form approved by the University's Human Subjects Ethics Sub-committee. The participant then consumed 3 ml/kg body weight of warm water at 37.00 ± 0.18 ℃. Afterwards, the participant was asked to take off his own clothes, weigh body mass (with only underwear), and put on the experimental uniform. In the test, this newly designed cooling vest was worn over the construction uniform, consisting of a T-shirt and a pair of long pants. The specification of the uniform has been used as an industry standard to help workers combat heat stress (Chan et al., 2016a). The participant was also equipped with a HR belt (Polar T34 Transmitter, Finland), CorTemp data logger (CorTemp™, HQInc., USA), thermistor sensors (LT8A, Gram Co., Japan), and microclimate humidity sensors (Especmic, Japan) for recording the heart rate, the core temperature, the skin temperatures, and the microclimate humidity, respectively.

The participant then entered the environmental chamber, which was set to 37 ℃ temperature, 60% relative humidity, 0.3 m/s air velocity, and solar radiation of 450 W/m^2 to simulate the typical summer working environment of construction sites in Hong Kong (Yi et al., 2017a). The environmental chamber (LabTester, KSON, Taiwan) has a dimension of 3 m × 2.5 m × 2.2 m (length × width × height). The WBGT monitor was set in the chamber to ensure that the environment had reached 36.1 ℃ WBGT, which is a typically recorded value in the construction sites (Chan et al., 2012a; Wong et al., 2014). The subject remained seated in the environmental chamber for 30 minutes for the stabilization of muscle and core temperature. After the stabilization period, the participant performed intermittent running on a motorized treadmill (h/p/cosmos® pulsar, Germany).

6.3 PARTICIPANTS AND PROTOCOL II[6]

In Protocol I, PCS was used during exercise and recovery. The Protocol II was designed based on the results in Protocol I when the cooling intervention could not significantly reduce heat strain during exercise (i.e. the results in Protocol I failed the hypotheses) (Zhao et al., 2017b). In Protocol II, the cooling intervention with the newly designed cooling vest was applied only during the recovery period. Moreover, a period of exercise after passive recovery was included in Protocol II to examine the cooling effect of the newly designed cooling vest during recovery in improving subsequent work performance. Three hypotheses were made in Protocol II, namely, (1) PCS could reduce heat strain during recovery (between bouts of work), (2) PCS could reduce heat strain during the second stage exercise, and (3) PCS could enhance the second stage work performance (prolong the second stage exercise duration).

Twelve healthy males volunteered to participate in Protocol II (mean ± SD: age 22 ± 3.32 years; height 170 ± 5.42 cm; body mass 61 ± 8.05 kg; BMI 21.12 ± 2.17; resting heart rate 74 ± 5 beats/min). They have no history of diagnosed major health problem. All participants took exercises two or three times per week and were thought of physically active. They were asked to refrain from any medication/drug, smoking, caffeinated products, alcohol use, and doing intense exercises for at least 4 hours prior to each test.

Each participant undertook two experimental trials on separate days spaced at around one week, at the same time in the afternoon. Trials were conducted in a counter-balanced order and consisted of a repeated measures design in which subjects served as their own controls. Trials

[6] Presented in a published paper: Zhao, Y., Yi, W., Chan, A.P.C., Wong F.K.W., Yam, M.C.H. (2017b). Evaluating the physiological and perceptual responses of wearing a newly designed cooling vest for construction workers. Annals of Work Exposures and Health, 61(7), 883-901.

included VEST and CON, and were conducted in an environmental chamber. The whole protocol consisted of 30 min pre-exercise rest, 1st stage exercise (Exe1) (include a period of 48 min intermittent jogging/walking, 6 min active recovery), 30 min passive recovery, and 2nd stage running (Exe2) (include a period 48 min of intermittent jogging/walking, 6 min active recovery) (Figure 6.2). The cooling vest was used during the 30 min passive recovery in VEST condition (Figure 6.3). While in CON condition, no cooling vest was applied. Exercise was terminated and recovery was induced when any of the following circumstances occurred: (i) T_c reached 38.5 ℃; (ii) HR reached 95% of the age-predicted maximum HR (age-predicted maximum HR = 220 – age); (iii) participant requested to stop (due to difficulty in breathing, feeling very hot, or exhaustion); or (iv) they completed the 48 min intermittent jogging/walking. Rehydration with warm water (37 ℃; 3 ml/kg × body weight) was in the first 5 min of the passive recovery.

Figure 6.2 Protocol II of the experiment

	Pre-exercise rest			Exe1							Post-exercise recovery			
Preparation	←Rest→			←Warm up→		←Intermittent running→					←Active recovery→		←Passive recovery→		
Duration (min)	10	10	10	3	3	3	3	3	3	…	3	3	10	10	10
Exercise intensity				6 km/h, 2% slope	6 km/h, 4% slope	6 km/h, 8% slope	3 km/h, 2% slope	6 km/h, 8% slope	3 km/h, 2% slope	…	3 km/h, 1% slope	2 km/h, 1% slope			

#

△ on △ off

@

To be continued

Exe2							Post-exercise recovery	
←Warm up→		←Intermittent running→					←Active recovery→	
3	3	3	3	3	3	…	3	3
6 km/h, 2% slope	6 km/h, 4% slope	6 km/h, 8% slope	3 km/h, 2% slope	6 km/h, 8% Slope	3 km/h, 2% slope	…	3 km/h, 1% slope	2 km/h, 1% slope

#

(#: weight the nude body, △on: put on cooling vest, △off: put off cooling vest, @: fill in questionnaire)

Figure 6.3 Cooling vest worn during the passive recovery

6.4 MEASUREMENTS AND CALCULATION

6.4.1 Physiological measurements

Physiological data, including heart rate, core temperature, skin temperature, and microclimatic temperature and humidity were recorded at a sampling frequency of 30 s throughout the entire experiment. Core temperature was measured by a CorTemp data logger (CorTemp™, HQInc., USA) inside a bum bag, which was fastened around the participant's waist. A small digital camera was also connected to the data logger in order to monitor core temperature during the experiment. Heart rate was measured by a Polar® heart rate watch and a chest strap (Polar T34 Transmitter, Finland). Microclimate temperature and humidity at two locations (i.e., chest and back) were also continuously recorded using the microclimate sensor attached between the uniform and the skin. The thermistors were taped at four skin sites, i.e., chest (T_{chest}), forearm ($T_{forearm}$), thigh (T_{thigh}) and calf (T_{calf}) to measure the skin temperatures. The mean skin temperature ($\overline{T_{sk}}$) and mean body temperature ($\overline{T_b}$) was estimated according to Equation (6.1) and (6.2), respectively:

$$\overline{T_{sk}} = 0.3(T_{chest} + T_{forearm}) + 0.2(T_{thigh} + T_{calf}) \quad (6.1)$$

$$\overline{T_b} = 0.65T_c + 0.35\overline{T_{sk}} \quad (6.2)$$

From the value of $\overline{T_b}$, rate of body heat storage (ΔS) was calculated according to the Equation (6.3) (adapted from Burton 1935):

$$\Delta S\ (W/m^2) = [(0.97 \cdot m) \cdot (\Delta\overline{T_b}\ /\Delta t)]/A_{\mathrm{D}} \quad (6.3)$$

Where 0.97 is the specific heat of the body (in W ·h kg^{-1} ℃$^{-1}$), m is the body mass (in kg), A_{D} is the body surface area (in m^2), $\Delta\overline{T_b}\ /\Delta t$ is the change in $\overline{T_b}$ over time (in ℃/h). ΔS was calculated and presented separately for different exercises (including Exe1 and Exe2) and passive recovery periods.

Based on heart rate and core temperature, the physiological strain index (PSI) was further determined according to Moran et al. (1998), shown in Equation (6.4),

$$\mathrm{PSI} = \frac{5 \times (T_{ci} - T_{c0})}{39.5 - T_{c0}} + \frac{5 \times (HR_i - HR_0)}{HR_{max} - HR_0} \quad (6.4)$$

where, T_{c0} and HR_0 are the average value of core temperature and heart rate taken during the last 10 min stabilization period prior to entering the chamber, T_{ci} and HR_i are simultaneous measurements taken at any time during experiment, and HR_{max} is the maximum heart rate observed in the experiment, and is substituted by 180 beats/min if it is less than 180 beats/min. PSI describes heat strain quantitatively during continuous exercise (Moran et al., 2002). The PSI was scaled to a range of 0–10, indicating from no heat stress (0) to very high stress (10).

Nude body mass (with underwear) was recorded before and after each trial with an electronic scale accurate to 0.01 kg (Sam Hing Scales Fty Ltd, Hong Kong). Sweat loss was determined from the difference in nude body mass, adjusted by fluid intake. Sweat rate in liters per hour (L/h) was estimated from body mass change divided by the experiment time.

6.4.2 Perceptual measurements

The participant was asked to report their subjective ratings, including rates of perceived exertion (RPE), thermal sensation (TS), comfort sensation (CS), and skin wetness sensation (WS) every 3 min during whole heat exposure. RPE was assessed by the Borg CR-10 scale, ranging from 0 (rest) to 10 (maximal exertion) (Table 6.1). Thermal sensation (TS) (Gagge et al., 1967; ASHRAE Standard, 2004), wetness sensation (WS) (Gagge et al., 1967), and overall comfort sensation (CS) (Chan et al., 2016a; Song and Wang, 2016) were assessed by a seven-point scale (Table 6.1). After the passive recovery period, the participant was further asked to complete a self-administered questionnaire to describe the perceptual sensations on the cooling vest. In the questionnaire, seven items of subjective attributes were rated by scales 1–7, namely, from breathable to air-tight, from dry to damp, from light to heavy, from cold to hot, from comfortable to uncomfortable, from allow movement to not allow movement, and from like to not like (OSHC, 2013).

Table 6.1 Perceptual rating scales on perceived exertion (RPE), thermal sensation (TS), wetness sensation (WS), and comfort sensation (CS)

Scale	0	1	2	3	4	5	6	7	8	9	10
RPE	Rest	Very light	Light	Moderate	Somewhat hard	Heavy		Very heavy			Maximal
TS	-	Cold	Cool	Slightly cool	Neutral	Slightly warm	Warm	Hot	-	-	-
WS	-	Dry		Moist		Wet		Dripping wet	-	-	-
CS	-	Comfortable		Slightly comfortable		Uncomfortable		Very uncomfortable	-	-	-

Note: RPE is rate of perceived exertion; TS is thermal sensation; WS is wetness sensation; CS is comfort sensation.

6.4.3 Statistical analysis

Descriptive statistics (mean ± SD) were reported for dependent variables. A two-way [Time (every 3 minutes during the whole heat exposure) × Condition (CON versus VEST)] repeated measures ANOVA was conducted to analyse any treatment differences for core temperature, heart rate, PSI, $\overline{T_{sk}}$, and $\overline{T_b}$. The Greenhouse-Geisser correction was designated as statistical significance in case of the Mauchly's test of Sphericity was significant, suggesting that the violation of Mauchly's test of Sphericity assumption. Student paired t-tests for each time point were performed whenever there is significance from repeated measures analysis. Paired t-tests were also used to compare the work duration, body heat storage, and sweat rate between the two conditions. The levels of statistical significance in all tests were $p < 0.05$ (*) and $p < 0.01$ (**). Further, the magnitudes of change between the two conditions were estimated according to Cohen's d effect size. The effect size was interpreted on Cohen's scale: 0 to 0.19 are classified as 'negligible', 0.2–0.4 as 'small', 0.5–0.7 as 'moderate', and > 0.8 as 'large' effects. All data analyses were conducted by the statistical software program SPSS v.20 (IBM Inc., Armonk, NY).

6.5 RESULTS OF PROTOCOL I

6.5.1 Work performance

The exercise duration in VEST and CON was 36.4 ± 7.79 min and 36.2 ± 5.62 min, respectively (no significant difference, $p = 0.95$). The number of participants who stopped exercise upon reaching the core temperature of 38.5 ℃, maximal heart rate, and subjective request was 7, 2, and 1, respectively in VEST; and 8, 1, and 1, respectively in CON, respectively.

6.5.2 Core temperature

A 2 × 4 (condition × test bout) repeated measures ANOVA revealed a significant main effect for the condition (F = 3.87, p = 0.01) and test bout (F = 332.57, p < 0.01). Figure 6.4 (a) shows the core temperature in the entire heat exposure for VEST and CON. The core temperature was stable and remained at 37.37 ± 0.23 ℃ during the pre-exercise rest. During the exercise and active recovery period, the core temperature gradually increased to 37.91 ± 0.24 ℃ and 38.57 ± 0.18 ℃, respectively. A Significant difference in core temperature was observed during passive recovery between VEST (38.07 ± 0.24 ℃) and CON (38.27 ± 0.25 ℃) (p < 0.01; d = 0.82, large effect).

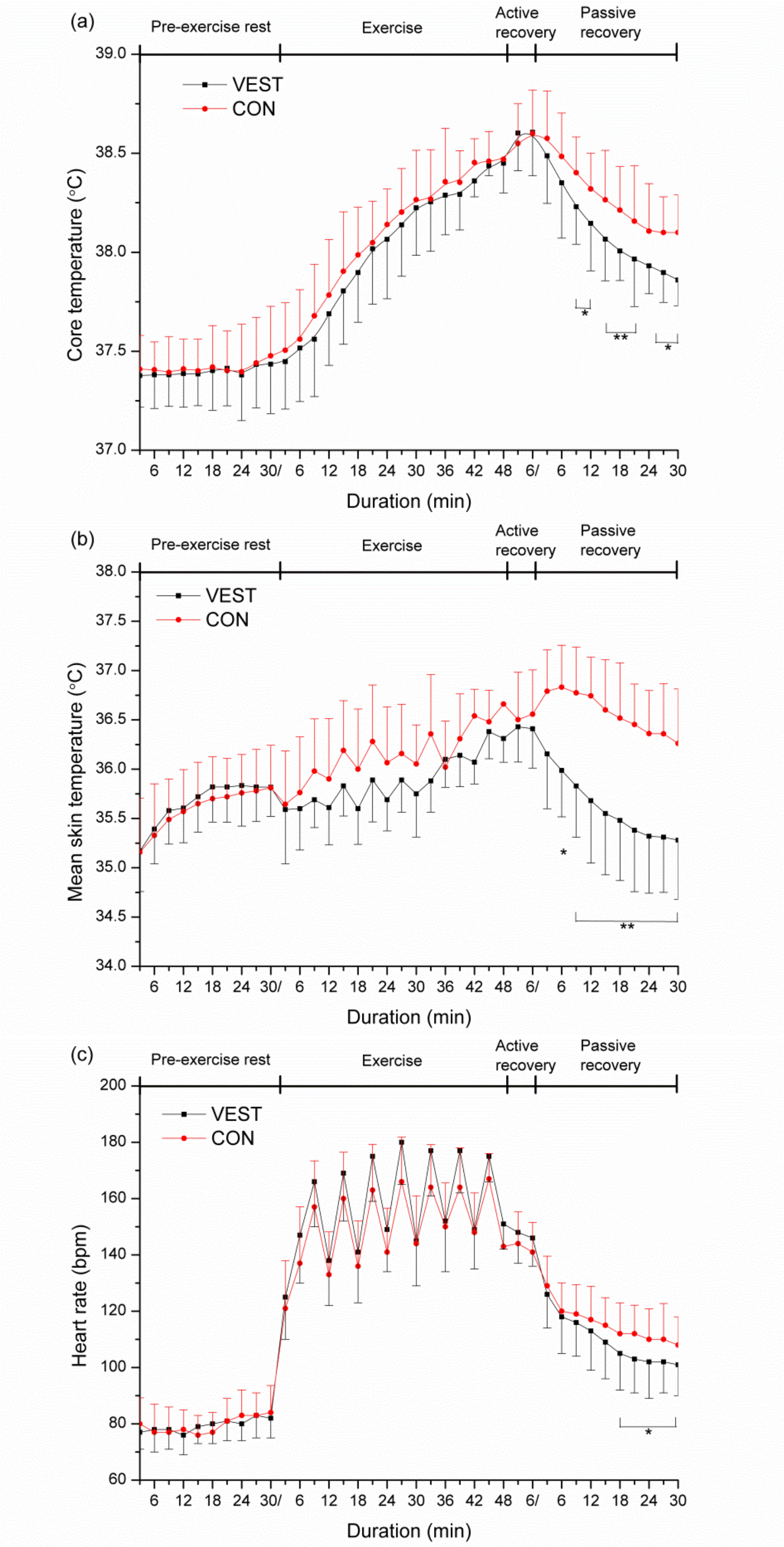
6.5.3 Skin temperature

A 2 × 4 (condition × bout) repeated measures ANOVA revealed a significant main effect for the condition (F = 4.37, p = 0.01) and test bout (F = 154.56, p < 0.01). Figure 6.4 (b) exhibits the change in $\overline{T_{sk}}$ during the entire heat exposure for VEST and CON. During exercise, a significantly lower $\overline{T_{sk}}$ was found in VEST compared to CON (p = 0.04; d = 0.53, moderate effect). During passive recovery, the $\overline{T_{sk}}$ in VEST was significantly lower than CON (p < 0.01; d = 0.98–1.70, large effect).

6.5.4 Heart rate

A 2 × 4 (condition × bout) repeated measures ANOVA revealed a significant main effect for the condition ($F = 5.91$, $p = 0.01$) and test bout ($F = 232.35$, $p < 0.01$). Figure 6.4 (c) shows the change in the heart rate in the entire heat exposure for VEST and CON. A significantly lower heart rate was found in VEST compared to CON during passive recovery ($p < 0.05$; $d = 0.63–0.96$, moderate to large effect).

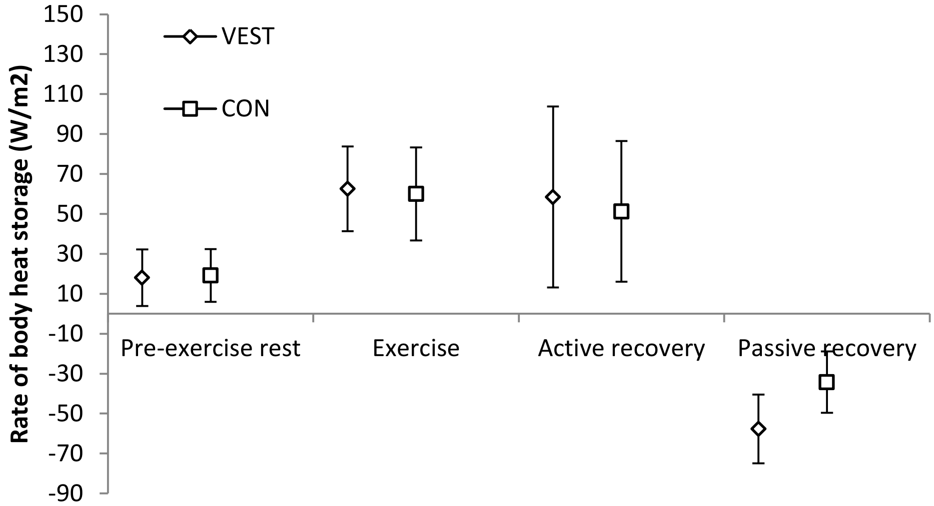
Figure 6.4 Physiological responses during the experiment (a) core temperature, (b) mean skin temperature, and (c) heart rate



6.5.5 Change in body heat storage

A 2 × 4 (condition × bout) repeated measures ANOVA revealed a significant main effect for the condition ($F = 65.17$, $p < 0.01$) and test bout ($F = 424.55$, $p < 0.01$). The increasing rate of body heat storage during exercise was similar between VEST and CON ($p = 0.79$), with an average value of 62.20 W/m^2 (Figure 6.5). During passive recovery, a significantly decreasing rate of body heat storage was observed in VEST (−57.65 W m^{-2}) compared with that in CON (−34.28 W m^{-2}) ($p < 0.01$; $d = 1.43$, large effect).

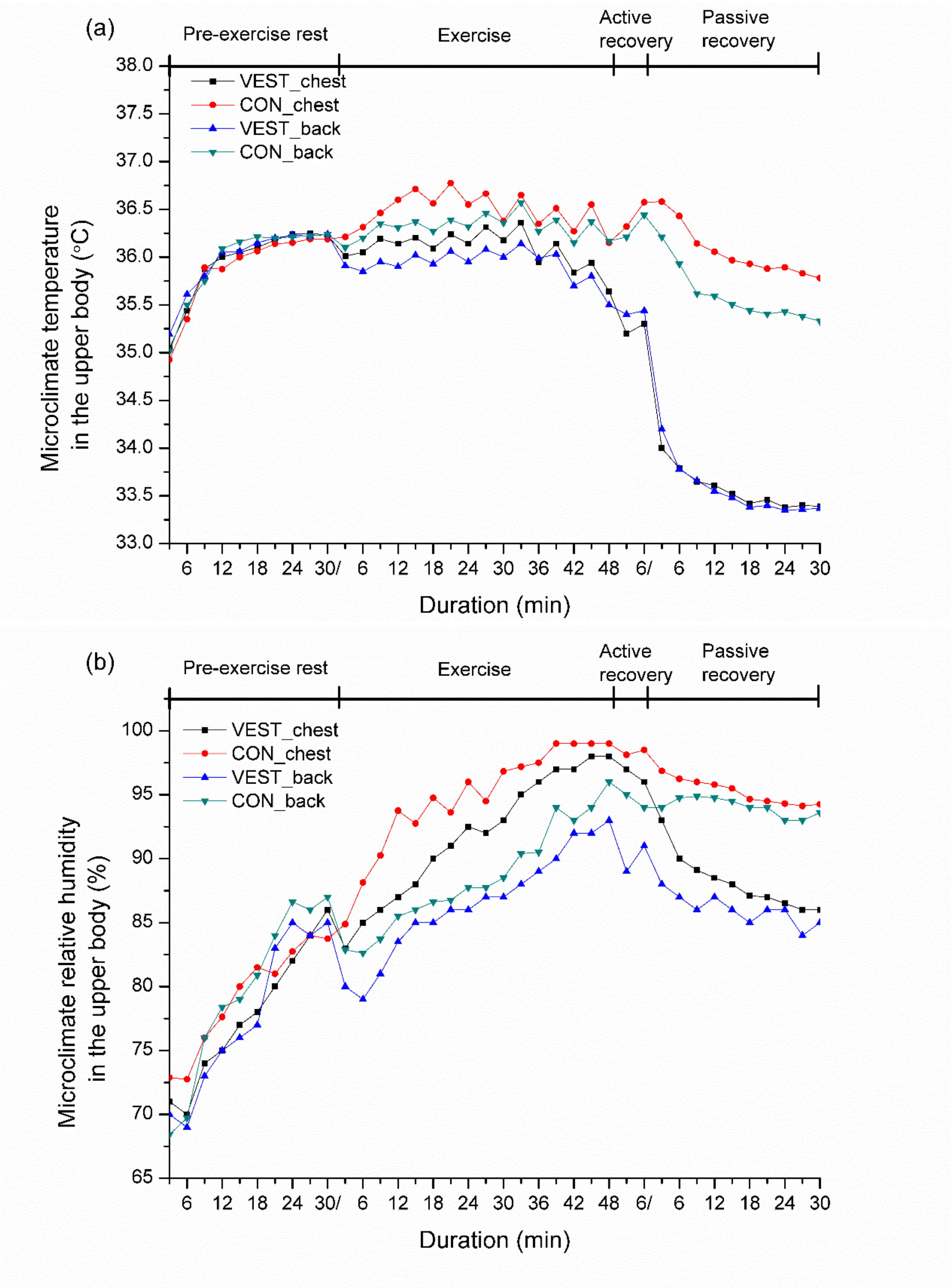
Figure 6.5 Rate of heat storage during the experiment



6.5.6 Microclimate temperature and humidity

Microclimate temperature and humidity at the chest and back during the entire heat exposure were compared (Figure 6.6). Repeated measures ANOVA demonstrated a significant difference in microclimate temperatures at the chest and back between VEST and CON ($p < 0.01$) across the test bouts. Repeated measures ANOVA also revealed a significant difference in microclimate relative humidity at the chest and back between conditions ($p < 0.05$). During the pre-exercise rest, microclimate temperature and humidity in the torso showed no significant difference between the conditions. During exercise, the torso microclimate temperatures at the chest and back in VEST (36.11 ± 0.68 ℃ for the chest; 35.98 ± 0.70 ℃ for the back) were significantly lower than those in CON (36.51 ± 0.66 ℃ for the chest, d = 0.60, moderate effect; 36.33 ± 0.65 ℃ for the back, d = 0.52, moderate effect). A significant reduction in chest and back microclimate temperatures in VEST (33.56 ± 0.83 ℃ at the chest, 33.55 ± 0.93 ℃ at the back) compared to CON (36.05 ± 0.78 ℃ at the chest, 35.58 ± 0.85 ℃ at the back) was observed throughout passive recovery. A significant reduction of microclimate relative humidity at the chest and back was observed in VEST (88.88 ± 9.25% at the chest, 87.81 ± 8.98% at the back) during passive recovery compared to that in CON (95.23 ± 8.12% at the chest, 94.05 ± 9.65% at the back).

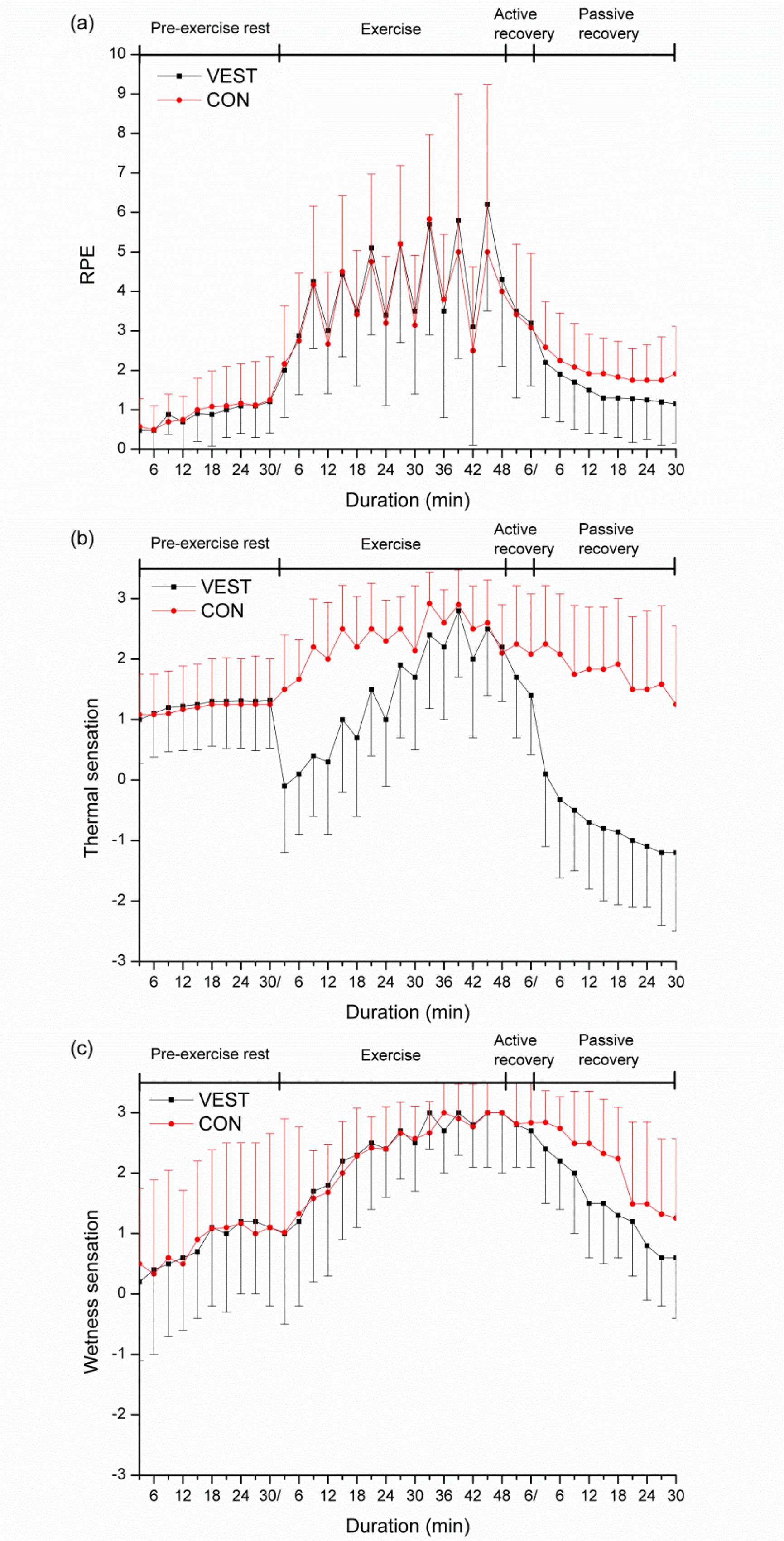
Figure 6.6 (a) Microclimate temperature and (b) microclimate relative humidity in the upper body region during the experiment



6.5.7 Perceptual responses

Perceptual ratings were compared (Figure 6.7). No significant difference was observed in RPE between two conditions during the entire heat exposure ($F = 1.33$, $p = 0.31$). RPE significantly changed over test bouts ($F = 258.32$, $p < 0.01$). Significant main effects were found in thermal sensation for the condition ($F = 76.32$, $p < 0.01$) and test bout ($F = 199.31$, $p < 0.01$). Significant main effects were also found in wetness sensation for the condition ($F = 16.35$, $p < 0.01$) and test bout ($F = 77.31$, $p < 0.01$). During the pre-exercise rest, RPE and thermal and wetness sensations showed no significant difference between conditions, with an average value of 1.01 $\pm$ 0.83 and 0.82 $\pm$ 1.02, respectively. During exercise, thermal sensation in VEST was 1.41 $\pm$ 1.14, significantly lower than that in CON (2.32 $\pm$ 0.73) ($p = 0.03$; $d = 0.95$, large effect). During passive recovery, the cooling vest significantly improved the body thermal and wetness sensation in VEST (–0.76 $\pm$ 1.16 in thermal sensation; 1.41 $\pm$ 0.89 in wetness sensation) compared to CON (1.74 $\pm$ 1.13 in thermal sensation, $d = 2.18$, large effect; 2.07 $\pm$ 0.98 in wetness sensation, $d = 0.70$, moderate effect).

Figure 6.7 (a) RPE, (b) thermal sensation, and (c) wetness sensation during the experiment



6.5.8 Sweat rate

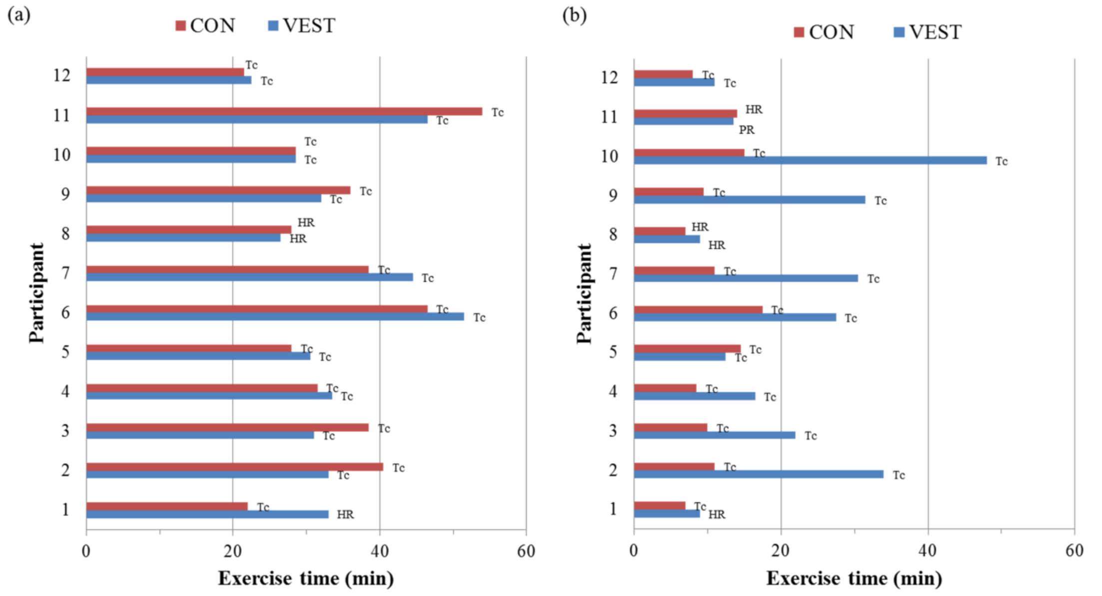
No significant difference in sweat rate was found between VEST (0.64 ± 0.17 L/h), and CON (0.65 ± 0.15 L/h) ($p = 0.53$).

6.6 RESULTS OF PROTOCOL II

6.6.1 Exercise duration

When cooling vest was worn in the passive recovery period, the average duration of Exe2 was significantly improved as compared with CON (22.08 ± 12.30 min for VEST; 11.08 ± 3.4 min for CON, $p = 0.006$; $d = 1.22$). The duration of Exe1 showed no significant difference under the two conditions (34.42 ± 8.62 min for VEST; 33.46 ± 9.77 min for CON, $p = 0.981$; $d = 0.10$). In Exe1 of CON, the numbers of participants who stopped exercising at T_C = 38.5 ℃ and maximal HR were 11 and 1, respectively. In Exe1 of VEST, the numbers of participants who stopped exercising at T_C = 38.5 ℃ and maximal HR were 10 and 2, respectively (Figure 6.8a). In Exe2 of CON, 10 and 2 participants stopped exercising at T_C = 38.5 ℃ and maximal HR, respectively. In Exe2 of VEST, 9, 2, and 1 participants stopped exercising at T_C = 38.5 ℃, maximal HR, and participant request (he felt very uncomfortable in his calf muscle), respectively (Figure 6.8b).

Figure 6.8 Exercise duration of individual participants in VEST and CON: (a) 1st stage exercise; (b) 2nd stage exercise



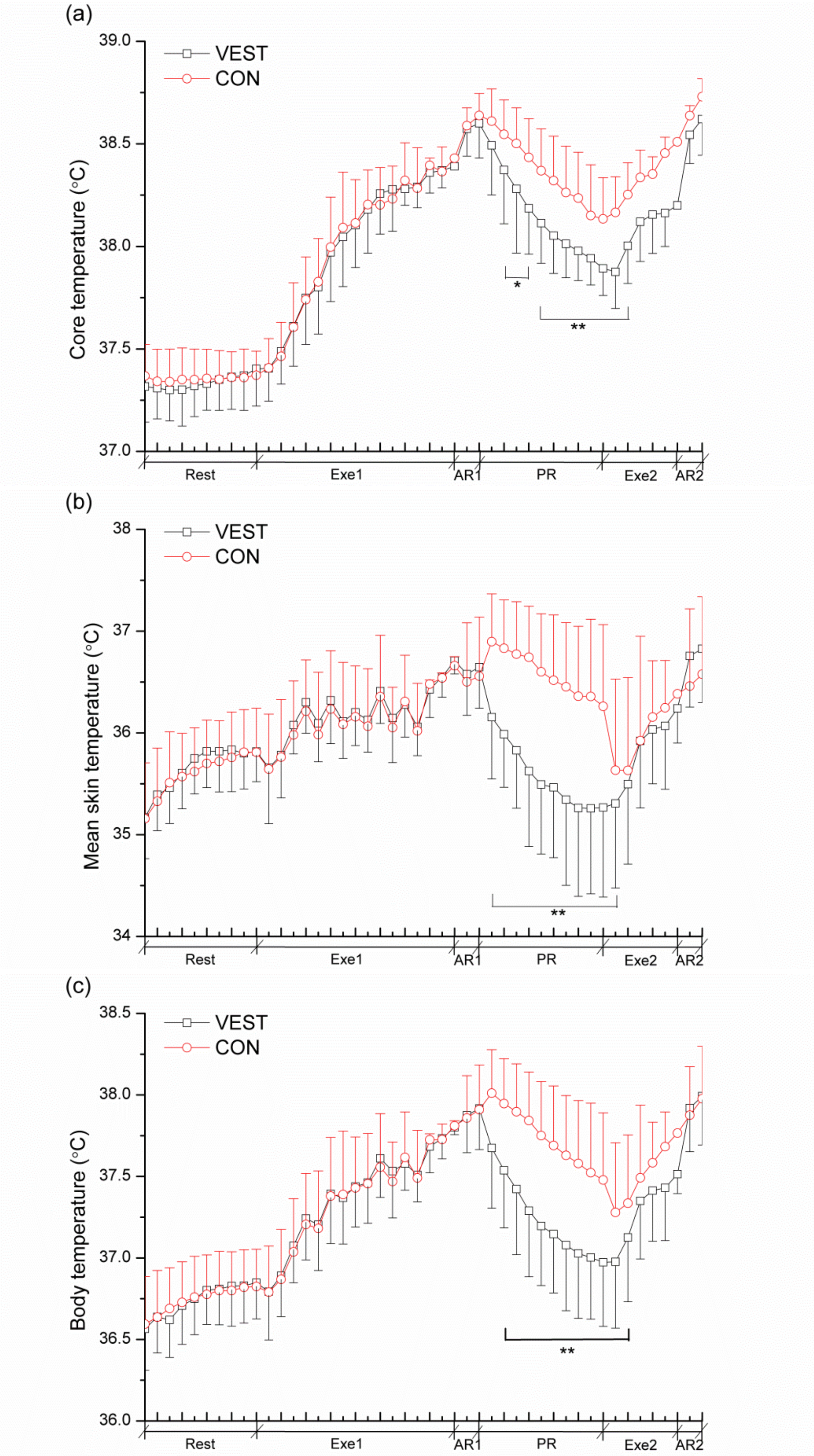
Note: T_C, HR, and PR means that the exercise was terminated upon T_C = 38.5 ℃, maximum HR, and participants' request, respectively.

6.6.2 Body temperatures and heat storage

T_c, $\overline{T_{sk}}$ and $\overline{T_b}$ during rest, exercise, and recovery were compared between two conditions (Figure 6.9). Repeated measures ANOVA found that T_c, $\overline{T_{sk}}$ and $\overline{T_b}$ were significantly lower during the passive recovery ($p = 0.006$ for T_c, $p = 0.002$ for $\overline{T_{sk}}$, and $p = 0.005$ for $\overline{T_b}$) and Exe2 ($p = 0.046$ for T_c, $p = 0.05$ for $\overline{T_{sk}}$, and $p = 0.05$ for $\overline{T_b}$) in VEST than CON. No significant differences were found in T_c, $\overline{T_{sk}}$, and $\overline{T_b}$ between VEST and CON during Exe1. Significantly lower core temperature in VEST compared with CON was observed from the 6th min to the end of passive recovery ($p < 0.05$, $p < 0.01$; Cohen's d = 0.58–1.42, moderate to very large effect), and the first nine min of Exe2 ($p < 0.01$; d = 1.30–1.67, large effect)

(Figure 6.9a). At the end of 30 min passive recovery, a pronounced decrease was observed in T_c in VEST compared with CON (37.89 ± 0.13 ℃ vs. 38.13 ± 0.20 ℃), averaging 0.24 ± 0.23 ℃ lower (d = 1.42). Significant lower $\overline{T_{sk}}$ was observed immediately after putting on the cooling vest from the 3rd min to the end of passive recovery ($p < 0.01$; d = 1.18–1.76), and the first three min of Exe2 ($p < 0.05$; d = 0.38) (Figure 6.9b). Combining T_c and $\overline{T_{sk}}$, the $\overline{T_b}$ in VEST was also significantly reduced during passive recovery and the first 6^{th} min of Exe2 as compared with CON (Figure 6.9c).

Figure 6.9 Body temperatures in VEST and CON during the experiment (a) T_c; (b) $\overline{T_{sk}}$; (c) $\overline{T_b}$.



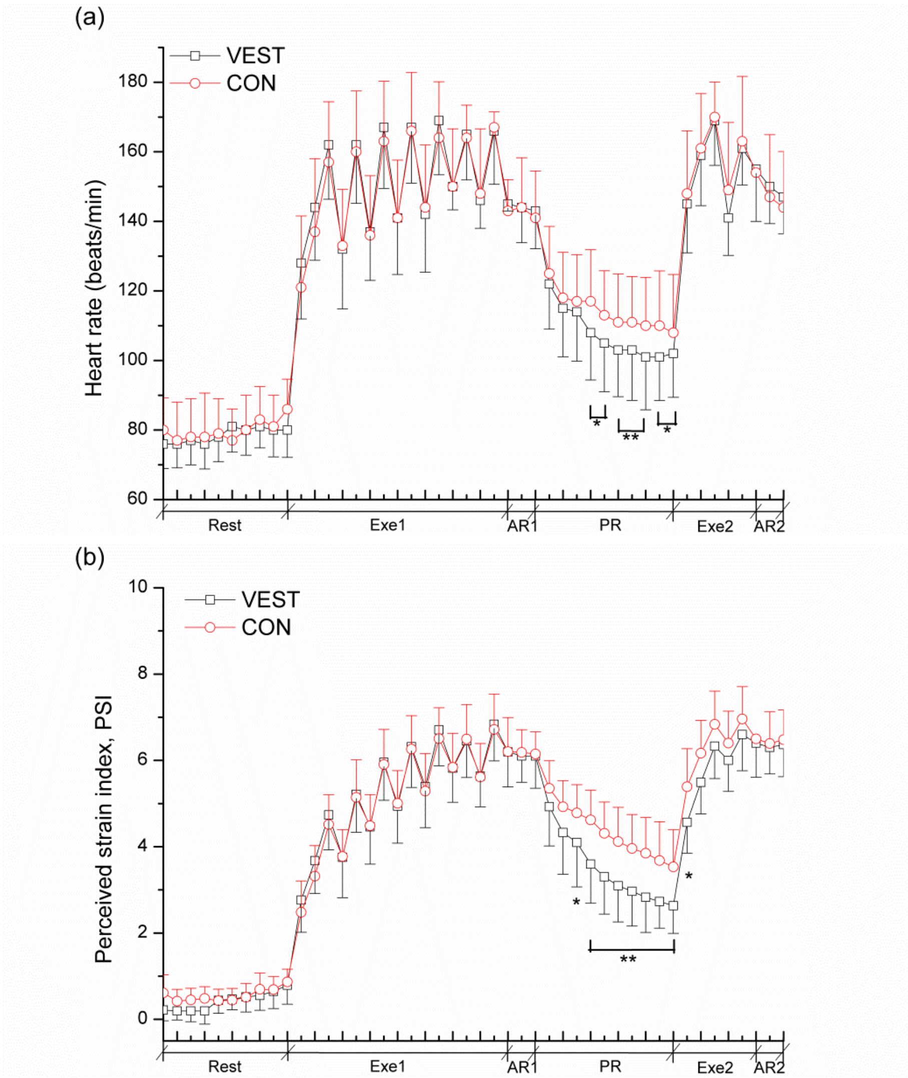
NOTE: The non-solid square and circle represent the mean values of VEST and CON, respectively, at 3-minute interval. The error bar represents standard deviation. AR1 = first stage active recovery; AR2 = second stage active recovery; Exe1 = first stage exercise; Exe2 = second stage exercise; PR = passive recovery. (*, $p < 0.05$; **, $p < 0.01$ means a significant difference between VEST and CON)

The increase rate of body heat storage during Exe1 was similar between VEST (59.52 ± 25.17 W m^{-2}) and CON (61.52 ± 24.84 W m^{-2}) ($p = 0.69 > 0.05$). During passive recovery, significant negative body heat storage was observed in VEST (−67.54 ± 19.81 W m^{-2}) as compared with CON (−30.72 ± 17.98 W m^{-2}) ($p = 0.000 < 0.01$). During the subsequent Exe2, no significant differences were noted in heat storage between two conditions (70.26 ± 25.31 W m^{-2} for VEST and 68.58 ± 28.24 W m^{-2} for CON; $p = 0.091 > 0.05$).

6.6.3 Heart rate and PSI

There were no significant differences in heart rate between two conditions during the period of Exe1. Starting from the 12th min and throughout the remainder of the rest period, heart rate was significantly lower in VEST as compared with the control ($p < 0.05$; d = 0.56–0.67) (Figure 6.10a). At the end of passive recovery, heart rate was significantly lower in the VEST (101 ± 14 beats/min) as compared with the CON (110 ± 17 beats/min) ($p < 0.05$; d = 0.58). Heart rate was almost the same between two conditions during both exercises, exhibiting intermittent changes primarily determined by the activity level in the protocol of the experiment. A similar pattern was found in PSI (Figure 6.10b). Significantly lower heart rate in VEST compared with CON was observed from the 9th min to the end of passive recovery (Figure 6.4b; $p < 0.05$; Cohen's d = 0.57–1.12).

Figure 6.10 (a) Heart rate and (b) PSI in VEST and CON during the experiment

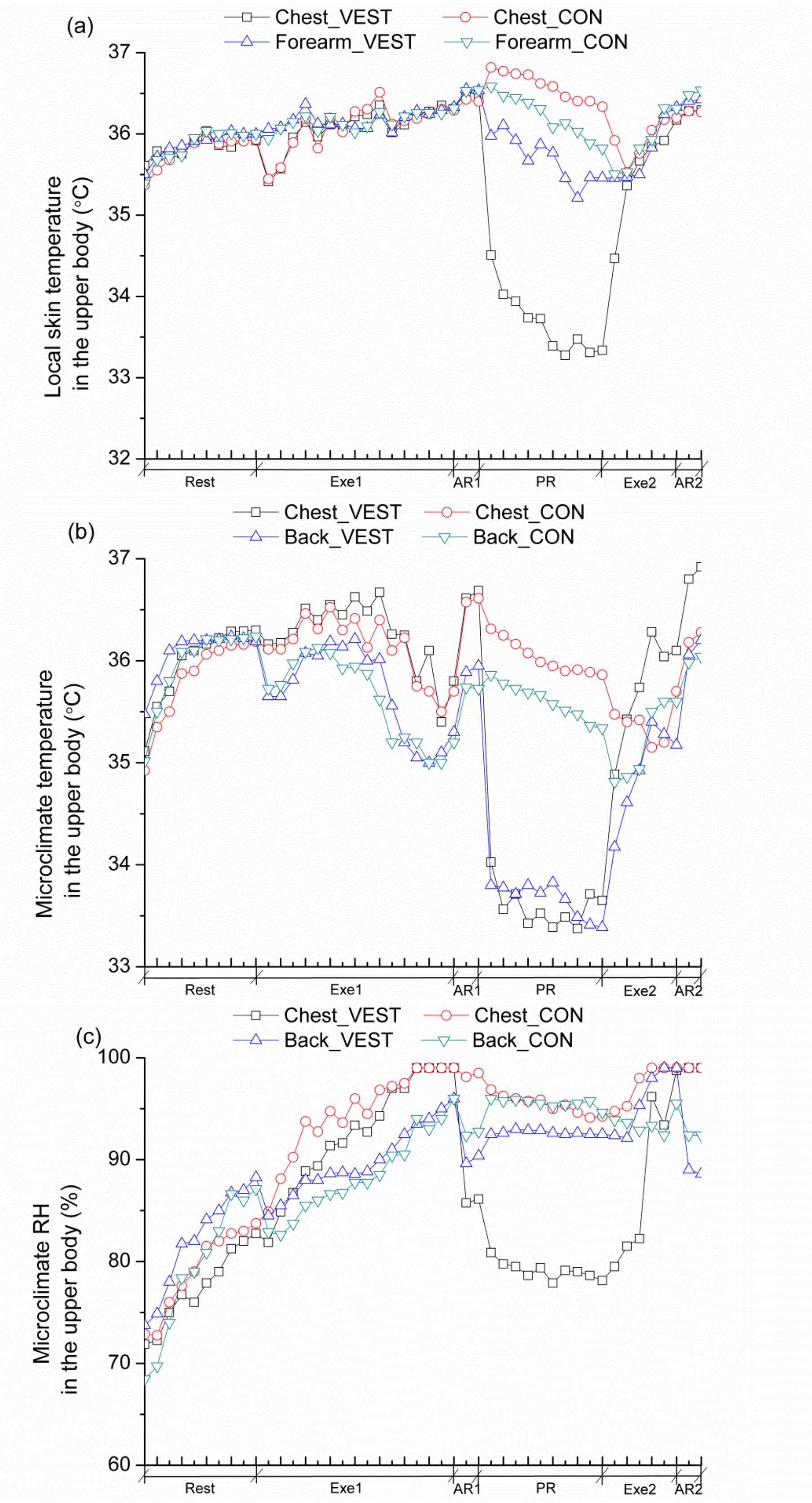


NOTE: The non-solid square and circle represent the mean values of VEST and CON, respectively, at 3-minute interval. The error bar represents standard deviation. AR1 = first stage active recovery; AR2 = second stage active recovery; Exe1 = first stage exercise; Exe2 = second stage exercise; PR = passive recovery. (*, $p < 0.05$; **, $p < 0.01$ means a significant difference between VEST and CON)

6.6.4 Local skin temperatures and microclimate humidity

A similar response pattern was evident with local skin temperature and microclimate temperature in the upper body (Figure 6.11a and Figure 6.11b). Chest, forearm, and back temperatures were significantly lower throughout the passive recovery (for chest 33.66 ± 0.31 ℃ in VEST vs 36.59 ± 0.17 ℃ in CON; for forearm 34.69 ± 0.25 ℃ in VEST vs 36.23 ± 0.24 ℃ in CON; for back 33.65 ± 0.14 ℃ in VEST vs 35.59 ± 0.16 ℃ in CON) in VEST than CON ($p < 0.01$). Significant reduction of the microclimate relative humidity in the upper body, especially in the chest region, in VEST (averaging 78.98 ± 7.92% for chest; 92.72 ± 5.44% for back) compared with CON (averaging 95.37 ± 7.87% for chest; 95.61 ± 3.89% for back) was also observed throughout the passive recovery ($p < 0.05$) (Figure 6.11c).

Figure 6.11 (a) Local skin temperatures and (b) microclimate temperature (c) microclimate relative humidity (RH) in VEST and CON during the experiment

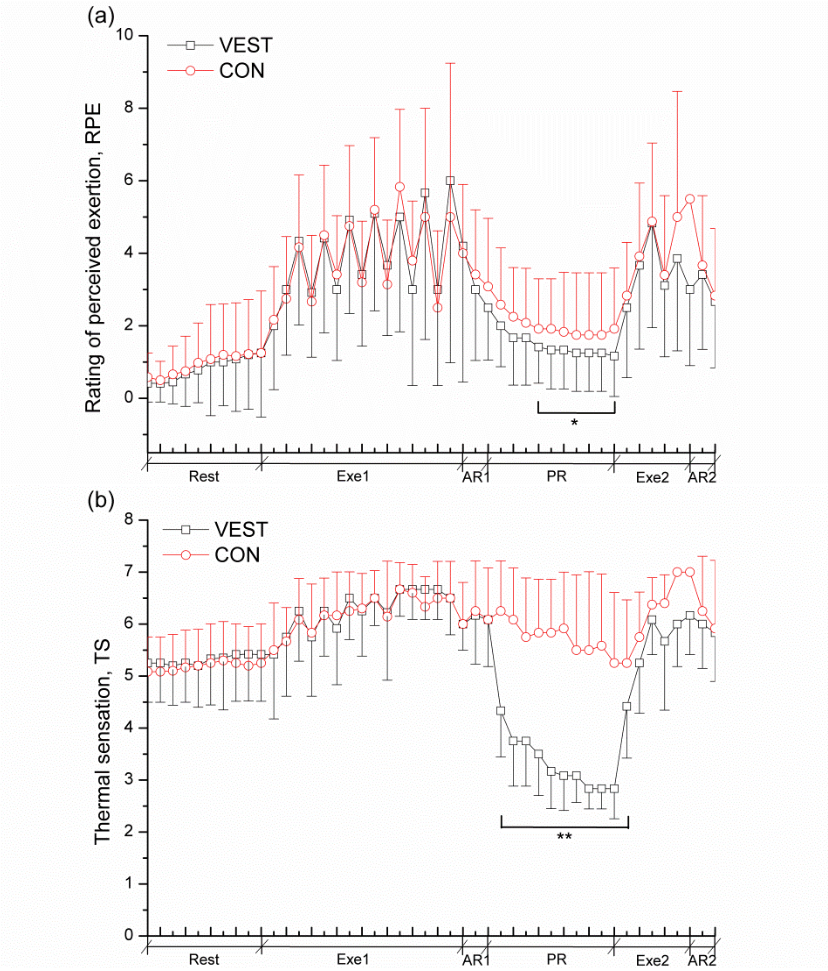


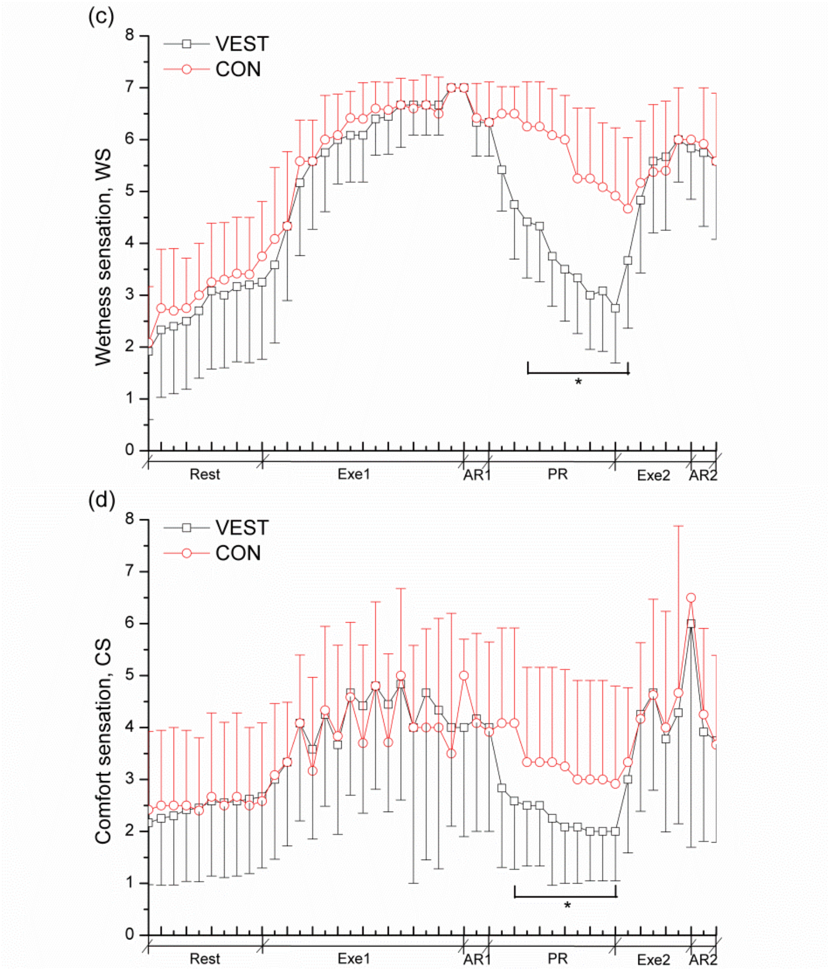
NOTE: The non-solid circle, square, up triangle, and down triangle represent the mean values in VEST and CON, respectively, at 3-minute interval. AR1 = first stage active recovery; AR2 = second stage active recovery; Exe1 = first stage exercise; Exe2 = second stage exercise; PR = passive recovery.

6.6.5 Perceptual responses

The ratings of thermal, wetness, and comfort sensations in two conditions were compared (Figure 6.12). The use of cooling vest improved the body thermal comfort. Notably, significant reductions occurred during passive recovery. The average TS, WS, and CS during passive recovery in VEST was 3.1 ± 1.0 (slightly cool to neutral), 3.7 ± 1.1 (neutral), and 2.3 ± 0.5 (slightly comfortable to comfortable), respectively. These values were significantly lower than those in CON (5.6 ± 1.1 [slightly hot to hot], 5.7 ± 1.3 [slightly wet to wet], and 3.2 ± 0.6 [slightly comfortable to neutral]). Small to moderate effect was observed in RPE (d = 0.11–0.53), whereas moderate to large effect was observed in TS, WS, and CS (d = 0.54–3.15 for TS, d = 0.48–2.69 for WS, d = 0.54–1.68 for CS).

Figure 6.12 (a) Perceived exertion, (b) thermal sensation, (c) wetness sensation, and (d) comfort sensation in VEST and CON during the experiment

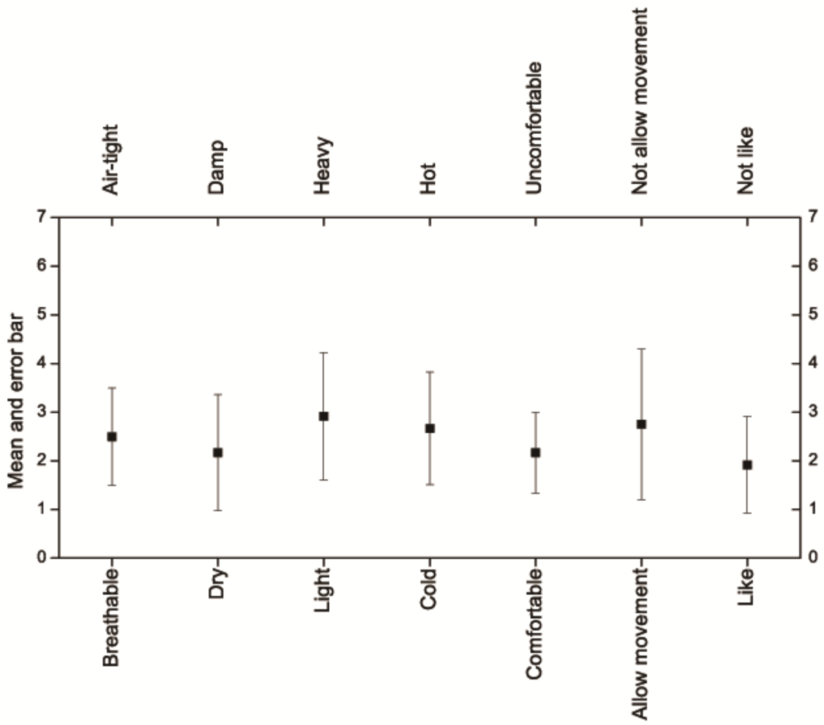




NOTE: The non-solid square and circle represent the mean values of VEST and CON, respectively, at 3-minute interval. The error bar represents standard deviation. AR1 = first stage active recovery; AR2 = second stage active recovery; Exe1 = first stage exercise; Exe2 = second stage exercise; PR = passive recovery. (*, $p < 0.05$; **, $p < 0.01$ means a significant difference between VEST and CON)

Furthermore, the questionnaire survey found that this cooling vest was highly appraised by participants with subjective ratings ranging from 1 to 3 (Figure 6.13). The rating for breathable-airtight, dry-damp, light-heavy, cold-hot, comfortable-uncomfortable, allow movement-not allow movement, and like-not like was 2.50 ± 1.00, 2.17 ± 1.19, 2.92 ± 1.31, 2.67 ± 1.15, 2.17 ± 0.83, 2.75 ± 1.54, and 1.92 ± 1.00, respectively.

Figure 6.13 Perceptual sensations of the hybrid cooling vest after passive recovery



NOTE: Values are presented as mean and standard error

6.6.6 Sweat rate

No significant difference in sweat rate was found between VEST (0.640 ± 0.17 L/h) and CON (0.642 ± 0.16 L/h) ($p = 0.98$).

6.7 DISCUSSION

The aim of this chapter is twofold: (1) examine the effectiveness of a newly designed cooling vest on attenuating heat strain during work and recovery periods and (2) ascertain whether improvements in physiological and perceptual strains caused by the cooling vest during recovery could prolong subsequent bouts of exercise/work. Human wear trials were carried out under the work–rest protocol in a climate chamber that simulated a typical hot and humid environment in Hong Kong's construction sites during summer season.

Under such a hot and humid condition (controlled at 37 ℃, 60% relative humidity), the cooling vest provided a cooler microclimate around the body, as indicated by the significantly lower microclimate temperature at the chest and back region in VEST compared to CON. The temperature gradient between the skin surface and the ambient environment improved the conductive heat dissipation. Meanwhile, the water vapour pressure gradient between the sweating skin (100% relative humidity) and the ambient environment enhanced evaporative heat loss. The moving air ventilated by the small fans further contributed the convective and evaporative heat loss. A significant dropping in local skin temperatures (i.e., chest, back and forearm) was observed in VEST compared to CON. It can be found that when the cooling vest was used, local skin temperature was very close to the normal skin temperature (about 33 ℃), which would not cause skin irritation due to extreme coldness (Yazdanirad and Dehghan, 2016). Driven by the remarkable dropping in skin temperatures, body core temperature declined significantly a period after the cooling vest was worn. Skin temperature was immediately reduced as soon as the vest was worn (throughout the passive recovery), while core temperature was significantly decreased in VEST from the 10^{th} min of the passive recovery. The decrease in core temperature lagged behind the skin temperature. One explanation is that it took time for conductive heat transfer from the skin surface, go through subcutaneous fat and underlying muscle, to the body's central core (Otte et al., 2002).

The core temperature and heart rate are considered as the main indicators of heat strain during both work and rest (Yi et al., 2017a). A critically high core temperature or hear rate is related to heat exhaustion (Cheung and McLellan, 1998; González-Alonso et al., 1999; Sawka et al., 1992). The present study set core temperature of 38.5 ℃ and maximal heart rate (95% of the age-predicted maximal heart rate) as the criteria to terminate exercise and proceed to recovery stage. At the end of exercise, no significant difference was found in core temperature and heart rate between VEST and CON, which provided a similar body thermal state for the subsequent recovery. The change in RPE during exercise showed similar pattern with that in heart rate, which was mainly influenced by the level of exercise intensity (Chan et al., 2012c; Miyamoto et al., 2006; Yi et al., 2017a). This study used intermittent exercise intensity, resulting in intermittent increase in RPE and hear rate during exercise. The rating of thermal sensation was highly associated with the change in skin temperature in a warm to hot ambient environment (Gagge et al., 1969; Song and Wang, 2016). Compared with CON, skin temperature and thermal sensation were significantly alleviated in VEST during the exercise and recovery periods. Participants' wetness sensation was influenced by the moisture accumulation on the skin in the clothing (Hatch et al., 1990). Wetness sensation was significantly attenuated in VEST as compared to CON during only the recovery period. One explanation was that body movement during exercise can promote air ventilation and enhance evaporation (Gavin, 2003). Whereas, participants remained seated during recovery and the evaporation of the sweat on the skin solely depended on the air ventilation of the cooling vest.

In protocol I, the cooling vest was worn throughout the entire heat exposure (including exercise and recovery) in VEST. Whereas, in protocol II, the cooling vest was worn only in recovery in VEST. The protocol II was proposed based on the results in protocol I, which found that the heat strain was significantly reduced during recovery but not significantly attenuated during exercise. The results indicated that the cooling vest could not effectively reduce heat strain during exercise. The results can be comparable to some previous studies, which reported small to moderate cooling effect without significance during exercise period (Ciuha et al., 2016; Kenny et al., 2011; Zhang et al., 2010). In comparison, a number of studies observed a moderate to large cooling effect with significance during exercise (Bennett et al., 1995; Caldwell et al., 2012; Kim et al., 2011). In Ciuha et al. (2016), Kenny et al. (2011), Zhang et al. (2010), and the present study, participants were asked to wear basic clothes (e.g., T-shirt, shorts, and pants) with no protective garment in the control group. In Bennett et al. (1995); Caldwell et al. (2012); Kim et al. (2011), participants in the control group were required to wear protective clothing (characterised as impermeable to sweat evaporation), which might enlarge the difference from the cooling condition and further aggravate risk of heat stress. Another reason was from the added weight of cooling clothes, which could increase metabolic heat production during exercise. When the garment's cooling effect could not compensate for its added metabolic heat production, the cooling garment will negatively affected exercise performance (Lu et al., 2015). The cooling power of the newly designed cooling vest measured on a thermal manikin was approximately 70 W (Yi et al., 2017c). According to Wang et al. (2013)'s equation, the added weight of the cooling vest (1.26 kg) resulted in an estimated metabolic cost of 7.3 W. The measured cooling power of the vest was larger than its metabolic heat production. However, the high cooling power measurement on the thermal manikin did not necessarily indicate a physiological performance improvement since the human thermal regulation is a complex process with a series of physiological regulatory behaviours, including sweating, vasoconstriction, and vasodilatation (Kenny and Flouris, 2014). During exercise period, the insulation and added mass of the cooling vest might offset the cooling power, as shown by an insignificant reduction in core temperature and heart rate in VEST.

Heat storage accumulated during exercise in the heat, resulting in early termination of exercise or reduced work performance (Drust et al., 2005; González-Alonso et al., 1999). A period of recovery was induced after exercise to reduce heat strain and accelerate fatigue recovery. In a hot environment, the accumulated heat in the exercise cannot be easily alleviated to achieve a satisfactory recovery depending on the body's own heat dissipation system through sweating and skin vasodilation. According to Kenny and Flouris (2014), much less than 50% of the heat storage can be offset after 1 h of recovery. In the current study, less than 30% of heat gained during the exercise was lost in the control group. By contrast, heat storage reduction was approximately 55% in the cooling group after the 30 min recovery. The newly designed cooling vest could significantly reduce physiological (core temperature and heart rate) and perceptual strains during passive recovery. After recovery, the core temperature was reduced by approximately 1.0 ℃ (from 38.7 ℃ to 37.8 ℃) in VEST, as compared to 0.5 ℃ (from 38.7 ℃ to 38.2 ℃) in CON. Therefore, a lower onset core temperature for the following exercise can be achieved in VEST than in CON. This low core temperature resulted in an increased heat storage prior to arriving at the critical limiting core temperature, which contributed to improving the exercise duration (Arngrimsson et al., 2004).

It was observed in protocol II that the duration of exercise was largely prolonged. The use of the newly designed cooling vest during recovery showed an approximately 200% increase in subsequent work duration. The current data were comparable to those found in previous studies. Some studies employed cooling garment during the entre heat exposure including both exercise and rest periods. Bennett et al. (1995) found a 0.4 ℃ decrease in rectal temperature after 30 min using an ice vest between bouts of exercise and a 130% increase in exercise duration. Cadarette et al. (2003) used liquid cooling garment under a work–rest schedule of 20 min treadmill walking and 10 min rest, resulting in a 0.5 ℃ reduction in maximal rectal temperature and around 185% increase in work time. Considering actual work situations, several studies used the cooling garment during only the recovery period. The study by Barr et al. (2009) used an ice vest together with hand and forearm immersion during a 15 min recovery period, resulting in a 0.5 ℃ reduction in core body temperature and a 160% increase in work time compared to the control. Amorim et al. (2010) examined 40 min recovery between two bouts of exercise, indicating that the water-perfused vest during the recovery reduced 0.2 ℃ in body core temperature and increased 165% duration in subsequent bout of exercise. Results from the aforementioned studies suggest that the use of cooling suits in the recovery period is comparably effective with that throughout the entire heat exposure.

The optimal cooling intervention with the newly designed cooling vest during recovery period was proposed based on the results in Protocol I and II. The current research considered work environment, work activity, and schedule to determine an optimal cooling intervention for the construction industry. The newly designed cooling vest is individualised and portable, and can be applied in construction sites with elevated platforms, uneven grounds and confined spaces. Installing blowers and cold water reservoirs are generally difficult and impractical under such a congested environment. Although fanning by blowers was found to be the most effective post-exercise cooling method in a mildly hot environment of 31 ℃ with 70% of relative humidity among different cooling techniques (i.e., hand immersion and cooling garments) in Barwood et al. (2009a), it is not recommended to use in areas with high air temperature and humidity since because the increased air movement is associated with heat stress when the air temperature is approximately 37.8 ℃ (with relative humidity higher than 35%) (CDC, 1995; Wolfe, 2003). The newly designed cooling vest provides combined cooling through ventilation fans (convective and evaporative cooling which exhibits higher performance in a relatively dry environment) and PCM packs (conductive cooling which shows better capacity in a hot and humid environment than in a hot and dry one). Therefore, it could be a superior alternative in a wide range of hot conditions and has high application potential in the construction industry. In some situations (not applicable to situations requiring continuously pour of concrete until completion), work and rest schedule is allowed and optimised for the construction industry. It was observed in Protocol I that the cooling vest worn during exercise neither significantly reduced heat strain nor improved the work duration. The whole-body mode activity (treadmill walking), which is better than the upper (arm ergometer) or lower body (cycle ergometer) modes, was used in the current study to simulate actual work intensity in construction sites (Chan et al., 2012a). However, construction work was not fully considered. Complex tasks, such as forceful pulling and heavy lifting, have more requirements on the ergonomic design of the added clothing (cooling garment); thus, wearing the cooling garment throughout the work session continues to be a challenge in the construction industry (Chan et al., 2016c). The newly designed cooling vest largely (with significance) alleviated heat strain during recovery. Moreover, the subsequent work performance was significantly improved after using this cooling vest during recovery (Protocol II). Therefore, construction workers should be instructed/encouraged to wear the newly designed cooling vest during their regular breaks between repeated bouts of work.

Limitations in the human wear trials in the climatic chamber should be acknowledged. First, blinding participants in the treatment was difficult, similar to most cooling research, because these participants were requested to wear chilled vests (Jones et al., 2012). Second, the participants recruited in the current study consisted only of young healthy males, thereby limiting the results to aged population, females, and people with poor physical fitness; these types of population are seldom employed in the construction industry but may be vulnerable to heat-related illnesses and injuries.

6.8 SUMMARY

In this chapter, human wear trials of the newly designed cooling vest were conducted in a climatic chamber with a controlled hot and humid environment (37 ℃ temperature and 60%

relative humidity) that simulated the summer days on Hong Kong's construction sites. Treadmill exercise was designed to simulate construction work intensity. Physiological (i.e. core temperature, heart rate and skin temperature) and perceptual responses (i.e. RPE, thermal sensation, wetness sensation and comfort sensation) were measured throughout the experiment. In Protocol I, the cooling vest was worn during the exercise and recovery periods. The results reveal that the newly designed cooling vest significantly reduces heat strain during recovery but does not significantly alleviate heat strain during exercise. Consequently, Protocol II, which used the cooling vest only during recovery, is proposed. In the cooling vest group, heat storage during recovery is reduced by approximately 120%, and subsequent work duration after recovery is improved by approximately 100%. Therefore, the ergonomic requirements and logistic arrangements of construction sites should be considered, and optimal cooling interventions should be provided for a wide range of construction work conditions. The optimal cooling intervention that used the newly designed cooling vest during recovery is proposed. This process can be a valid and practical countermeasure in alleviating thermoregulatory and cardiovascular strain and improving work performance in a hot and humid environment. It will improve the health and well-being of construction workers. Indeed, workers in other occupations who need to labour under direct sunlight or those who are subjected to heat stress may also benefit.

CHAPTER 7 APPLICABILITY OF PCS[7]

7.1 INTRODUCTION

This chapter aims to examine the applicability of the proposed cooling intervention with the newly designed cooling vest through field studies. A series of field studies were thus carried out at the construction training grounds in Hong Kong during the summer season. A total of 14 construction workers participated in the field experiment, in which their physiological (core temperature and heart rate) and perceptual (ratings of perceived exertion and thermal sensation) responses were measured throughout the entire heat exposure. More than 140 construction workers were involved in the on-site questionnaire survey, in which their subjective assessment of the newly designed cooling vest was collected.

7.2 METHODS OF DATA COLLECTION

7.2.1 Participants

A total of 154 local construction workers from timber formworks group (74 participants) and bar fixing group (80 participants) were involved in the on-site questionnaire survey. Meanwhile, 14 local male construction workers (core subjects) from bar fixing group participated in the field experiment. The participants have no history of major health problems and symptoms of heat-related illness. All the participants had acclimatised to work

[7] Presented in a published paper: Zhao, Y., Yi, W., Chan, A.P.C., Wong D.P. (2018). Impacts of cooling intervention on the heat strain attenuation of construction workers. International Journal of Biometeorology, 62, 1625-1634.

in a thermal environment for over one month (from June to August). The participants were briefed on the objectives and procedures of the field study, and each provided a signed written consent form. Their participation was based on voluntary consent, and the participants could withdraw at any time. All procedures were approved by the Human Subjects Ethics Sub-Committee of the authors' host organization.

7.2.2 Procedure

Field studies were carried out between August and September 2016. A total of 14 visits were made at two construction training grounds in Hong Kong. Construction work involved daily morning and afternoon sessions that lasted from 9:00 am to 4:00 pm with a 1-h lunch break at noon (12:00 noon to 1:00 pm). 14 participants in the field experiment were from seven steel bar-fixing groups. 154 participants in the questionnaire survey were from eight steel bar fixing groups and seven timber formworks groups. Each worker participated in two wear trials, i.e., cooling and control condition, on two separate days in a counter-balanced order. Each day, 2 workers participated in the field experiment (one took the cooling trial and the other took the control trial) and approximately 22 workers participated in the questionnaire survey (half took the cooling trial and the other half took the control trial). The instructor in each work group assigned similar construction work to the participants during their two-day wear trials. Each morning, participants wore the construction work uniform upon arrival at the construction training ground. They were required to gather at 8:30 am to put on a heart rate belt (Polar WearLink®, Finland) (Figure 7.1). Then, they rested for 30 min to stabilise their heart rate. Participants provided their demographic information, including age, gender, ethnicity, and personal health data, including smoking habit, alcohol drinking habit and sleeping hours. Their height, body mass, resting heart rate, and tympanic temperature were measured. The participants started their usual daily work at 9:00 am in the morning and 1:00 pm in the afternoon. Rest periods of 15 min and 30 min were scheduled between repeated bouts of work in the morning and afternoon, respectively (i.e., 10: 15 am to 10: 30 am in the morning and 3:00 pm to 3:30 pm in the afternoon) (Yi and Chan, 2014b). Thus, a total of six test bouts were involved, i.e., first stage morning work (MW1), morning rest (MR), second stage morning work (MW2), first stage afternoon work (AW1), afternoon rest (AR), and second stage afternoon work (AW2). In the rest periods, participants were allowed to drink water and wipe off sweat as usual. In the cooling condition (Cooling), participants were asked to wear the cooling vest over their work uniform during rest periods, Figure 7.2 shows a group of participants wearing the cooling vest. No cooling vest was applied in the control condition (Control). At the end of the each rest period, participants were required to fill out a questionnaire about their perceived cooling effect, wetness sensation, thermal comfort, and fatigue recovery after rest. The seven-point Likert scale was used for these subjective attributes, with the lowest level (1) to the highest level (7), e.g., 7 represented the highest perceived cooling effect, the best skin wetness sensation and thermal comfort, and the most fatigue recovery. Participants were further requested to report their subjective rating towards the cooling vest based on the seven-point Likert scale (from 1 to 7, the larger the better), including questions about the likeness of wearing the PCS, fitness of the PCS, and the effectiveness of the PCS to reduce heat strain. After the two-day wear trials, participants were asked whether they preferred to wear this cooling vest during rest periods. Their comments on this cooling vest were further collected.

Figure 7.1 Participant construction worker with the heart rate belt

Figure 7.2 A group of participants wearing the cooling vest during rest

7.2.3 Measurements and calculation

To examine heat strain, meteorological and physiological data were collected. A heat stress monitor (QUESTemp °36, Oconomowoc, WI, USA) was used to collect microclimatological parameters, including dry bulb temperature, wet bulb temperature, globe temperature, relative humidity, and wind speed at a sampling rate of 1 min. The WBGT monitor was set up near the participants' worksite at abdomen level (1.1 m above the ground). Heart rate of all participants was recorded by a heart rate monitor (Polar Team Pro) at 1-s intervals. Tympanic temperature of the 14 core subjects was measured with an infrared tympanic electronic thermometer (Genius TM^2, Covidien, USA) every 5 min. Tympanic thermometry has proved to be an accurate and noninvasive method to evaluate the body temperature (Dzarr et al., 2009). Tympanic temperature was then adjusted to exhibit the core temperature equivalent, i.e., Core Mode = Ear Mode + 1.04 ℃, which has been used by Chan et al. (2012c); Chan et al. (2012d) in laboratory and field studies. The 14 core subjects were further requested to report ratings of perceived exertion (RPE) (Borg CR-10 scale) (Borg, 1998) and thermal sensation (ranging from 1 [cold] to 7 [hot]) (Parsons, 2014; Standard, 2004) every 5 min. All data were synchronised and transformed into 5 min averages. Physiological strain index (PhSI), which is based on core temperature and heart rate, was determined as shown in Equation (7.1),

$$\text{PhSI} = \frac{5 \times (T_{ci} - T_{c0})}{39.5 - T_{c0}} + \frac{5 \times (HR_i - HR_0)}{HR_{max} - HR_0} \quad (7.1)$$

where T_{c0} and HR_0 are the mean value of core temperature and heart rate measured during rest prior to starting construction work in the morning; T_{ci} and HR_i are real-time measurements during the experiment; and HR_{max} is the maximum heart rate measured in the experiment (substituted by 180 bpm if it is less than 180 bpm). PhSI was scaled to a range of 0–10, representing from no strain (0) to very high strain (10) (Moran et al., 2002).

Perceptual strain index (PeSI), which is based on RPE and thermal sensation, was determined as shown in Equation (7.1) (Tikuisis et al., 2002),

$$\text{PeSI} = \frac{5 \times RPE_i}{10} + \frac{5 \times (TS_i - 1)}{6} \quad (7.2)$$

where, RPE_i and TS_i are real-time measurements taken every 5 min during the experiment. PeSI was scaled to a range of 0 (no heat strain) to 10 (very high strain).

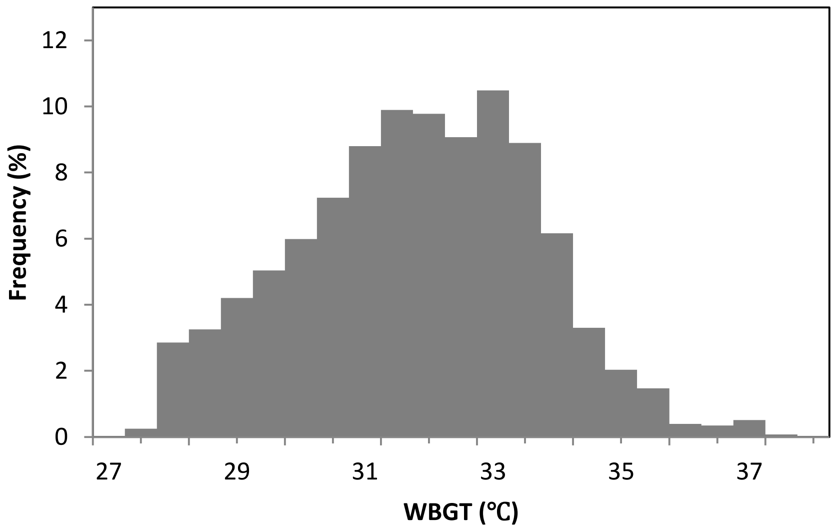
7.2.4 Statistical analysis

Descriptive statistics (mean ± standard deviations [SD]) was presented for dependent variables. A two-way (condition [cooling and control] × test bout [MW1, MR, MW2, AW1, AR, and AW2]) repeated-measures ANOVA was performed to evaluate any treatment differences. The Greenhouse–Geisser correction was designated as statistical significance when the Mauchly's test of sphericity was significant. Paired t-test was conducted to compare the difference in physiological and perceptual strain between two conditions at a certain test bout. Statistical significance levels were set as $p < 0.05$ (*) and $p < 0.01$ (**). The effect size based on Cohen's d value was further calculated to examine the magnitudes of change between conditions. Based on Cohen's scale, the effect size was interpreted as negligible (d = 0–0.19), small (d = 0.2–0.4), moderate (d = 0.5–0.7), and large (d ≥ 0.8).

7.3 RESULTS

The frequency distributions of meteorological data are shown in Figure 7.3. During the field study, participants were exposed to high-environmental stress that ranged from 28 ℃ (2.86%) to 37 ℃ (0.51%) with a mean value of 31.56 ± 1.87 ℃ WBGT.

Figure 7.3 Frequency distributions of meteorological data during the field study

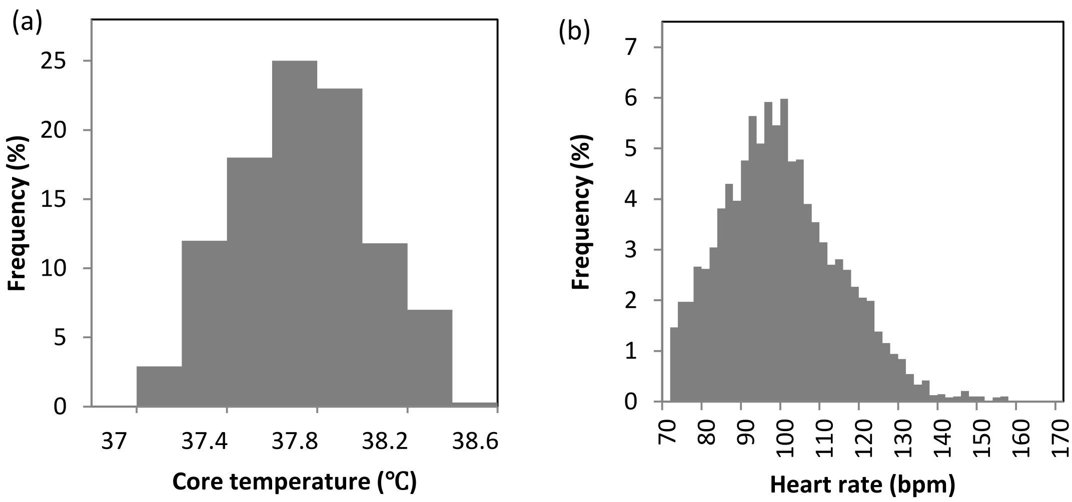


7.3.1 Field experiment

All the 14 participants were Chinese male. The average age, height, body mass, BMI, resting heart rate and tympanic of the 14 core subjects was 29 ± 3.32 yrs, 171 ± 5.63 cm, 62 ± 6.75 kg, 21.2 ± 2.17, 72 ± 5 beats/min and 36.16 ± 0.63 ℃, respectively. Of the core subjects, 50%, 21%, and 29% did not smoke at all, had one to four cigarettes per day, and had five cigarettes or more per day, respectively. Of the core subjects, 43%, 57%, and 7% did not drink at all, consumed one cup of beer/red wine/white spirit per day, and two cups or more beer/red wine/white spirit per day, respectively. The 14 core subjects slept 7.2 ± 0.7 h per day.

Core temperature ranged from 37.4 ℃ (12.10 %) to 38.2 ℃ (11.83%) (mean ± SD = 37.82 ℃ ± 0.87 ℃) (Figure 7.4a). The most frequent heart rate was from 84 to 108 bpm (accounting for more than 61.90%), and the average heart rate was 100 ± 15 bpm (Figure 7.4b). The RPE mainly ranged from 3 (30.02%) to 5 (15.10%), suggesting that core subjects experienced a moderate to hard physical workload (Figure 7.4c). The most frequent thermal sensation vote was 4–5 (54%), indicating that core subjects perceived the environment as more or less hot (Figure 7.4d). The dominated values of PhSI and PeSI ranged between 2.5 to 4.5, indicating that the perceived heat strain was low to moderate (Figure 7.4e and Figure 7.4f).

Figure 7.4 Frequency distributions of physiological and perceptual parameters



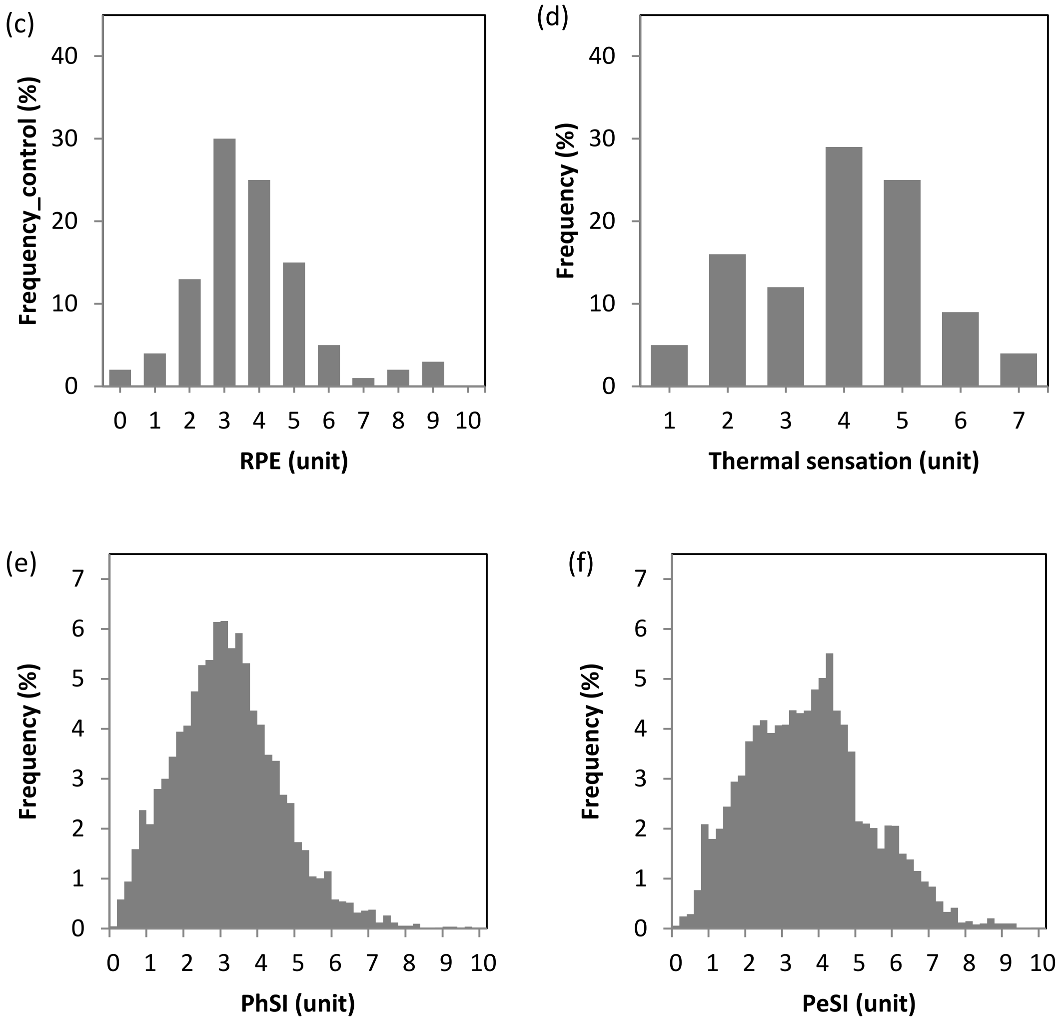
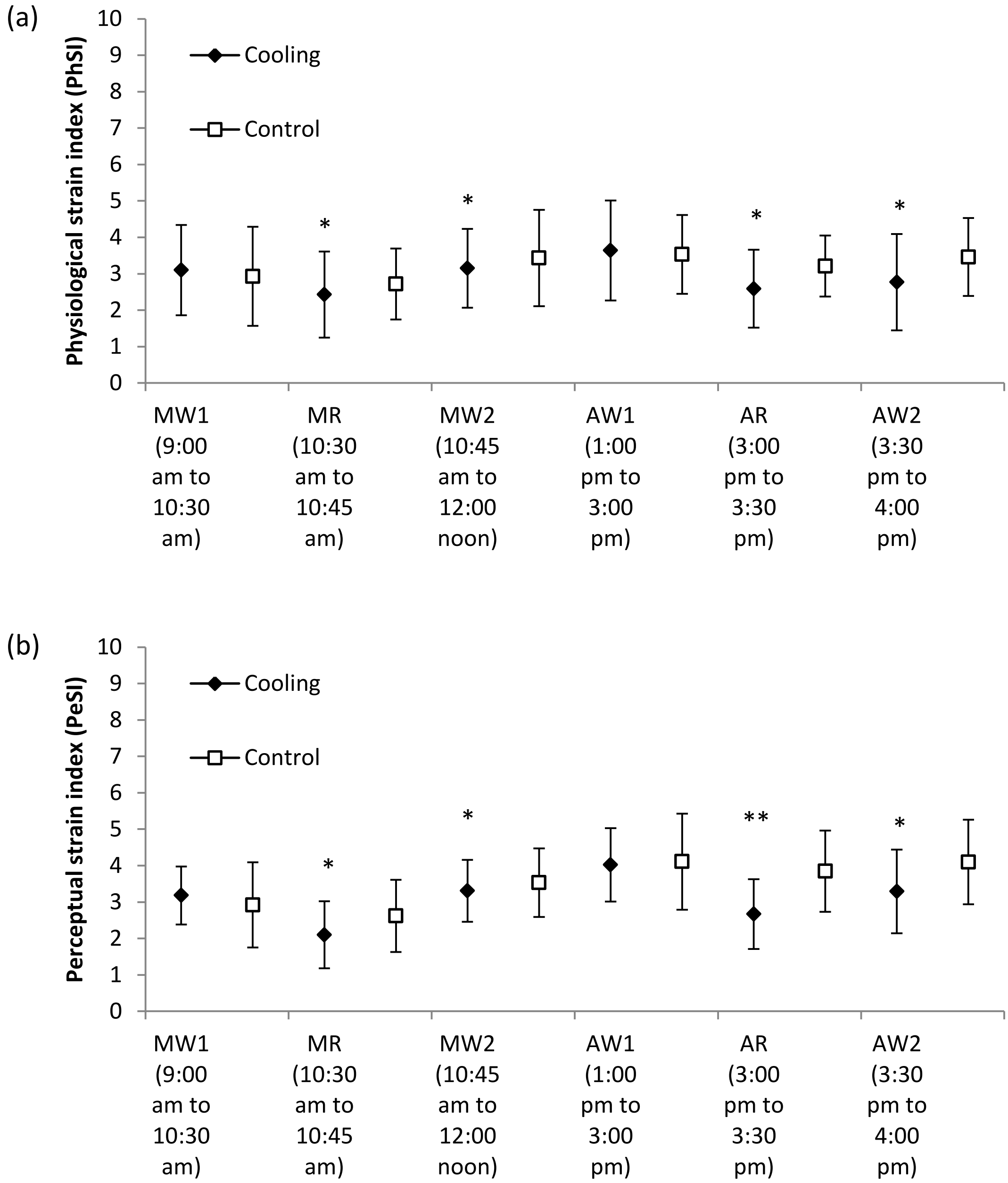


Figure 7.5 shows the change in PhSI and PeSI under the cooling and control condition during the field experiment. A 6 × 2 (condition × bout) repeated-measures ANOVA revealed significant difference in PhSI and PeSI between Cooling and Control across the entire test ($p = 0.03$ for PhSI; $p = 0.02$ for PeSI). Paired t-test observed that PhSI and PeSI were significantly lower in Cooling than in Control at MR ($p = 0.03$, $d = 0.27$ small cooling effect for PhSI; $p = 0.02$, $d = 0.54$ moderate cooling effect for PeSI) and MW2 ($p = 0.03$, $d = 0.23$ small cooling effect for PhSI; $p = 0.02$, $d = 0.24$ small cooling effect for PeSI), AR ($p = 0.04$, $d = 0.64$ moderate cooling effect for PhSI; $p = 0.01$, $d = 1.14$ large cooling effect for PeSI),

and AW2 (p = 0.04, d = 0.57 moderate cooling effect for PhSI; p = 0.03, d = 0.70 moderate cooling effect for PeSI).

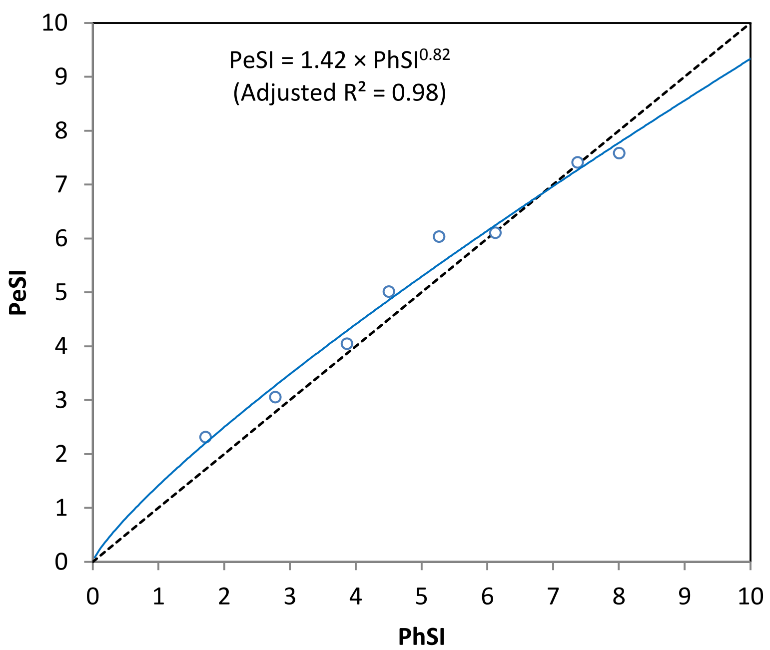
Figure 7.5 Change in (a) PhSI and (b) PeSI during the whole heat exposure



NOTE: Error bar is the standard deviation (N = 14; *$p < 0.05$, **$p < 0.01$). [first stage morning work (MW1), morning rest (MR), second stage morning work (MW2), first stage afternoon work (AW1), afternoon rest (AR), and second stage afternoon work (AW2)]

The correlation between PhSI and PeSI was significant ($r = 0.72$, $p < 0.01$). A power function was generated to further explore the relationship between the average PhSI and PeSI (adjusted $R^2 = 0.98$, Figure 7.6). Based on the relationship shown by the power function, PeSI was then substituted with the corresponding PhSI. Thus, combined thermal sensation and RPE votes in PeSI can predict the level of PhSI (Gallagher Jr et al., 2012).

Figure 7.6 Relationship between PhSI and PeSI



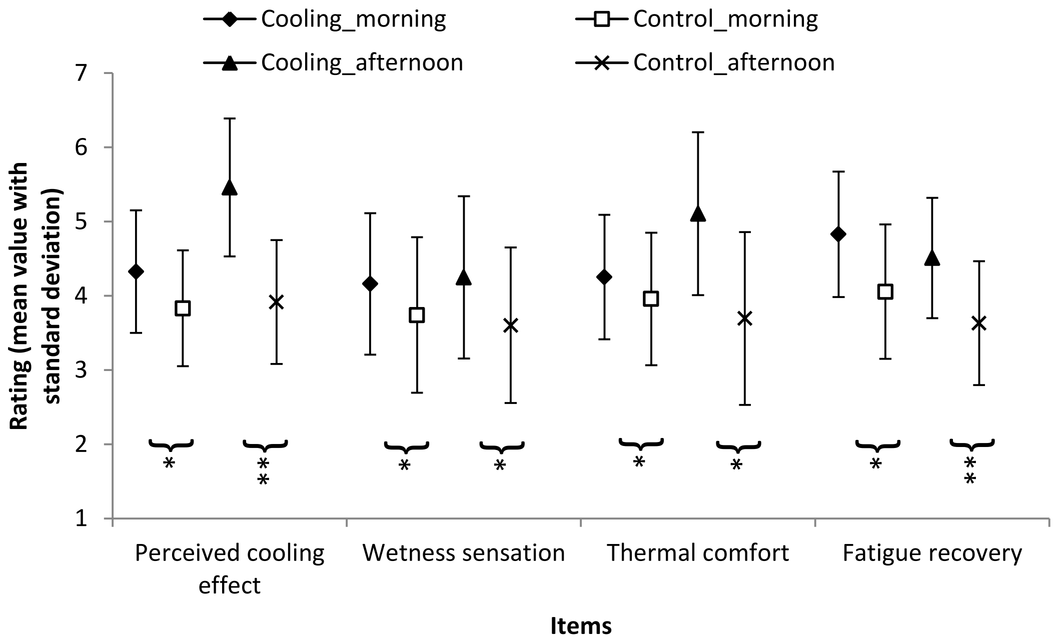
NOTE: each nonsolid circle refers to the average PhSI corresponding to each level of average PeSI

7.3.2 On-site questionnaire

In the on-site questionnaire survey, a total of 143 pairs of completed questionnaires (73 pairs from bar fixing workers and 70 pairs from timber formworks workers) were finally collected. Data from 11 participants were excluded due to incomplete record of heart rate (heart rate belt dropped off during work), incomplete questionnaires, and voluntary withdrawal (workers were injured or uncomfortable during work). The average age, height, body mass, BMI, and resting heart rate of the 143 participants was 32.3 ± 8.2 yrs, 171.2 ± 5. 6 cm, 68.5 ± 10.5 kg, 23.3 ± 3.2, and 71 ± 4 beats/min, respectively. Of the participants, 39%, 27%, and 34% did not smoke at all, had one to four cigarettes per day, and had five cigarettes or more per day, respectively. Of the participants, 36%, 55%, and 9% did not drink at all, consumed one cup of beer/red wine/white spirit per day, and two cups or more beer/red wine/white spirit per day, respectively. The 143 participants slept 7.1 ± 0.6 h per day.

Results of the questionnaire survey in the morning and afternoon sessions are shown in Figure 7.7. Subjective ratings between Control and Cooling were significantly different. In general, Cooling was rated significantly higher (the higher the better) than Control on all the subjective items ($p < 0.05$). Subjective ratings in Cooling ranged from 4 to 6, suggesting a satisfactory level for the cooling intervention.

Figure 7.7 Ratings of subjective sensations in the questionnaire survey



Error bar is the standard deviation (N = 143; *p < 0.05, **p < 0.01)

Participants' subjective rating towards the cooling vest on the likeness of wearing the PCS, fitness of the PCS, and the effectiveness of the PCS to reduce heat strain was 6.4 ± 0.8, 5.7 ± 1.4, and 6.0 ± 1.3, respectively, suggesting a high level of satisfaction. After the two-day wear trials, 91% of the 143 participants preferred to wear the newly designed cooling vest to reduce heat strains during rest periods. Only 9% workers dislike to wear the PCS because of the improper size (some workers are overweight but the size of the PCS is insufficient), taking cigarettes, and sleeping on their stomach.

7.4 DISCUSSION

The current study implemented a cooling intervention with a newly designed cooling vest during the recovery period between bouts of construction work. The construction work included morning (9:00 am to 12:00 noon) and afternoon (1:00 pm to 4:00 pm) sessions. In each session, two repeated bouts of work were intermitted by a period of rest (15 min rest in the morning and 30 min rest in the afternoon). The cooling intervention significantly reduced physiological and perceptual strain in recovery and subsequent work periods.

During the rest period, workers recovered from fatigue and prepared for subsequent work. In a moderate temperature situation (e.g., < 27 ℃ WBGT), body heat that accumulated during work is dissipated through the evaporation of sweat (driven by the large water vapour pressure gradient between the sweating skin [100%] and the environment) and the conduction of heat from the body core to the ambient environment (driven by the sufficient temperature gradient between the body and the environment) (Barwood et al., 2009a). However, the local WBGT reading in Hong Kong's construction sites during summer season always exceeds 28 ℃. Heat conditions are particularly severe on the floor/roof that is directly exposed to sunlight or in confined places that lacks ventilation. In such an environment, the natural dissipation of heat from the body to the ambient environment is blocked. Heat storage may continue to increase to a noncompensable level. Many studies have reported that during recovery, core temperature is not significantly attenuated and even increases in a hot environment without appropriate cooling countermeasures (Barr et al., 2011; Kim et al., 2011; Teunissen et al., 2014). In the current study, a significantly lower physiological/perceptual strain was observed in the cooling group compared with the control group during rest in the morning session ($p < 0.05$, $d = 0.27–0.50$, small cooling effect). The difference in physiological and perceptual strain between the cooling and control groups was even larger during rest period in the afternoon session ($p < 0.05$, $d = 0.64–1.07$, large cooling effect). The environment in the afternoon is hotter than that in the morning, which exposes workers in the control group to a higher risk of heat stress when no cooling intervention is implemented.

The participant workers were from the steel bar-fixing and timber formwork groups. A wide range of activities were included, such as heavy lifting, forceful pulling, climbing, and bar fixing. Air temperature, relative humidity, wind speed, and solar radiation varied throughout time. By contrast, laboratory tests usually use treadmill walking/running and ergometer with certain intensity under constant environmental conditions (Yi et al., 2017d). Although the laboratory test can assess the cooling capability and effectiveness of a cooling product, the field study can further evaluate its applicability under real settings. During the second work bout in the morning and afternoon sessions, heat strain was significantly attenuated in Cooling compared with that in Control. The attenuated core temperature by the cooling vest during recovery could increase the heat storage capacity in the subsequent work (Bongers et al., 2014). With reduced heat strain in the cooling condition, work performance and productivity was expected to improve. According to several laboratory studies, exercise duration is prolonged after a period of cooling. To examine the performance improvement in practical situations, construction activity (categorised as direct, productive, indirect, and non-productive activities) was recorded and construction labour productivity was thus calculated as the unit output divided by labour inputs (Li et al., 2016).

The field experiment was conducted during the hot summer season on construction training grounds. The mean WBGT during the experiment was 31.56 ℃. According to occupational safety and health organizations, preventive measures should be adopted when WBGT exceeds 28 ℃, and serious health effects may occur when WBGT exceeds 31 ℃ (Hong Kong Observatory). It was observed that WBGT significantly correlated with physiological and perceptual strain indices (PhSI–WBGT, r = 0.27; PeSI–WBGT, r = 0.33). However, this correlation was weaker than that those in PhSI–RPE (0.44), PhSI–thermal sensation (0.40), PeSI–core temperature (r = 0.40), and PeSI–heart rate (r = 0.67). PhSI and PeSI reflect combined body heat strain from thermoregulatory and cardiovascular systems. Core temperature, heart rate, RPE, and thermal sensation were taken from human subjects, whereas WBGT was taken from the environmental condition in which the human subjects worked. WGBT is the most convenient parameter for use on sites and can be easily interpreted in the industry (Parsons, 2006). It has been widely used as a heat stress threshold to determine the maximum allowable exposure duration to hot conditions and to develop benchmarks in guidelines (Rowlinson et al., 2014). The increase in WBGT significantly contributes to heat strain level. Other factors, including exercise intensity, clothing insulation, and personal characteristics (e.g., hydration level, body fat, and smoking/drinking habit) can cause variations in body heat strain (Chan et al., 2012a). This study applied the cooling vest during rest under the cooling condition. The cooling vest created a cooler microclimate around the body and contributed to a difference between the body and the local WBGT. The ideal situation of assessing heat strain is to collect physiological responses from working individuals (Chan and Yang, 2016). Wearable early-warning systems (e.g., watch strap) that continuously monitor the workers' physiological and perceptual responses (heart rate and RPE) can be developed to safeguard wellbeing (Yi et al., 2016).

7.5 SUMMARY

Although the effectiveness of the cooling intervention has been experimentally investigated in other studies under strictly controlled conditions in an environmental chamber, its cooling effect has been rarely assessed in an actual outdoor situation. In this chapter, the applicability of cooling intervention with the newly designed cooling vest during rest in between bouts of construction work is tested in an outdoor environment. Results show that physiological and perceptual strains are significantly attenuated during rest periods and subsequent work periods after cooling. Moreover, this cooling intervention shows practical contributions. The newly developed wearable cooling vest may be used as a practical cooling intervention in construction sites wherein a blower or water reservoir (cold water submission) cannot be installed due to limited space, uneven ground and lack of electricity and water supply. Besides, the proposed cooling vest can be used in combination with the existing anti-heat strain measures such as providing adequate cool and fresh drinking water, arranging intermittent recovery/rest periods in-between heat exposures, and providing shelters.

CHAPTER 8 CONCLUSIONS AND RECOMMENDATIONS

8.1 INTRODUCTION

This chapter provides an overview of the research findings and highlights the contributions, significance and limitations of this study. Suggestions and directions for future research are also presented in this chapter.

8.2 SUMMARY OF MAJOR FINDINGS

This study aims to develop an optimal cooling intervention with a newly designed personal cooling system (PCS) for the construction industry. Specific objectives are as follows: (1) to review various PCSs for combating occupational heat stress and improving work performance, (2) to engineer and design a tailor-made PCS for the construction industry, (3) to assess the cooling capability of the newly developed PCS by using a sweating thermal manikin, (4) to evaluate the effectiveness of the newly developed PCS in reducing heat stress and determine an optimal cooling intervention with the newly developed PCS through wear trials in the laboratory, and (5) to examine the applicability of the cooling intervention with the newly developed PCS through field wear trials.

8.2.1 Tailor-made PCS for the construction industry

The newly developed PCS is a two-layer cooling vest that is specifically designed to be worn over the construction uniform, which was previously designed by our research team. Hybrid cooling, which includes ventilation fans and phase change material (PCM) packs, is formulated for the newly designed PCS. Ventilation fans enhance convective and evaporative heat transfer, whereas PCM packs facilitate conductive heat dissipation from the body to the ambient environment. The newly designed cooling vest (Vest B) is superior to the commercial cooling vest (Vest CB) in terms of cooling sources, fabrics, aesthetics, ergonomics and industry-specific design, presented in Table 8.1.

Table 8.1 Characteristics of the new cooling vest (Vest B) and the commercial cooling vest (Vest CB)

Items	Commercially available cooling vest (Vest CB)	Newly designed cooling vest (Vest B)
Cooling power	56–49 W	86–67 W
Total weight	1.10 kg	1.26 kg
Fabrics	Mesh spacer fabrics for inner layer, nylon taffeta fabrics for the outer layer.	Mesh spacer fabrics for inner layer, nylon taffeta fabrics for the outer layer. Lightweight, high water vapor permeability, anti-abrasion and UV protection
UV protection	UPF 50+	UPF 50+
Cooling packs	0 ℃ ICE	28 ℃ PCM, can be solidified in an air-conditioned room
Cooling duration	0.6 h with hybrid cooling sources; 4 h with ventilation fans powered by four alkaline batteries	1 h with hybrid cooling sources; 7 h with ventilation fans powered by a lithium battery pack
Covering area of the cooling packs	300 cm^2	960 cm^2
Arrangement of the cooling packs	3 ICE packs on the lower back region	8 PCM packs are evenly placed on the chest and back region of the body considering the distribution of sweat gland

Items	Commercially available cooling vest (Vest CB)	Newly designed cooling vest (Vest B)
Ventilation fans	Air flow rate of 13 L/s to 0 L/s powered by AA battery (non-rechargeable)	Air flow rate of 22 L/s to 8 L/s powered by lithium battery (rechargeable)
Ventilation design	The ventilation fans are fixed at the lower back	The ventilation fans are fixed at the lower back with two openings at the upper back of the vest to enhance air circulation thereby facilitating sweat evaporation.
Fit-design	NA	A zipper was designed on two sides of the vest to control the thickness of the gap between the skin and the garment. A larger gap thickness at the lower back enhances convective and evaporative heat transfer along the skin surface. At the upper back, the much smaller air gap ensures a close contact between the PCM packs and the skin surface to increase convective and conductive cooling.
Mobility and compact design	√	√
Aesthetics	Dark blue vest	Light gray vest with PolyU Logo, which matched the anti-heat stress work uniform (developed in a previous research project).
Visibility and safety	NA	Reflective strips are on both sides (front and rear) of the vest
Ergonomics	NA	Narrow elastic bands in the collar and cuff match the construction uniform and make the clothing elegant and convenient for body activity. Wide and high resilience elastic bands in the waist can appear neat and tidy, and enhance safety (to prevent that the clothing got caught on something in the workplace). Fans were firmly installed as if the cloth and fan were one, thereby enhancing the safety.

8.2.2 Cooling power of the PCS

After completing the engineering and design of the PCS, a series of thermal manikin tests were conducted to examine its cooling power. The cooling power of the PCS was measured on a sweating thermal manikin in a climatic chamber that controlled at 34 ℃ air temperature and 60% relative humidity to simulate a typical hot and humid environment at construction sites in Hong Kong during summer. With combined cooling sources (i.e., PCM + Fan-on), the newly designed PCS has a much higher cooling power (in the torso region that the vest covered) of 67–87 W than the trade cooling vest (52–58 W) (Yi et al., 2017c).

8.2.3 Optimal cooling intervention with the PCS

On the basis of the “triangle” evaluation system, human wear trials were performed after thermal manikin tests to assess the effectiveness of the cooling intervention with the newly designed PCS in reducing body heat strain and improving work performance.

Laboratory experiments were conducted in a climatic chamber that simulated the outdoor hot and humid environments with 37 ℃ and 60% relative humidity. Twelve participants were randomly assigned to the cooling [VEST] and control condition [CON] in a counterbalanced order. Human physiological (body core temperature, heart rate, skin temperature and sweat rate) and perceptual (perceived exertion, thermal sensation, wetness sensation and overall comfort sensation) responses were measured during the experiment. To investigate how to employ the cooling intervention with the newly designed PCS (e.g. intervening time and duration), two protocols were developed. The first protocol consisted of treadmill exercise (up to 48 min jogging/walking) followed by a 30 min recovery. PCS was used during the entire heat exposure (including exercise and recovery) in the cooling condition in the first protocol. Physiological (core temperature and heart rate) and perceptual strains (thermal sensation and perceived exertion) were significantly attenuated during the recovery period (compared with the control condition; no PCS applied). It was found that the core temperature and heart rate were not significantly reduced during the exercise period (compared with the control condition; no cooling applied). Moreover, ergonomic and logistic problems were found in the construction industry. That is, wearing PCS throughout the work session is considered impractical for the workers who perform daily tasks during summer. Thus, another protocol with cooling intervention only at the recovery period (PCS was worn only during the 30 min recovery) was proposed. The second protocol consisted of two bouts of treadmill exercise (each was up to 48 min jogging/walking) intermitted by 30 min recovery. The major finding manifested that PCS significantly alleviates thermo-physiological strain during the recovery period. Core temperature in VEST is 0.42 ℃ lower than that in CON at the end of recovery period. Heart rate in VEST is 9 bpm lower than that in CON at the end of recovery period. At the initial 10 min of the Exe2, heat strain in VEST is significantly lower than that in CON ($p < 0.05$). The average duration of Exe2 in VEST was significantly improved as compared with CON (22.08 ± 12.30 min for VEST; 11.08 ± 3.4 min for CON, $p = 0.006$; $d = 1.22$). A remarkable reduction of body heat storage by 119.9% and an improvement in subsequent exercise (i.e. second-stage exercise) duration by 99.3% were achieved while wearing the PCS (compared with the control condition; no PCS applied). Consequently, an optimal cooling intervention was determined in which the newly designed PCS was used during rest between repeated bouts of work.

8.2.4 Applicability of the cooling intervention with the PCS

Field studies were further executed to evaluate the applicability of the optimal cooling intervention with the newly designed PCS. More than 140 participants engaged in timber formworks (42%) and bar bending (58%) participated in on-site wear trials and questionnaire surveys. In a two-day wear trial study, each participant randomly participated in the Cooling (cooling intervention with the newly designed PCS was applied during rest between bouts of work) and Control (no cooling intervention was applied) trials. At the end of the each rest period, a short questionnaire survey was conducted to assess participants' subjective ratings on their perceived cooling effect, thermal comfort, wetness sensation and fatigue recovery after rest. Participants' subjective ratings towards the cooling vest, including questions about the likeness of wearing the PCS, fitness of the PCS and effectiveness of the PCS to reduce heat strain were also collected. These subjective attributes were measured by using the seven-point Likert scale, which ranges from the lowest level (1) to the highest level (7) (the higher the better). For example, 7 indicates the highest perceived cooling effect, the best thermal comfort and wetness sensation, and the most fatigue recovery. Furthermore, the participants were asked after two-day wear trials to indicate whether they preferred to wear the PCS during rest. A significant difference in subjective ratings between Control and Cooling was observed. In general, the cooling condition was rated significantly higher (a high rating is favourable) than the control condition on all the subjective items ($p < 0.05$).

Subjective ratings in the cooling condition ranged from 4 to 7, thereby suggesting a satisfactory to highly satisfactory level on the cooling intervention. Moreover, 91% preferred to wear the PCS to reduce heat strain during rest periods.

In the field experiment, a total of 14 steel bar fixing workers were invited to participate. In the cooling condition, the PCS was worn over the rest period (between work bouts) in the morning and afternoon sessions. The field experiment was conducted to examine the effectiveness of the cooling intervention with the newly designed PCS in improving physiological and perceptual responses in a real work setting. Their ear temperature was measured by using an infrared tympanic electronic thermometer every 5 min. Heart rate was recorded by a heart rate monitor at 1 s interval. Participants were requested to report RPE (Borg CR-10 Scale) and thermal sensation (1 [cold] to 7 [hot]) every 5 min. All data were synchronised and transformed into 5 min averages. Physiological strain index (PhSI) based on heart rate and core temperature was determined. Perceptual strain index (PeSI) based on RPE and thermal sensation was further determined. A 6×2 (condition × bout) repeated measures ANOVA revealed a significant difference in PhSI and PeSI between Cooling and Control during the entire test ($p < 0.05$). A paired t-test found that PhSI and PeSI were significantly lower in Cooling than in Control at morning rest (MR), 2nd bout of morning work (MW2), afternoon rest (AR), and 2nd bout of afternoon work (AW2).

Overall, the optimal cooling intervention with the newly designed PCS promotes the well-being of construction workers given the declined physiological and perceptual strains during rest periods, thereby possibly resulting in improved work performance in the subsequent work session.

8.3 SIGNIFICANCE AND CONTRIBUTIONS

8.3.1 Alternative approach for conducting construction safety and health research

Traditional safety and health research in the construction industry primarily relied on case studies and quantitative surveys. In this study, a cooling intervention with the newly designed PCS was proposed. Experimentation was adopted as a reliable and feasible approach to conducting construction safety and health research. The efficacy, effectiveness and applicability of the PCS were examined after its development through a series of laboratory experiments and field studies. The experimentation adopted in the present study established the causal relationships between an intervention (independent variable) and an outcome (dependent variable). Cause–effect relationship is the fundamental of scientific reasoning (Yi and Chan, 2014c). Nevertheless, traditional methods (including case studies and surveys) in construction safety and health research typically do not clarify the unambiguous causal relationship (Yi and Chan, 2014c). Moreover, intervention studies suggest a solution to the criticism that academia and construction practitioners do not work closely in most construction research projects. Practitioners argue that the academia frequently focuses on subjects and issues that may be unrelated to the construction industry (Azhar et al., 2010; Laufer et al., 2008; Rahman and Kumaraswamy, 2008). Several construction practitioners perceive that academic research is impractical and inapplicable in actual construction situations. By contrast, researchers consider that practitioners generally ignore innovation research ideas that can significantly improve the practices and procedures in the industry (Azhar et al., 2010). An intervention study provides a platform for academic researchers and practitioners to collaborate in conducting construction safety and health research.

8.3.2 Facilitating cooling intervention research in construction

Numerous previous studies examined the effectiveness of PCS in firefighting, sports events, military activities and hazmat operations. However, limited research focused on developing a cooling intervention with the PCS for the construction industry. In view of this, the current study designed a tailor-made PCS, which can be used in construction sites with confined spaces, elevated platforms and uneven grounds, where installation of blowers and provision of cold water reservoirs are typically impractical. An optimal cooling intervention with the newly designed PCS was determined in this study. The cooling intervention would promote the well-being of construction workers through a reduced heat strain and improved work performance. The findings of the current study also demonstrate that the PCS is applicable in industrial settings and eventually in large populations and locations. Thus, the convincing research findings enable the academia and practitioners to promote the use of cooling intervention in the construction industry.

8.4 LIMITATIONS OF THE STUDY

The participants in the present study were all healthy males aged 19 to 35 years old and represented the main labour force. Thus, the results of the present study are inapplicable to women and the elderly, who are susceptible to heat strain and sensitive to the improved or worsened thermal/wetness sensation caused by the cooling vest. The sample size in this study was determined based on the required treatment difference in the core temperature and heart rate (determined by literature review and expert evaluation) and standard deviation. A large sample should be included to validate the questionnaire survey results and evaluate the relationship between personal characteristics (age, drinking/smoking habit and body fat) and heat strain level.

The duration of the second work bout after rest designed in the present study is shorter than the regular work duration in actual situations on construction worksites in Hong Kong according to the CIC guidelines. Heat strain achieved the highest reduction under the cooling condition at the end of recovery (at the start of subsequent work) and gradually increased to a value that is similar to that under the control condition at the end of subsequent work. In prolonged work duration, the cooling effect can be neglected in the later stage of work. Therefore, frequent intermittent rest with cooling duration was encouraged after considering the characteristics of the construction work activity (e.g. pouring of concrete should be continuously conducted once commenced).

In the field study, core temperature was estimated with tympanic ear temperature measurements given the invasive procedure for measuring core temperature. The estimated core temperature is less accurate than the direct measurement of core temperature, although the validity and applicability of an estimated core temperature in describing the variation in physiological heat strain have been demonstrated in laboratory and field studies (Chan et al., 2012c; Chan et al., 2012d).

8.5 FUTURE RESEARCH DIRECTIONS

This study presents a research framework for developing a cooling intervention with the PCS in the construction industry. The effectiveness and applicability of the cooling intervention with the newly designed PCS have been demonstrated through a case study in Hong Kong. Based on the current research framework, academia and industry practitioners should replicate research procedures and generate convincing results in other contexts or settings to formulate guidelines on implementing the cooling intervention. Cost–benefit analysis (Ikpe et al., 2012) can be introduced in future studies to support decision making in formulating guidelines at company-, industrial-, or national-levels. Costs are represented by the money invested by contractors to design and implement cooling intervention to prevent heat stress. Benefits can be obtained by contractors in terms of reduced heat-related illnesses and fatalities through the implementation of cooling intervention in the construction industry. A questionnaire survey is designed to elicit cost-and-benefit information from personnel who are responsible for safety and health performance in the construction industry (e.g., safety and health managers). Statistical techniques (e.g. benefit-cost ratio) are adopted to facilitate the comparison between costs and benefits (Preez, 2004). Upon the identification of benefits alongside the costs of cooling intervention, the consideration of economic support for cooling intervention becomes possible.

Certain barriers, including the change in cofactors that confound the measurement of intervention effect (e.g. techniques for measuring exposures), change in participation (research subjects or partners) and sociopolitical and ethical issues, exist in the intervention implementation research (Goldenhar et al., 2001). *"It may take years to before an intervention is completely implemented as planned"* (Goldenhar et al., 2001). In the present study, the effectiveness and applicability of the cooling intervention with the newly designed PCS in alleviating heat strain have been validated through laboratory experiments and field studies. A longitudinal study is needed in future studies to examine the long-term effects of the cooling intervention on preventing heat-related illnesses and safety accidents. Compared with cross-sectional research that analyses multiple variables at a given instance, longitudinal studies use continuous measures to follow-up on particular individuals over periods (that usually last for years) (Caruana et al., 2015). Longitudinal studies are designed to identify changes that a cooling intervention has induced in terms of the rate of heat-related injuries, as well as attitudes and behaviours towards heat-stress prevention.

8.6 SUMMARY

This chapter summarises the research findings, highlights the significance and contributions, acknowledges the limitations and suggests future research directions. This study presents a fresh and rigorous approach to provide considerable scientific evidence on the effectiveness and applicability of the cooling intervention with the newly designed PCS as a precautionary measure for alleviating heat stress in the construction industry.

APPENDICES

APPENDIX 1: Supplemental tables in literature review

Table 1 Search strategy and results from each included database

Search term/No.	MEDLINE	EMBASE	EMBASE Classic	CINAHL	Web of Science	SPORTDisscus
1. cool	5639	8155	1022	1,170	285,047	3,393
2. cooling	22703	33286	6889	1,422	272,278	1,494
3. cooled	7459	10111	2262	344	272,278	270
4. OR/terms 1 to 3	32613	46649	9231	2,691	285,047	4,874
5. occupation	20067	48390	9179	11,745	55,139	6,579
6. occupational	231315	263311	24940	93,752	101,578	21,524
7. work	599621	867006	78108	149,546	2,288,699	71,920
8. working	165095	237742	22501	53,635	2,292,707	21,298
9. workers	128018	141538	25629	53,149	196,969	9,131
10.construction	90143	103079	9388	23,311	437,209	17,599
11. steel	20649	29010	4518	1,217	327,090	2,260
12. iron	156777	231777	27242	7,322	430,249	6,869
13. utility maintenance	2	2	0	11	3,855	18
14. mining	27327	35146	1836	2,218	163,265	1,380
15. miners	4405	4861	2062	274	11,446	898
16. oil	93001	166945	21898	8,153	437,557	4,656
17. gas	230330	332090	42601	11,280	1,038,574	5,947
18. glass	60052	82004	11868	2,924	407,962	2,417
19. manufacturing	19695	37268	1531	1,876	275,840	3,188
20. cleaning	15223	26223	3360	3,287	138,388	2,149
21. horticulture	438	1025	84	1,629	4,775	495
22. farmer	2712	4345	854	1,069	55,927	1,482
23. agriculture	43711	55587	2736	4,118	97,029	2,751
24. catering	1054	15307	874	277	7,227	415
25. chemical	654952	1098396	61016	14,865	1,314,667	5,633
26. nuclear	453476	1285682	52148	7,395	680,569	3,442
27. biological	1306995	995456	51761	68,174	744,254	13,727
28. NBC	521	802	197	64	2,771	1,507
29. toxic	183748	234634	40189	6,011	202,438	1,127
30. firefighting	296	407	7	1,932	973	77
31. firefighters	1218	1423	20	4,842	2,576	474
32. military	70049	61835	4934	17,492	82,457	7,383
33. army	10730	19630	5951	2,886	27,568	4,239
34. soldiers	5954	6933	1694	2,175	18,296	1,655
35. aircrew	916	1030	233	67	1,382	182
36. OR/terms 5 to	3836653	5202498	319532	447,969	7,920,680	188,523

Search term/No.	MEDLINE	EMBASE	EMBASE Classic	CINAHL	Web of Science	SPORTDisscus
35						
37. exercise	239889	353821	29511	91,569	306,305	191,471
38. exercising	7650	9710	977	1,915	306,305	4,587
39. time	2888017	3349896	260451	292,031	5,146,249	158,266
40. duration	407171	787387	65819	46,838	500,429	17,279
41. endurance	26738	32329	1494	7,416	35,772	24,246
42. tolerance	226355	291954	31973	14,205	316,644	5,547
43. performance	582220	1038623	34820	89,668	2,516,044	166,922
44. OR/terms 37 to 43	3882041	5114755	420503	462,839	7,829,615	463,592
45. AND 4, 21, 29	3321	5168	565	198	40,067	380
46. Limit 30 to English language	3147	4890	441	198	996[a]	320

[a] Search also refined by appropriate categories: physiology; sports science; public, environmental and occupational health; ergonomics; cardiac cardiovascular systems; respiratory system.

Table 2 Investigation protocol for each included study

Ref.	Origin	Participants	Environmental conditions	Exercise protocol	Cooling intervention	Personal Protective Equipment (occupation & military)	Cooling system	Effect size and performance improvement
Amorim et al. 2010	University of New Mexico, US	8 males, 2 females	42 ± 1 ℃, 30 ± 5% RH, 0.8 m/s air velocity	100 min heat exposure (two bouts of 50 min treadmill walking intermittent by 41 min rest)	During rest	Body armor	LCG, vest, 16 ℃ inlet water	3.07 [1.69, 4.45], +65.20%
Barwood et al. 2009	University of Portsmouth, UK	8 heat acclimated males	45 ℃, 10% RH	6 h heat exposure (cycles of treadmill walking/rest)	Whole exposure	Body armor	ACG, vest, inlet air at ambient temperature	0.81 [-0.22, 1.84], +29.71%
Bennett et al. 1995	Naval Health Research Center, US	12 male firefighters	34.4 ± 0.5 ℃, 65% RH	120 min heat exposures (two cycles of 30 min rest/30 min treadmill walking)	Whole exposure	Firefighting ensemble	PCG1, 4-pack cool vest	1.87 [0.88, 2.85], + 29.31%
							PCG2, 6-pack cool vest	1.99 [0.98, 3.00], + 31.87%
Bishop et al. 1991	University of Alabama, US	14 air force personnel (12 males, 2 females)	26 ℃ WBGT	4 h heat exposure (cycles of 45 min treadmill walking/15 min rest)	During rest	US military chemical protective ensemble	ACG, 15-20 ℃ inlet air	2.15 [1.19, 3.10], + 12.26%
							LCG, 13 ℃ inlet water	1.86 [0.95, 2.77], + 15.56%

Ref.	Origin	Participants	Environmental conditions	Exercise protocol	Cooling intervention	Personal Protective Equipment (occupation & military)	Cooling system	Effect size and performance improvement
Cadarette et al. 2003	US Army Research Institute of Environmental Medicine, US	8 volunteers (6 males and 2 females)	38 ℃, 30% RH	4 h heat exposure (cycles of 20 min treadmill walking/10 min rest)	Whole exposure	Toxicological agent protective suit	LCG1, 172 ±34 W cooling power	2.33 [0.98, 3.68], + 84.78%
							LCG2, 178 ±41 W cooling power (18 ℃)	2.04 [0.76, 3.31], + 89.13%
Cadarette et al. 2001	US Army Research Institute, US	8 volunteers (6 males and 2 females)	38 ℃, 30% RH	2 h heat exposure (cycles of 20 min treadmill walking/10 min rest)	Whole exposure	Toxicological agent protective suit	LCG1, 186 ±58 W cooling power	1.99 [0.73, 3.25], + 130.43%
							LCG2, 200 ±36 W cooling power (18 ℃)	2.05 [0.77, 3.32], + 80.43%
Caldwell et al. 2012	University of Wollongong, Australia	8 male students	48 ℃, 20% RH	2 h heat exposure (eight bouts of 13 min cycling/2 min rest)	Whole exposure	Biological and chemical protective clothing	LCG, 15 ℃ inlet water	2.46 [1.07, 3.84], + 11.11%
Chan et al. 2017	The Hong Kong Polytechnic University	12 male students	37 ℃, 60% RH	Two bouts of 60 min treadmill exercise intermittent by 30 min rest	During rest	NA	HCG, PCM + air ventilation	1.19 [0.31, 2.07], + 100.45%

Ref.	Origin	Participants	Environmental conditions	Exercise protocol	Cooling intervention	Personal Protective Equipment (occupation & military)	Cooling system	Effect size and performance improvement
Ciuha et al. 2016	Jozef Stefan International Postgraduate School, Slovenia	10 healthy heat-unacclimatised male volunteers	45 ℃, 20% RH, 0.89 m/s	two bouts of 50 min walk (3.2km/h) intermittent by 20 min rest	During rest	Body armor	ACG, inlet air at ambient temperature	1.28 [0.30, 2.27], + 16.82%
Chinevere et al. 2008	US Army Research Institute of Environmental Medicine, US	6 heat acclimated volunteers	35 ℃, 75% RH, 1.1m/s	2 h treadmill walking	Whole exposure	Body armor	ACG, inlet air at ambient temperature	1.27 [-0.02, 2.56], + 20.83%
Kenny et al. 2011	University of Ottawa, Canada	10 males	35 ℃, 65 % RH	120 min treadmill walking	Whole exposure	Nuclear biological chemical (NBC) suit	PCG	2.05 [0.93, 3.18], + 11.88%
Kim et al. 2011	National Institute for Occupational Safety and Health, US	3 firefighters and 3 non-firefighters	35 ℃, 50 % RH	three cycles of 15 min treadmill running at 75% VO_{2max}/10 min rest	Whole exposure	Firefighter ensemble	LCG, 18 ℃	2.08 [0.56, 3.60], + 54.43%
							LCG + air ventilation	3.46 [1.42, 5.49], + 59.68%

Ref.	Origin	Participants	Environmental conditions	Exercise protocol	Cooling intervention	Personal Protective Equipment (occupation & military)	Cooling system	Effect size and performance improvement
McLellan et al. 1999	Defence and Civil Institute of Environmental Medicine, Canada	8 males	40 ℃, 30 % RH	3h exposure, 4.8 km/h, 5 % grade	Whole exposure	NBC overgarment	ACG, 12 ℃ inlet air	7.82 [4.55, 11.10], + 147.18%
Muir et al. 1999	University of Alabama, US	6 males	28 ℃ WBGT	2 h treadmill walking	Whole exposure	Impermeable protective suit	PCG, ice packs to torso	2.27 [0.69, 3.85], + 88.24%
Muza et al. 1988	US Army Research Institute of Environmental Medicine, US	6 male soldiers	40.6 ℃, 8.6 % RH	250 min heat exposure (cycles of 50 min treadmill walking/50 min rest)	Whole exposure	Chemical protective clothing	ACG1, ambient air flow at 10 cubic foot per minute (cfm)	0.41 [-0.74, 1.56], + 18.75%
							ACG2, ambient air flow at 18 cfm	1.13 [-0.13, 2.38], + 42.05%
Pimental et al. 1987	US Army Research Institute of Environmental Medicine, US	4 males	49 ℃, 20 % RH, 1.1m/s	300 min heat exposure (cycles of 45 min treadmill walking/15 min rest) at mean metabolic rate of 315 W	Whole exposure	Chemical protective clothing	ACG1, 26.4 ℃, 61.9 % RH inlet air	2.71 [0.39, 5.03], + 232.88%
							ACG2, 27℃, 29.5% RH	7.14 [2.04, 12.24], + 278.08%
							ACG3, 27℃, 41.7% RH	6.14 [1.70, 10.59], + 287.67%

Ref.	Origin	Participants	Environmental conditions	Exercise protocol	Cooling intervention	Personal Protective Equipment (occupation & military)	Cooling system	Effect size and performance improvement
Vallerand et al., 1991	Defence and Civil Institute of Environmental Medicine, Canada	7 males	37±0.5℃, 50 ±5% RH	150 min heat exposure (10min treadmill walking & 20min rest & cycles of 10/10min ergo-cycling/rest	Whole exposure	Aircrew chemical defence ensemble	ACG, vest, 13℃	4.62 [2.34, 6.89], + 25%
							LCG, vest, 13℃	3.08 [1.37, 4.78], + 15.38%
Zhang et al. 2010	University of Alabama, US	10 males	30 ℃ WBGT	4 h treadmill walking	Whole exposure	NA	PCG, carbon dioxide cooling shirt	0.70 [-0.21, 1.61], + 31.08%

Table 3 Physiotherapy Evidence Database (PEDro) scale scores for each included study

	eligibility criteria were specified (not scored)	subjects were randomly allocated to groups[a]	allocation was concealed	groups were similar at baseline	blinding of subjects	blinding of intervention administrators	blinding of assessors	outcome measure obtained from≥85% subjects	all subjects received intervention/intention to treat analysis	between group statistical comparisons reported	between group variability reported	PEDro score	Sample size calculation
Amorim et al. 2010	0	0	0	1	0	0	0	1	1	1	1	5	0
Barwood et al. 2009	0	0	0	1	0	0	0	1	1	1	1	5	0
Bennett et al., 1995	0	0	0	1	0	0	0	1	1	1	1	5	0
Bishop et al., 1991	0	0	0	1	0	0	0	1	1	1	1	5	0
Cadarette et al., 2003	0	1	0	1	0	0	0	1	1	1	1	6	0
Cadarette et al. 2001	0	0	0	1	0	0	0	1	1	1	1	5	0
Caldwell et al. 2012	0	0	0	1	0	0	0	1	1	1	1	5	0
Ciuha et al. 2016	1	1	0	1	0	0	0	1	1	1	1	6	0

	eligibility criteria were specified (not scored)	subjects were randomly allocated to groups[a]	allocation was concealed	groups were similar at baseline	blinding of subjects	blinding of intervention administrators	blinding of assessors	outcome measure obtained from≥85% subjects	all subjects received intervention/intention to treat analysis	between group statistical comparisons reported	between group variability reported	PEDro score	Sample size calculation
Chinevere et al. 2008	0	1	0	1	0	0	0	1	1	1	1	6	1
Kenny et al. 2011	0	1	0	1	0	0	0	1	1	1	1	6	0
Kim et al. 2011	0	1	0	1	0	0	0	1	1	1	1	6	0
McLellan et al. 1999	0	1	0	1	0	0	0	1	1	1	1	6	0
Muir et al. 1999	0	0	0	1	0	0	0	1	1	1	1	5	0
Muza et al. 1988	0	0	0	1	0	0	0	1	1	1	1	5	0
Pimental et al., 1987	0	0	0	1	0	0	0	1	1	1	1	5	0
Vallerand et al., 1991	0	1	0	1	0	0	0	1	1	1	1	6	
Zhang et al., 2010	1	1	0	1	0	0	0	1	1	1	1	7	0

[a] In crossover study, subjects were allocated randomly in the order in which treatments were received

APPENDIX 2: Data collection sheet used in the laboratory experiment

Project title: Developing a personal cooling system (PCS) for combating heat stress in the construction industry													
Date:		Name:		Age:	Height:		Weight:		95%HRmax:			Test No.:	
Trial: Control/Cooling			Physiological parameters			Sweating			Subjective ratings				
			HR	Core Temperature	Skin Temperature	Nude mass	Fluid intake	**Stop Time**	RPE	TS	WS	CS	Nude mass
Pre-exercise													
	10 min	0											
	10 min	0											
	10 min	0											
Start time													
Warm-up	3 min	6km/h, 2%											
	3 min	6km/h, 4%											
1st bout work	**3 min**	**6km/h, 8%**											
	3 min	3km/h, 2%											
	3 min	**6km/h, 8%**											
	3 min	3km/h, 2%											
	3 min	**6km/h, 8%**											
	3 min	3km/h, 2%											
	3 min	**6km/h, 8%**											
	3 min	3km/h, 2%											
	3 min	**6km/h, 8%**											
	3 min	3km/h, 2%											
	3 min	**6km/h, 8%**											

	3 min	3km/h, 2%											
	3 min	**6km/h, 8%**											
	3 min	3km/h, 2%											
	3 min	**6km/h, 8%**											
	3 min	3km/h, 2%											
Activity Recovery	**3 min**	**3km/h, 1%**											
	3 min	2km/h, 1%											
Passive Recovery													
	10 min	0											
	10 min	0											
	10 min	0											
Warm-up	3 min	6km/h, 2%											
	3 min	6km/h, 4%											
2nd bout work	**3 min**	**6km/h, 8%**											
	3 min	3km/h, 2%											
	3 min	**6km/h, 8%**											
	3 min	3km/h, 2%											
	3 min	**6km/h, 8%**											
	3 min	3km/h, 2%											
	3 min	**6km/h, 8%**											
	3 min	3km/h, 2%											
	3 min	**6km/h, 8%**											
	3 min	3km/h, 2%											
	3 min	**6km/h, 8%**											
	3 min	3km/h, 2%											

	3 min	**6km/h, 8%**											
	3 min	3km/h, 2%											
	3 min	**6km/h, 8%**											
	3 min	3km/h, 2%											
Activity Recovery	**3 min**	**3km/h, 1%**											
	3 min	2km/h, 1%											

APPENDIX 3: Questionnaire used in the laboratory experiment

The Hong Kong Polytechnic University

Construction Health and Safety Research Team

Research Project:

Developing a personal cooling system (PCS) for combating heat stress in the construction industry

Name: Date:

A. Subjective ratings on the cooling vest (After exercise)

Subjective ratings	**1**	**2**	**3**	**4**	**5**	**6**	**7**	
1. Breathable	☐	☐	☐	☐	☐	☐	☐	Air-tight
2. Dry	☐	☐	☐	☐	☐	☐	☐	Damp
3. Light	☐	☐	☐	☐	☐	☐	☐	Heavy
4. Cool	☐	☐	☐	☐	☐	☐	☐	Hot
5. Comfortable	☐	☐	☐	☐	☐	☐	☐	Uncomfortable
6. Allow movement	☐	☐	☐	☐	☐	☐	☐	Not allow movement
7. Not interference job performance	☐	☐	☐	☐	☐	☐	☐	Interference
8. Like	☐	☐	☐	☐	☐	☐	☐	Not like

B. Subjective ratings on the cooling vest (After recovery)

Subjective ratings	**1**	**2**	**3**	**4**	**5**	**6**	**7**	
1. Breathable	☐	☐	☐	☐	☐	☐	☐	Air-tight
2. Dry	☐	☐	☐	☐	☐	☐	☐	Damp
3. Light	☐	☐	☐	☐	☐	☐	☐	Heavy
4. Cool	☐	☐	☐	☐	☐	☐	☐	Hot
5. Comfortable	☐	☐	☐	☐	☐	☐	☐	Uncomfortable
6. Allow movement	☐	☐	☐	☐	☐	☐	☐	Not allow movement
7. Not interference job performance	☐	☐	☐	☐	☐	☐	☐	Interference
8. Like	☐	☐	☐	☐	☐	☐	☐	Not like

C. The Purpose of Collecting Personal Information

Your personal information is collected by the Construction Safety Research Team of The Hong Kong Polytechnic University for the project of *developing a personal cooling system (PCS) for combating heat stress in the construction industry*. The aim is studying on the subjective comfort, practicability, and acceptability of the newly designed PCS. We will not disclose your personal information which will only be used for the project reports and be destroyed after the project is completed. If you have any questions, please contact the project director Prof Albert Chan (Tel: 2766 5814).

<u>This is the end of the questionnaire, thank you!</u>

研究項目:

開發一套個人冷卻設備供建築工人抵禦高溫

姓名: 日期:

A. 請選出主觀感覺 (運動後)

主觀感覺刻度	**1**	**2**	**3**	**4**	**5**	**6**	**7**	
1. 透氣	☐	☐	☐	☐	☐	☐	☐	悶焗
2. 乾	☐	☐	☐	☐	☐	☐	☐	濕
3. 輕	☐	☐	☐	☐	☐	☐	☐	重
4. 冷	☐	☐	☐	☐	☐	☐	☐	熱
5. 舒服	☐	☐	☐	☐	☐	☐	☐	不舒服
6. 易於活動	☐	☐	☐	☐	☐	☐	☐	阻礙活動
7. 不幹擾工作效能	☐	☐	☐	☐	☐	☐	☐	幹擾工作效能
8.喜歡	☐	☐	☐	☐	☐	☐	☐	不喜歡

B. 請選出主觀感覺 (休息後)

主觀感覺刻度	**1**	**2**	**3**	**4**	**5**	**6**	**7**	
1. 透氣	☐	☐	☐	☐	☐	☐	☐	悶焗
2. 乾	☐	☐	☐	☐	☐	☐	☐	濕
3. 輕	☐	☐	☐	☐	☐	☐	☐	重
4. 冷	☐	☐	☐	☐	☐	☐	☐	熱
5. 舒服	☐	☐	☐	☐	☐	☐	☐	不舒服
6. 易於活動	☐	☐	☐	☐	☐	☐	☐	阻礙活動
7. 不幹擾工作效能	☐	☐	☐	☐	☐	☐	☐	幹擾工作效能
8.喜歡	☐	☐	☐	☐	☐	☐	☐	不喜歡

C. 收集資料目的

你所提供的個人資料將由香港理工大學建築及房地產學系建築健康及安全研究小組收集，目的旨在研究一套個人冷卻設備在主观感觉上的舒适性，我們將會小心處理你所提供的資料，加以保密，數據將會在此研究結束後作撰寫研究報告之用，並在研究完成後銷毀。如對這份問卷有任何查詢，請聯絡香港理工大學建築及房地產學系研究项目“開發一套個人冷卻設備供建築工人抵禦高溫”首席調查員陳炳泉教授（電話: 2766 5814）。

§ 问卷结束，感谢您的参与 §

APPENDIX 4: Data collection sheet used in the field experiment

Project title: Developing a personal cooling system (PCS) for combating heat stress in the construction industry																					
Date:			Name:						Age:								Weight:		Trial: Cooling/Control		
			Work activity																		
	Time	Duration	A1	A2	A3	A4	A5	A6	B1	B2	B3	B4	B5	C1	C2	Ear T	HR	RPE	TS	WS	CS
Work		2 min																			
		2 min																			
		2 min																			
		2 min																			
		2 min																			
		2 min																			
		2 min																			
		2 min																			
		2 min																			
		2 min																			
		… …																			
Rest		5 min																			
		5 min																			
		5 min																			
Work		2 min																			
		2 min																			
		2 min																			
		2 min																			
		2 min																			

		2 min																			
		2 min																			
		2 min																			
		2 min																			
		2 min																			
		… …																			
Lunch break																					
Work		2 min																			
		2 min																			
		2 min																			
		2 min																			
		2 min																			
		2 min																			
		2 min																			
		2 min																			
		2 min																			
		2 min																			
		2 min																			
		… …																			
Rest		5 min																			
		5 min																			
		5 min																			
		5 min																			
		5 min																			

		5 min																			
Work		2 min																			
		2 min																			
		2 min																			
		2 min																			
		2 min																			
		2 min																			
		2 min																			
		… …																			

Note:

A. Direct/productive work activities

A-1 Use of wrenches/scissors to band, cut, connect and adjust reinforcement bars (绑扎钢筋)

A-2 Place reinforcement bars (放置钢筋)

A-3 Adjust reinforcement bars (调整钢筋)

A-4 Lift reinforcement bars (抬钢筋)

A-5 Use meter sticks for measurements (量尺度)

A-6 Bending (弯钢筋)

B. Indirect/non-productive work activities

B-1 Walking for tools/material (为了工作任务的行走)

B-2 Waiting for materials to be lifted (为了工作需要的等待)

B-3 Read the bill of materials to understand the work (看图纸/计划/安排)

B-4 Discuss the work with foreman or each other (跟管工/同事讨论工作)

B-5 Take materials (拿物料)

C. Idle work activities

C-1 Ready to work but “on hold.” (准备工作，等待分配任务)

C-2 Drink, smoke, chat, sit, stroll, use phones, go to toilet, etc. (个人休息)

APPENDIX 5: Questionnaire used in the field survey

The Hong Kong Polytechnic University

Construction Health and Safety Research Team

Research Project:

Developing a personal cooling system (PCS) for combating heat stress in the construction industry

The objective of this study is to evaluate the personal cooling system (PCS) for comfort, suitability, practicality, and acceptability, and rating of perceived exertion scale on the basis of human psychological responds. In order to achieve this objective, please give us your valuable advises by ticking the enclosed questionnaire on the scales. Thank you very much for your cooperation.

PART I：PERSONAL INFORMATION

1. Name： ___________________ 2. Gender： ___________________

3. Date of birth： _______________ 4. Height （cm）： _____________

5. Weight（kg）： _____________ 6. Trade： ___________________

7. Sleeping time： __________hours 8. Work experience： _________

9. Residence :_______①Hong Kong ②Mainland China ③Nepal ④Pakistan ⑤Other

10. Education level：_______①Below ②Primary ③Secondary ④Certificate/Diploma ⑤Degree or higher

11. Do you take warm-up or stretch for more than 5 min before work？ ①Yes ②No

12. Do you take warm-up or stretch for more than 5 min after work？ ①Yes ②No

13. Smoking habit

a. Frequency

①Never or less than 1 times per month ②1 to 3 times per month ③1 times per week ④2 times per week ⑤3 times per week ⑥4 times per week ⑦5 times per week ⑧6 times per week ⑨7 times per week

b. Quantities per time

①0 ②1 ③2 ④3 ⑤4 ⑥5 or more _____

14. Alcohol habit

A. Red wine

a. Frequency

①Never or less than 1 times per month ②1 to 3 times per month ③1 times per week ④2 times per week ⑤3 times per week ⑥4 times per week ⑦5 times per week ⑧6 times per week ⑨7 times per week

b. Quantities per time（cup/bottle）

①0 ②1 ③2 ④3 ⑤4 ⑥5 or more _____

B. Brandy

a. Frequency

①Never or less than 1 times per month ②1 to 3 times per month ③1 times per week

④2 times per week ⑤3 times per week ⑥4 times per week ⑦5 times per week

⑧6 times per week ⑨7 times per week

b. Quantities per time（cup/bottle）

①0 ②1 ③2 ④3 ⑤4 ⑥5 or more _____

C. Beer

a. Frequency

①Never or less than 1 times per month ②1 to 3 times per month ③1 times per week

④2 times per week ⑤3 times per week ⑥4 times per week ⑦5 times per week

⑧6 times per week ⑨7 times per week

b. Quantities per time（cup/bottle）

①0 ②1 ③2 ④3 ⑤4 ⑥5 or more _____

PART II：WEAR TRIAL IN THE MORNING（1st DAY）

Condition: wear the cooling vest（ ）; not wear the cooling vest（ ）

After work in the morning (10:15 am)

(1) Please tick the box you agree with most（✔）

Thermal sensation during work in the morning	1 Cold	2 Cool	3 Slightly cool	4 Neutral	5 Slightly warm	6 Warm	7 Hot				
RPE during work in the morning	0 Not at all	1 Very light	2 Light	3 Moderate	4 Somewhat hard	5 Heavy	6	7 Very heavy	8	9	10 Maximal

After 15 min rest in the morning (10:30 am)

(2) Please tick the heat stress precautionary measures that you took during rest

(Multiple choice)

No ( ) Drink water ( ) Wash face ( ) Other, please indicate (______)

(3) Please tick the box you agree with most（✔）

Thermal sensation after rest in the morning	1 Cold	2 Cool	3 Slightly cool	4 Neutral	5 Slightly warm	6 Warm	7 Hot				
RPE after rest in the morning	0 Not at all	1 Very light	2 Light	3 Moderate	4 Somewhat hard	5 Heavy	6	7 Very heavy	8	9	10 Maximal

(4) Please tick the box you agree with most（✔）

Subjective rating	1	2	3	4	5	6	7
Cooling effect during rest (the larger the cooler)	☐	☐	☐	☐	☐	☐	☐
Wetness sensation during rest (the larger the drier)	☐	☐	☐	☐	☐	☐	☐
Comfort sensation during rest (the larger the more comfortable)	☐	☐	☐	☐	☐	☐	☐
Fatigue recovery after rest (the larger the more restored)	☐	☐	☐	☐	☐	☐	☐
Only for cooling group							
	1	**2**	**3**	**4**	**5**	**6**	**7**
Likeness of wearing the PCS during rest (the larger the better)	☐	☐	☐	☐	☐	☐	☐
Fitness of the PCS (the larger the more fit)	☐	☐	☐	☐	☐	☐	☐
The PCS effectively prevents heat strain (the larger the more effective)	☐	☐	☐	☐	☐	☐	☐

PART III：WEAR TRIAL IN THE AFTERNOON（1st DAY）

<u>After work in the afternoon (3:00 pm)</u>

(5) Please tick the box you agree with most（✔）

<u>Thermal sensation</u> during work in the afternoon	1 Cold	2 Cool	3 Slightly cool	4 Neutral	5 Slightly warm	6 Warm	7 Hot				
<u>RPE</u> during work in the afternoon	0 Not at all	1 Very light	2 Light	3 Moderate	4 Somewhat hard	5 Heavy	6	7 Very heavy	8	9	10 Maximal

After 30 min rest in the afternoon (3:30 pm)

(6) Please tick the heat stress precautionary measures that you took during rest

(Multiple choice)

No (   )   Drink water (   )   Wash face (   )   Other, please indicate (______)

(7) Please tick the box you agree with most（✔）

Thermal sensation after rest in the afternoon	1 Cold	2 Cool	3 Slightly cool	4 Neutral	5 Slightly warm	6 Warm	7 Hot				
RPE after rest in the afternoon	0 Not at all	1 Very light	2 Light	3 Moderate	4 Somewhat hard	5 Heavy	6	7 Very heavy	8	9	10 Maximal

(8) Please tick the box you agree with most（✔）

Subjective rating	**1**	**2**	**3**	**4**	**5**	**6**	**7**
Cooling effect during rest (the larger the cooler)	☐	☐	☐	☐	☐	☐	☐
Wetness sensation during rest (the larger the drier)	☐	☐	☐	☐	☐	☐	☐
Comfort sensation during rest (the larger the more comfortable)	☐	☐	☐	☐	☐	☐	☐
Fatigue recovery after rest (the larger the more restored)	☐	☐	☐	☐	☐	☐	☐

Only for cooling group

	1	**2**	**3**	**4**	**5**	**6**	**7**
Likeness of wearing the PCS during rest (the larger the better)	☐	☐	☐	☐	☐	☐	☐
Fitness of the PCS (the larger the more fit)	☐	☐	☐	☐	☐	☐	☐
The PCS effectively prevents heat strain (the larger the more effective)	☐	☐	☐	☐	☐	☐	☐

PART IV：WEAR TRIAL IN THE MORNING（2nd DAY）

Condition: wear the cooling vest（ ）; not wear the cooling vest（ ）

After work in the morning (10:15 am)

(9) Please tick the box you agree with most（✔）

Thermal sensation during work in the morning	1 Cold	2 Cool	3 Slightly cool	4 Neutral	5 Slightly warm	6 Warm	7 Hot				
RPE during work in the morning	0 Not at all	1 Very light	2 Light	3 Moderate	4 Somewhat hard	5 Heavy	6	7 Very heavy	8	9	10 Maximal

After 15 min rest in the morning (10:30 am)

(10) Please tick the heat stress precautionary measures that you took during rest (Multiple choice)

No ( ) Drink water ( ) Wash face ( ) Other, please indicate (______)

(11) Please tick the box you agree with most（✔）

Thermal sensation after rest in the morning	1 Cold	2 Cool	3 Slightly cool	4 Neutral	5 Slightly warm	6 Warm	7 Hot				
RPE after rest in the morning	0 Not at all	1 Very light	2 Light	3 Moderate	4 Somewhat hard	5 Heavy	6	7 Very heavy	8	9	10 Maximal

(12) Please tick the box you agree with most（✔）

Subjective rating	1	2	3	4	5	6	7
Cooling effect during rest (the larger the cooler)	☐	☐	☐	☐	☐	☐	☐
Wetness sensation during rest (the larger the drier)	☐	☐	☐	☐	☐	☐	☐
Comfort sensation during rest (the larger the more comfortable)	☐	☐	☐	☐	☐	☐	☐
Fatigue recovery after rest (the larger the more restored)	☐	☐	☐	☐	☐	☐	☐
Only for cooling group							
	1	**2**	**3**	**4**	**5**	**6**	**7**
Likeness of wearing the PCS during rest (the larger the better)	☐	☐	☐	☐	☐	☐	☐
Fitness of the PCS (the larger the more fit)	☐	☐	☐	☐	☐	☐	☐
The PCS effectively prevents heat strain (the larger the more effective)	☐	☐	☐	☐	☐	☐	☐

PART V：WEAR TRIAL IN THE AFTERNOON（2nd DAY）

After work in the afternoon (3:00 pm)

(13) Please tick the box you agree with most（✔）

Thermal sensation during work in the afternoon	1 Cold	2 Cool	3 Slightly cool	4 Neutral	5 Slightly warm	6 Warm	7 Hot			
RPE during work in the afternoon	0 Not at all	1 Very light	2 Light	3 Moderate	4 Somewhat hard	5 Heavy	6	7 Very heavy	8	9	10 Maximal

After 30 min rest in the afternoon (3:30 pm)

(14) Please tick the heat stress precautionary measures that you took during rest (Multiple choice)

No (   )   Drink water (   )   Wash face (   )   Other, please indicate (______)

(15) Please tick the box you agree with most（✔）

Thermal sensation after rest in the afternoon	1 Cold	2 Cool	3 Slightly cool	4 Neutral	5 Slightly warm	6 Warm	7 Hot				
RPE after rest in the afternoon	0 Not at all	1 Very light	2 Light	3 Moderate	4 Somewhat hard	5 Heavy	6	7 Very heavy	8	9	10 Maximal

(16) Please tick the box you agree with most（✔）

Subjective rating	**1**	**2**	**3**	**4**	**5**	**6**	**7**
Cooling effect during rest (the larger the cooler)	☐	☐	☐	☐	☐	☐	☐
Wetness sensation during rest (the larger the drier)	☐	☐	☐	☐	☐	☐	☐
Comfort sensation during rest (the larger the more comfortable)	☐	☐	☐	☐	☐	☐	☐
Fatigue recovery after rest (the larger the more restored)	☐	☐	☐	☐	☐	☐	☐
Only for cooling group							
	1	**2**	**3**	**4**	**5**	**6**	**7**
Likeness of wearing the PCS during rest (the larger the better)	☐	☐	☐	☐	☐	☐	☐
Fitness of the PCS (the larger the more fit)	☐	☐	☐	☐	☐	☐	☐
The PCS effectively prevents heat strain (the larger the more effective)	☐	☐	☐	☐	☐	☐	☐

(17) After two-day wear trials , do you prefer to wear the PCS during scheduled rest periods in summer？

Yes (   )   No (   )

(18) Please give your comments on this PCS (e.g., fabrics, ventilation fans, clothing design, and logistic arrangement)

____

____

____

____

PART VI：The Purpose of Collecting Personal Information

Your personal information is collected by the Construction Safety Research Team of The Hong Kong Polytechnic University for the project of developing a personal cooling system (PCS) for combating heat stress in the construction industry. The aim is studying on the subjective comfort, practicability, and acceptability of the newly designed PCS. We will not disclose your personal information which will only be used for the project reports and be destroyed after the project is completed. If you have any questions, please contact the project director Prof Albert Chan (Tel: 2766 5814).

This is the end of the questionnaire, thank you !

香港理工大學

建築及房地產學系建築安全研究隊伍

開發一套個人冷卻設備供建築工人抵禦高溫

炎熱的夏季工作環境導致中暑及其相關事故頻發，嚴重影響戶外勞動者的健康安全。理大建造業健康及安全研究小組非常關注工人於酷熱環境工作的健康安全問題，為此專為地盤工人設計一件混合型抗熱背心。此次研究目的是評估新製混合型抗熱背心的有效性、舒適度、實用性及可接受度。煩請受試者提供你們寶貴的意見，完成此項問卷調查。感謝您的合作！

第一部分：基本資料

1. 姓名： ____________________ 2. 性別： ____________________

3. 出生年月： ________________ 4. 身高 （cm）：______________

5. 體重（kg）： ______________ 6. 工種： ____________________

7. 每日睡眠時間： ___________小时 8. 建造業工作經驗： __________

9. 户别：_______①香港或居港 7 年以上 ②中國內地 ③尼泊爾 ④巴基斯坦 ⑤其他

10. 教育程度：_______①小學②中三 ③中六 ④文憑 ⑤副學士 ⑥學士 ⑦其他

11. 你在每天工作前有沒有進行多於 5 分鐘的熱身運動或拉筋？①有 ②無

12. 你在每天工作後有沒有進行多於 5 分鐘的熱身運動或拉筋？①有 ②無

13. 吸煙習慣 （請在適當位置勾選 √）

a. 頻率

①從不或少於一個月 1 日 ②一個月 1-3 日 ③一星期 1 日 ④一星期 2 日

⑤一星期 3 日 ⑥一星期 4 日 ⑦一星期 5 日 ⑧一星期 6 日 ⑨一星期 7 日

b. 一日的分量（支）

①0 ②1 ③2 ④3 ⑤4 ⑥5 或以上，請寫出大約數量_____

14. 飲酒習慣 （請在適當位置勾選 √）

A. 紅酒

a. 頻率

①從不或少於一個月 1 日 ②一個月 1-3 日 ③一星期 1 日 ④一星期 2 日

⑤一星期 3 日 ⑥一星期 4 日 ⑦一星期 5 日 ⑧一星期 6 日 ⑨一星期 7 日

b. 一日的分量（罐）

①0 ②1 ③2 ④3 ⑤4 ⑥5 或以上

B. 白蘭地/燒酒

a. 頻率

①從不或少於一個月 1 日 ②一個月 1-3 日 ③一星期 1 日 ④一星期 2 日

⑤一星期 3 日 ⑥一星期 4 日 ⑦一星期 5 日 ⑧一星期 6 日 ⑨一星期 7 日

b. 一日的分量（罐）

①0 ②1 ③2 ④3 ⑤4 ⑥5 或以上

C. 啤酒

a. 頻率

①從不或少於一個月 1 日 ②一個月 1-3 日 ③一星期 1 日 ④一星期 2 日

⑤一星期 3 日 ⑥一星期 4 日 ⑦一星期 5 日 ⑧一星期 6 日 ⑨一星期 7 日

b. 一日的分量（罐）

①0 ②1 ③2 ④3 ⑤4 ⑥5 或以上

15. 當您夏季於戶外作業時，是否曾經出現以下中暑或輕微中暑的症狀（多選，請打✔）

口渴（ ） 乏力（ ） 心跳加速（ ） 冒冷汗（ ） 頭暈（ ） 頭痛（ ）

呼吸急促（ ） 抽筋（ ） 作嘔（ ） 昏厥（ ） 神智不清（ ）

其它，請說明（________________） 不清楚（ ） 無（ ）

16. 當您夏季於戶外作業時，經常使用的防暑降溫措施（多選，請打✔）

涼茶（ ） 飲水（ ） 防曬霜（ ） 防紫外線袖套（ ） 頭巾（ ）

領巾（ ） 遮蔭上蓋（ ） 手提風扇（ ） 穿著薄而透氣的衣物（ ）

其它，請說明（____________________）

第二部分：早上穿著實驗（第一天）

組別:　穿著抗熱背心（　　）;　未穿著抗熱背心（　　）

早晨休息前填寫 (10:15 am)

(1) 請選擇你最認同的選項（打✔）

<table>
<tr><td rowspan="2">今天早晨工作時<u>熱感覺</u></td><td>1
非常涼爽</td><td>2
涼爽</td><td>3
微涼</td><td>4
中等</td><td>5
微熱</td><td>6
熱</td><td>7
非常熱</td><td></td><td></td><td></td><td></td></tr>
<tr><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td rowspan="2">今天早晨工作時<u>辛苦程度</u></td><td>0
一點也不費力</td><td>1
非常輕鬆</td><td>2
輕鬆</td><td>3
中等</td><td>4
有點辛苦</td><td>5
辛苦</td><td>6</td><td>7
非常辛苦</td><td>8</td><td>9</td><td>10
極限</td></tr>
<tr><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
</table>

休息 15 分鐘後填寫 (10:30 am)

(2) 請指出您剛才休息時是否使用過以下降溫措施（多選，請打✔）

無（　　）　飲水（　　）　　洗面（　　）　　其它，請說明（__________）

(3) 請選擇你最認同的選項（打✔）

<table>
<tr><td rowspan="2">休息結束後<u>熱感覺</u></td><td>1
非常涼爽</td><td>2
涼爽</td><td>3
微涼</td><td>4
中等</td><td>5
微熱</td><td>6
熱</td><td>7
非常熱</td><td></td><td></td><td></td><td></td></tr>
<tr><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td rowspan="2">休息結束後<u>辛苦程度</u></td><td>0
一點也不費力</td><td>1
非常輕鬆</td><td>2
輕鬆</td><td>3
中等</td><td>4
有點辛苦</td><td>5
辛苦</td><td>6</td><td>7
非常辛苦</td><td>8</td><td>9</td><td>10
極限</td></tr>
<tr><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
</table>

(4) 請評價您的主觀感覺（打✔）數字越大，表示程度越強烈

主觀感覺	1	2	3	4	5	6	7
休息時我感覺的涼快程度(越大越涼快)	☐	☐	☐	☐	☐	☐	☐
休息時我皮膚的乾爽程度(越大越乾爽)	☐	☐	☐	☐	☐	☐	☐
休息時我的舒服程度(越大越舒服)	☐	☐	☐	☐	☐	☐	☐
我休息之後體力恢復的程度(越大恢復越多)	☐	☐	☐	☐	☐	☐	☐

僅（穿著抗熱背心組別）填寫

	1	2	3	4	5	6	7
休息時喜歡穿著抗熱背心的程度(越大越喜歡)	☐	☐	☐	☐	☐	☐	☐
背心合身的程度(越大越合身)	☐	☐	☐	☐	☐	☐	☐
背心有效幫助我抗熱的程度(越大越有效)	☐	☐	☐	☐	☐	☐	☐

第三部分：下午穿著實驗（第一天）

下午休息前填寫 (3:00 pm)

(5) 請選擇你最認同的選項（打✔）

今天下午工作時熱感覺	1 非常涼爽	2 涼爽	3 微涼	4 中等	5 微熱	6 熱	7 非常熱			
今天下午工作時辛苦程度	0 一點也不費力	1 非常輕鬆	2 輕鬆	3 中等	4 有點辛苦	5 辛苦	6	7 非常辛苦	8	9	10 極限

休息 30 分鐘後填寫 (3:30 pm)

(6) 請指出您剛才休息時是否使用過以下降溫措施（多選，請打✔）

無（ ） 飲水（ ） 洗面（ ） 其它，請說明 (__________)

(7) 請選擇你最認同的選項 (打✔)

休息結束後熱感覺	1 非常涼爽	2 涼爽	3 微涼	4 中等	5 微熱	6 熱	7 非常熱				
休息結束後辛苦程度	0 一點也不費力	1 非常輕鬆	2 輕鬆	3 中等	4 有點辛苦	5 辛苦	6	7 非常辛苦	8	9	10 極限

(8) 請評價您的主觀感覺（打✔）數字越大，表示程度越強烈

主觀感覺	1	2	3	4	5	6	7
休息時我感覺的涼快程度 (越大越涼快)	☐	☐	☐	☐	☐	☐	☐
休息時我皮膚的乾爽程度 (越大越乾爽)	☐	☐	☐	☐	☐	☐	☐
休息時我的舒服程度(越大越舒服)	☐	☐	☐	☐	☐	☐	☐
我休息之後體力恢復的程度 (越大恢復越多)	☐	☐	☐	☐	☐	☐	☐

僅 (穿著抗熱背心組別) 填寫

	1	2	3	4	5	6	7
休息時喜歡穿著抗熱背心的程度(越大越喜歡)	☐	☐	☐	☐	☐	☐	☐
背心合身的程度(越大越合身)	☐	☐	☐	☐	☐	☐	☐
背心有效幫助我抗熱的程度 (越大越有效)	☐	☐	☐	☐	☐	☐	☐

第四部分：早上穿著實驗（第二天）

<u>組別:　穿著抗熱背心（　　）;　未穿著抗熱背心（　　）</u>

<u>*早晨休息前填寫 (10:15 am)*</u>

(9) 請選擇你最認同的選項（打✔）

今天早晨工作時<u>熱感覺</u>	1 非常涼爽	2 涼爽	3 微涼	4 中等	5 微熱	6 熱	7 非常熱

今天早晨工作時<u>辛苦程度</u>	0 一點也不費力	1 非常輕鬆	2 輕鬆	3 中等	4 有點辛苦	5 辛苦	6	7 非常辛苦	8	9	10 極限

<u>*休息 15 分鐘後填寫 (10:30 am)*</u>

(10) 請指出您剛才休息時是否使用過以下降溫措施（多選，請打✔）

無（　　）　飲水（　　）　　洗面（　　）　　其它，請說明 (__________)

(11) 請選擇你最認同的選項（打✔）

休息結束後<u>熱感覺</u>	1 非常涼爽	2 涼爽	3 微涼	4 中等	5 微熱	6 熱	7 非常熱

休息結束後<u>辛苦程度</u>	0 一點也不費力	1 非常輕鬆	2 輕鬆	3 中等	4 有點辛苦	5 辛苦	6	7 非常辛苦	8	9	10 極限

(12) 請評價您的主觀感覺（打✔）數字越大，表示程度越強烈

主觀感覺	1	2	3	4	5	6	7
休息時我感覺的涼快程度(越大越涼快)	☐	☐	☐	☐	☐	☐	☐
休息時我皮膚的乾爽程度(越大越乾爽)	☐	☐	☐	☐	☐	☐	☐
休息時我的舒服程度(越大越舒服)	☐	☐	☐	☐	☐	☐	☐
我休息之後體力恢復的程度(越大恢復越多)	☐	☐	☐	☐	☐	☐	☐
僅（穿著抗熱背心組別）填寫							
	1	2	3	4	5	6	7
休息時喜歡穿著抗熱背心的程度(越大越喜歡)	☐	☐	☐	☐	☐	☐	☐
背心合身的程度(越大越合身)	☐	☐	☐	☐	☐	☐	☐
背心有效幫助我抗熱的程度(越大越有效)	☐	☐	☐	☐	☐	☐	☐

第五部分：下午穿著實驗（第二天）

下午休息前填寫 (3:00 pm)

(13) 請選擇你最認同的選項（打✔）

今天下午工作時<u>熱感覺</u>	1 非常涼爽	2 涼爽	3 微涼	4 中等	5 微熱	6 熱	7 非常熱			
今天下午工作時<u>辛苦程度</u>	0 一點也不費力	1 非常輕鬆	2 輕鬆	3 中等	4 有點辛苦	5 辛苦	6	7 非常辛苦	8	9	10 極限

休息 30 分鐘後填寫 (3:30 pm)

(14) 請指出您剛才休息時是否使用過以下降溫措施（多選，請打✔）

無（　） 飲水（　） 洗面（　） 其它，請說明 (__________)

(15) 請選擇你最認同的選項（打✔）

休息結束後熱感覺	1 非常涼爽	2 涼爽	3 微涼	4 中等	5 微熱	6 熱	7 非常熱				
休息結束後辛苦程度	0 一點也不費力	1 非常輕鬆	2 輕鬆	3 中等	4 有點辛苦	5 辛苦	6	7 非常辛苦	8	9	10 極限

(16) 請評價您的主觀感覺（打✔）數字越大，表示程度越強烈

主觀感覺	1	2	3	4	5	6	7
休息時我感覺的涼快程度(越大越涼快)	☐	☐	☐	☐	☐	☐	☐
休息時我皮膚的乾爽程度(越大越乾爽)	☐	☐	☐	☐	☐	☐	☐
休息時我的舒服程度(越大越舒服)	☐	☐	☐	☐	☐	☐	☐
我休息之後體力恢復的程度(越大恢復越多)	☐	☐	☐	☐	☐	☐	☐

僅（穿著抗熱背心組別）填寫

	1	2	3	4	5	6	7
休息時喜歡穿著抗熱背心的程度(越大越喜歡)	☐	☐	☐	☐	☐	☐	☐
背心合身的程度(越大越合身)	☐	☐	☐	☐	☐	☐	☐
背心有效幫助我抗熱的程度(越大越有效)	☐	☐	☐	☐	☐	☐	☐

(17) 結束兩日穿著實驗後，您願意於夏季作業時的定時休息時段使用抗熱背心嗎？

是（　　　　　　）　　　否（　　　　　　）

(18) 請評價該混合型抗熱背心（如布料、風扇、成衣設計、後勤安排等）

____

____

____

____

第六部分：收集資料目的

你所提供的個人資料將由香港理工大學建築及房地產學系建築健康及安全研究小組收集，目的旨在研究一套個人冷卻設備在主观感觉上的舒适性，我們將會小心處理你所提供的資料，加以保密，數據將會在此研究結束後作撰寫研究報告之用，並在研究完成後銷毀。如對這份問卷有任何查詢，請聯絡香港理工大學建築及房地產學系研究項目“開發一套個人冷卻設備供建築工人抵禦高溫”首席調查員陳炳泉教授（電話: 2766 5814）。

§问卷结束，感謝您的參與§

APPENDIX 6: Consent form used in the study

Consent To Participate In Research

Project Title

Developing a Personal Cooling System (PCS) for Combating Heat Stress in the Construction Industry

I hereby ________________ consent to participate voluntarily in the study conducted by Building and Real Estate of The Hong Kong Polytechnic University.

I understand that the collected data may be used for the research and publication. But the privacy of my personal information is properly protected and not released.

The researchers have clearly explained the study protocol to me and I understand the related benefit and risk. I participate in the study voluntarily.

I can choose whether to be in this study or not. If I volunteer to be in this study, I may withdraw at any time without consequences of any kind. I may withdraw my consent at any time and discontinue participation without penalty.

I have read the test instruction file.

Signature of participants ____________________________

Date ____

參與研究同意書

研究課題：

開發適用於建築業的個人冷凍設備

本人________同意參與由**香港理工大學建築與房地產學系**開展的上述研究。

本人知悉此研究所得的資料可能被用作日後的研究及發表，但本人的私隱權利將得以保留，即本人的個人資料不會被公開。

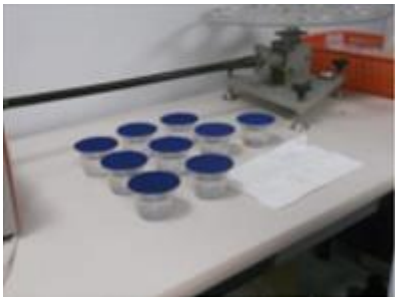
研究人員已向本人清楚解釋列在所附資料卡上的研究程序，本人明瞭當中涉及的利益及風險；本人自願參與研究項目。

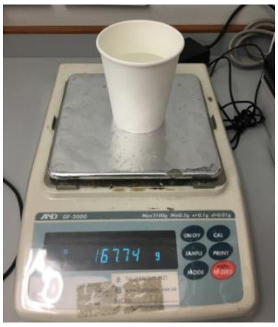
本人知悉本人有權就程序任何部分提出疑問，並有權隨時退出而不受任何懲處。

參與者簽署 ____________________

日期__________________________

APPENDIX 7: Equipment for collecting data

Equipment	Figure	Measurements
Hot wire anemometer (RS327-0640, Tecpel, Taiwan)		Air velocity (m/s)
Test dish		Water vapour permeability ($g/m^2/day$)
KES-F8-API (Kato Tech Co., Ltd., Kyoto, Japan)		Air resistance ($cc/s/cm^2$ at 100 pa)

CRAY 300 Conc UV-visible spectrophotometer (Agilent Technologies, Inc., USA)		Effective ultraviolet radiation (UVR) transmission (%)
Scale (GF-2000, A & D Company Ltd., Japan)		Mass (g)
Differential scanning calorimetry (DSC822e, Mettler Toledo, USA)		Heat of fusion (J/g) and melting temperature (℃)
Sweating thermal manikin		Cooling power of PCS (W/m^2)

Motorized treadmill (h/p/cosmos pulsar, Germany)		Exercise intense (km/h), slope (%), and exercise time (min)
Heat stress monitor (QUESTemp °36™, Australian)		Wet bulb globe temperature (℃)
CorTemp data logger (CorTrack™, HQInc., USA)		Core body temperature (℃)
Heart rate belt (Polar T34 Transmitter, Finland)		Heart rate (bpm)

Thermistor sensor and data logger (LT8A, Gram Co., Japan)	 	Skin temperature (℃)
Microclimate humidity sensor and data logger (RS14, Especmic, Japan)		Microclimate humidity (%)
Scale (E-SNO-PSL-150KPC, Sam Hing Scales Fty. Ltd., Hong Kong)		Mass (kg)
Multiple videos during the experiment (Designed by Mr I.K. Chan, Senior technician, Building and Real Estate Department, The Hong Kong Polytechnic University)		Digitalized images for (a) skin temperature data logger, (b) WBGT monitor, (c) subject, and (d) CorTemp data logger.

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