Developing a Personal Cooling System (PCS) for Construction Workers – An Experimental Approach

Albert P.C. Chan, W. Yi, Y. Zhao, Y. Yang, Francis K.W. Wong, Michael C.H. Yam, Daniel W.M. Chan, Edmond W.M. Lam, Y. Li, Y. Guo
The Hong Kong Polytechnic University, Hong Kong, China
albert.chan@polyu.edu.hk, yiwen96@163.com, zyj336699@126.com, jackie.yang@connect.polyu.hk, francis.wong@polyu.edu.hk, michael.yam@polyu.edu.hk, daniel.w.m.chan@polyu.edu.hk, edmond.wm.lam@polyu.edu.hk, tcliyi@polyu.edu.hk, yp.guo@polyu.edu.hk

Del P. Wong
Technological and Higher Education Institute of Hong Kong, Hong Kong, China
delwong.cuhk@gmail.com

Abstract
Heat stress, a potential occupational hazard, can reduce work productivity, increase incident rate, and induce heat illness. Construction workers often undertake outdoor work and sometimes work in the confined working space with poor ventilation. Working in these settings during summer puts workers in a vulnerable condition and exposes them to a high risk of heat related incidents. Personal cooling systems which lessen the risk of heat related injuries are commonly used in sports and military. However, their applicability and effectiveness in the construction industry has not yet been evaluated. This paper presents an overall research framework for developing a PCS for combating heat stress in the construction industry. The framework includes content analysis, semi-structured interview, PCS design, laboratory test, field study, and focus group meeting. Quantitative and qualitative research methods applied in conducting the research study will be discussed in this paper. Although this study applies specifically to the construction industry, similar research framework could be applied to other occupations as well which require routine exposure to extreme temperature conditions.

Keywords
Heat stress, Personal cooling systems, Construction

1 Introduction

In a hot environment it is important for the human body to regulate body temperature at a stable level. If not, several heat related incidents, such as dehydration, heat stroke, and elevated heart rate, may occur. Workers performing tasks in a hot and humid environment are at risk to heat related injuries and illnesses. Construction workers often have to carry out physically demanding outdoor activities with long working hours and hence are subject to a higher risk of heat stress (Yi and Chan, 2014). The increasing number of heat related incidents in the construction industry has aroused wide public concerns.

Personal cooling systems such as air-cooled garments, liquid cooling garments and phase change garments are commonly used for athletes, soldiers, astronauts, firefighters and workers wearing nuclear, biological, and chemical (NBC) protective clothing to reduce core body temperature and lessen the risk of heat related injuries (Yazdi and Sheikhzadeh, 2014). Many attempts have been made to introduce these products into construction workplaces where workers endure a hot environment. However, the effectiveness and applicability of these products in the construction industry remains a question unanswered.

Construction work is tough and hence demands additional attributes of PCS which should have good cooling performance, be light-weight, durable, and easy-to-maintain. It also needs to be heavy duty and fit well enough with workers' body shape so as not to present a hazard at work, while yet providing flexibility. PCS suitable for sports or military players may not necessarily be suitable for construction workers. There is a need to develop a tailor-made PCS to protect construction workers from heat related injuries while working in a hot environment.

This study presents a holistic research framework to assess the cooling performance and applicability of selected commercially available PCSs when applied in the construction industry, and to design a PCS which is suitable for construction workers after taking into consideration the distinctive features of the construction industry. The performance of the tailor-made PCS will then be evaluated using both laboratory tests and field study.

2 Background of study

Heat stress is 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"* (American Conference of Governmental Industrial Hygienist (ACGIH), 2011). The effect of heat stress is devastating. It was reported that 8,686 patients were taken to hospital in Japan due to heat stroke in the week of July 22-29, 2012, of whom, 16 died (Japan Today, 2012). The construction industry accounted for an overwhelming proportion of all heat stroke cases in Japan, 73.3% on average from 1989 to 2010 (Japan International Centre for Occupational Safety and Health, 2000). A desktop search from Hong Kong local newspaper archives using the search engine WISENEWS shows that there were at least 282 heat related incidents between 1998 and 2011 across all industries, with 73 cases related to construction, 22 of which were fatal.

When exposed to an extremely hot environment coupled with physically demanding work such as firefighting, military activities and sports, the human body may suffer heat strain which can lead to reduction of performance and work endurance, and high risk of heat illnesses (Gao et al, 2011). A properly designed PCS to lower the microclimate temperature around the human body is one of the measures to reduce the risk of heat stress (Gao et al., 2011). Various research studies have been conducted with different PCSs such as liquid cooling garments (Harrison and Belyavin, 1978; Vernieuw et al., 2007), air-cooled garments (Chinevere et al., 2008; Hadid et al., 2008), and phase change garments (e.g., Gao et al., 2010). The liquid- or air-cooled garments are classified as active cooling system which require external connections to liquid or air circulating supplies, while phase change garments can work independently without external energy during the cooling process. The phase change garment uses the precooled phase change materials (PCM), e.g. ice, salt, paraffin wax, etc., to cool down body temperature. Features and cooling capabilities of these PCSs have been tested in laboratory, as indicated in literature (e.g. Vernieuw et al., 2007; Hadid et al., 2008; Chou et al., 2008). When applied to different industries, their performance requires a more thorough evaluation.

3 Research framework

The research framework for developing a PCS for combating heat stress in the construction industry consists of content analysis, semi-structured interview, PCS design, laboratory test, field study, and focus group meeting. The research framework is illustrated in Fig.1.

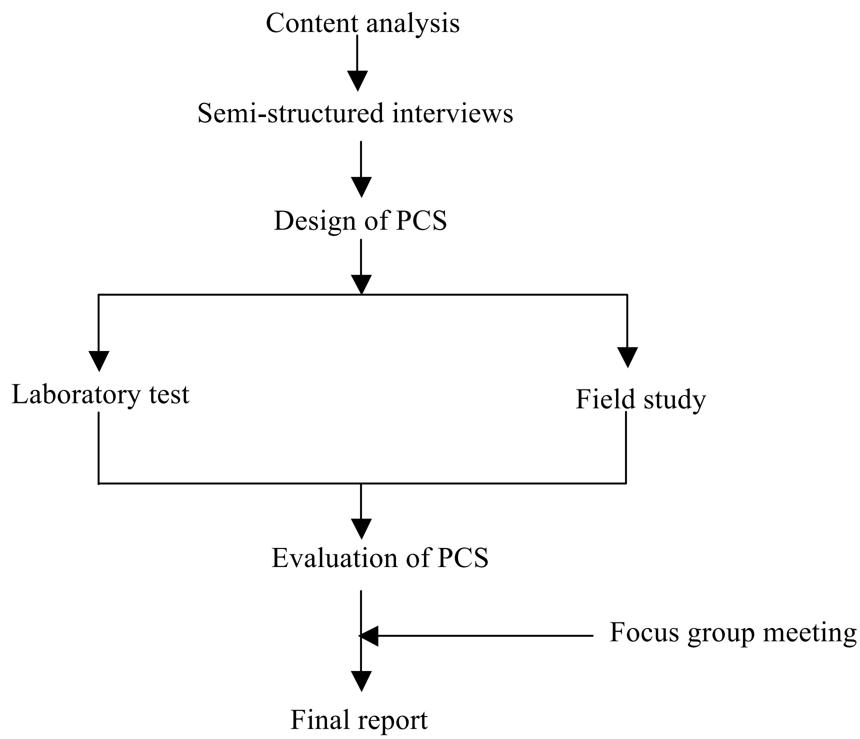

Figure 1 Overall framework of the research study

3.1 Content analysis

Content analysis is often used to determine the major facets of a data set, through simply enumerating the frequency an activity happens, or a topic is depicted (Fellows and Liu, 2008). The first step in conducting content analysis is to use electronic database search engines such as Scopus to identify the literature to be analyzed. The second step is to determine whether qualitative or quantitative content analysis to be used (Xu et al., 2010). Qualitative content analysis focused on depicting the meaning of the data (i.e. grouping data into categories). In quantitative content analysis, emphasis is placed on generating numerical values of the categorized data (ranking, frequencies, ratings, etc.) (Xu et al., 2010).

This study adopted the qualitative content analysis approach to examine the features and cooling capacity of commercially available PCSs. An extensive desktop review of those commercially available and commonly used PCSs was conducted. All previous studies by other researchers related to this study were consolidated, thereby enriching the understanding of current practices and hands-on experiences. The literature was sourced from international refereed journals, international refereed conference proceedings, textbooks, websites, magazines, newspapers, and so on. This desktop study underpins the foundation for the research and also contributes to the development of the questionnaire survey for assessing the PCSs in terms of comfort, suitability, practicality, acceptability, cooling capacity, and safety.

3.2 Semi-structured interview

To identify the shortcomings of existing measures for combating heat stress and the concerns about PCSs use in the construction industry, semi-structured interviews will be carried out. Semi-structured interview uses open-ended questions. All interviewees are encouraged to freely give their answers and examples, while the semi-structured interview format facilitates additional probing to elicit further information wherever necessary (Henderson and Ruikar, 2010). Face-to-face interviews will be carried out with senior management representatives of the selected contracting companies in Hong Kong. Telephone interviews will be conducted when the location of the interviewer and interviewee is too distant or their individual time demands cannot match. Each interview will be tape-recorded and transcribed for subsequent coding of data. The key themes of the interview questions include: (1) existing equipment/device for combating heat stress adopted in the construction industry, (2) key factors in selecting PCSs when used for construction work (e.g., weight, cooling effect, cooling duration, color, price, cleaning, maintenance, etc.), and (3) initiatives taken to facilitate the implementation of PCSs in the construction industry. Qualitative interview data transcribed into narratives will be coded by constant comparative method (Grove, 1998; Ryan and Bernard, 2000) in NVivo, software for qualitative data analysis (Hon et al., 2010).

3.3 PCS design

Garment samples of the PCSs collected in the previous study (Chan et al., 2013) will be used to analyze the design and measure the physical properties of the fabrics. The working patterns in relation to metabolic rates, sweating rates and cooling capacity will be studied together with the working environmental conditions such as temperature, humidity, wind velocity, solar ultraviolet (UV) and infra-red (IR) radiations (different environmental parameters and different work activities data are available in our previous work (Chan et al., 2012a, 2012b, 2012c). Then, a computer simulation to predict the potential heat stress level after wearing the PCS in a typical summer working environment will be carried out using models and computer software previously developed by other researchers (e.g. Li and Zhu, 2003; Li and Zhu, 2004; Mao et al., 2008). Data concerning PCS features collected in semi-structured interviews will be further included to improve the design of PCS. On the basis of the findings from the above work, a PCS for construction workers will be designed and engineered by: (1) selecting fabrics and cooling agents based on the results of their functional property tests such as thermal insulation, thermal radiation, air permeability, water vapor permeability, cooling capacity, and moisture management; (2) designing different styles of PCS with consideration given to the coverage ratio of the human body, tightness and ventilation; (3) carrying out systematic computational experiments to predict the heat stress levels and thermal comfort performance of the PCS under the working conditions of construction workers (see Figure 2); (4) pre-optimizing the designs according to the simulation results; (5) making block patterns for the pre-optimized design and PCS prototypes for pilot testing of thermal functional performance; and (6) producing a certain number of PCSs for wear trials and field studies.

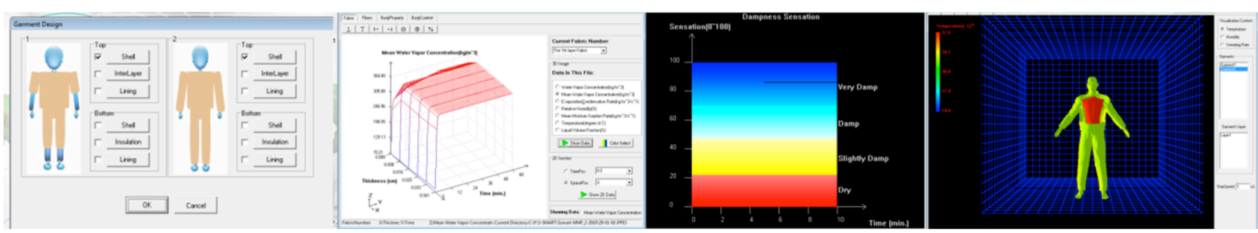

Figure 2 Computational experiments to design PCS prototypes

3.4 Laboratory test

Experiments will be carried out inside an environmental chamber with dimensions 3 m × 2.5 m × 2.2 m (length × width × height) to simulate the outdoor hot and humid environments (Chan et al., 2012b). The meteorological condition inside the environmental chamber will be maintained at 33°C temperature and 75% relative humidity (RH) to simulate the average meteorological condition of "very hot weather warning" issued by the Hong Kong Observatory in 2011 (Hong Kong Observatory, 2012).

Fifteen (15) construction workers will be invited to participate in the experimental studies. Repeated experiments will be made in which participants will complete self-paced exercises on a motorized treadmill until their core temperature reaches 38.5°C. The core temperature is set at 38.5°C as it is the average value for construction workers to work under a hot and humid environment in Hong Kong (Chan et al., 2012a, 2012c). In addition, this value is in agreement with the published literature on cooling

(Barwood et al., 2009). According to this literature the self-paced running exercise will last for about 25min covering ~3.3km. After that the participant will be allowed to recover for 40min (this is the duration to achieve maximum recovery after exercising to exhaustion, according to Chan et al., 2012c) during which no cooling intervention will be implemented. The participant will sit and rest on a backless chair without any active cooling intervention. This will be taken as a control condition. For the second treadmill run, the participant will put on the PCS and runs until the desired core temperature (i.e., 38.5°C) is achieved. Then the participant will be allowed to recover for another 40min still wearing the PCS (Table 1). Each participant runs on a motorized treadmill only twice that day. Comparisons between control and intervention trials will be made in terms of running distance and speed. Physiological responses will be monitored before, during, and after running.

Table 1 Experiment protocol

Task	Adaptation to chamber	1st self-paced running	1st recovery	2nd self-paced running	2nd recovery
Duration	30min	~25min	40min	~25min	40min
With or without intervention	Without PCS	Without PCS	Without PCS	With PCS	With PCS

During the experiment, objective physiological indices including core temperature, skin temperature, and heart rate will be measured. Participants will wear a heart rate monitor for continuous collection of heart rate data throughout the experiment. Continuous core body temperature and a dermal patch for skin temperature will be monitored by VitalSense (Philips Respironics) which is a non-invasive ambulatory temperature monitoring system with an ingestible telemetric capsule. To ensure the well-being and safety of the participants, a qualified registered nurse will be stationed inside the chamber to accompany the participants throughout the whole experiment in case of emergency and to collect the physiological data. Emergency first aid and cooling equipment will be deployed inside the chamber.

To determine the level of heat strain during exercise, Moran et al. (1998) developed a Physiological Strain Index (PSI) to describe heat strain in quantitative terms (Gotshall et al., 2004). PSI is calculated based on heart rate and core temperature records in humans. PSI will therefore be used in this study to measure how the newly designed PCS alleviates heat strain.

Participant's PSI values during the 30min adaptation period and the 1st self-paced running without PCS will be measured as a benchmark at 5-minute intervals, which will be compared with those measured when the participant is wearing the PCS. Statistical analysis will be performed by repeated measures of ANOVA test followed by the Fisher's least significant difference test whenever deemed appropriate (Muir et al., 1999).

3.5 Field study

To further evaluate its effectiveness, 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. Field studies will be conducted in different construction sites during the summer time of Hong Kong. Construction workers will be asked to rate the subjective attributes of the newly designed PCS (thermal comfort, usability, tactile comfort, and fabric hand) through a self-administrated questionnaire (Chan et al., 2013). The ratings of perceived exertion (RPE), defined as the intensity of subjective effort, stress, or discomfort felt during physical activity has been shown to be a simple and effective method for regulating exercise intensity (Coquart et al., 2009; Dunbar et al., 1992; Foster et al., 2001; Zeni et al., 1996). The scales use both verbal anchors and numbers that have been reported to possess both categorical and interval properties (Borg and Lindblad, 1976). The RPE scale is considered as a practical and cost-effective approach to quantify the physiological loads during exercise, and has been used in assessing the physiological conditions of rebar workers in the construction industry (Chan et al., 2012a).

3.6 Focus group meeting

At least three rounds of focus group meetings will then be arranged with these participants to seek opinions regarding comfort, suitability, practicality, cooling capacity, acceptability and safety of the PCS. Focus group meeting is considered as a convenient, effective way to collect a large amount of information from a group of participants to supplement the traditional one-to-one interview technique (Haslem, 2003). Focus group meetings will be organized to evaluate the newly designed PCS from a much wider audience. Each focus group meeting with approximately 30 participants will be instructed by a research team member, who will first make a short presentation of the newly designed PCS and set the stage with the prepared questions (Vaughn et al., 1996). The participants will then be divided into groups of five to six to sustain lively and active discussion. The research team members will be assigned to each group to trigger discussions and responses. Each group will then be asked to nominate a member to present the group's findings and recommendations at the end of the meeting (Chan et al., 2010). The information gathered from the focus group discussions will be analyzed, documented and triangulated with data solicited from other sources before drawing conclusions. The findings will be used to evaluate the effectiveness of the newly designed PCS. Refinement of the PCS will be made accordingly if deemed necessary.

4 Conclusions

This study describes an overall research framework for developing a wearable cooling system that will reduce the heat stress related injuries on construction site. The framework includes content analysis, semi-structured interview, PCS design, laboratory test, field study, and focus group meeting. Although this study applies specifically to the construction industry of Hong Kong, a similar research framework could be adopted in other industries and in other countries. This will be essential in safeguarding workers' occupational health and safety in the long run. Workers will be more comfortable too, regardless of heat stress, with likely beneficial effects on productivity and health.

Acknowledgements

The work described in this paper was fully supported by a grant from the Research Grants Council of the Hong Kong Special Administrative Region, China (RGC Project No. PolyU 510513). This paper forms part of the research project entitled "Developing a personal cooling system (PCS) for combating heat stress in the construction industry", from which other deliverables will be produced with different objectives/scopes but sharing a common background of study and research methodology.

References

American Conference of Governmental Industrial Hygienists (ACGIH) (2011). Threshold Limit Values for Chemical and Physiological Agents and Biological Exposure Indices. ACGIH, Cincinnati, OH2001. pp. 180-188.

Barwood M.J., Davey S., House J.R., and Tipton M.J. (2009). "Post-exercise cooling techniques in hot, humid conditions". *European Journal of Applied Physiology*, Vol. 107, No. 4, pp. 385-396.

Borg G. and Lindblad I. (1976). The determination of subjective intensities in verbal descriptions of symptoms. Reports from the Institute of Applied Psychology. Stockholm: University Stockholm.

Chan A. P. C., Wong F. K. W., Yam M. C. H., Chan D. W. M., and Hon C. K. H., Dingsdag,D., and Biggs, H. C. (2010). "Construction safety in the repair and maintenance Sector". *Proceedings of ISEC-5*, 21-27 September, 2009, Las Vegas

Chan A.P.C., Yam M.C.H., Chung J.W.Y. and Yi W. (2012a). "Developing a heat stress model for construction workers". *Journal of Facilities Management*, Vol. 10, No. 1, pp. 59-74.

Chan A.P.C., Wong F.KW, Wong D.P., Lam E.W.M., and Yi W. (2012b). "Determining an optimal recovery time after exercising to exhaustion in a controlled climatic environment: application to construction works". *Building and Environment*, Vol. 56, pp. 28-37.

Chan A.P.C., Yi W., Wong D.P., Yam M.C.H., and Chan D.W.M. (2012c). "Determining an optimal recovery time for construction rebar workers after working to exhaustion in a hot and humid environment". *Building and Environment*, Vol. 58, pp. 163-171.

Chan A.P.C., Yang Y., Wong D.P., Lam E.W.M. and Li Y. (2013). "Factors affecting horticultural and cleaning workers' preference on cooling vests". *Building and Environment*, Vol. 66, pp. 181-189.

Chinevere, T.D., Cadarette, B.S., Goodman, D.A., Ely, B.R., Cheuvront, S.N., and Sawka, M.N. (2008). "Efficacy of body ventilation system for reducing strain in warm and hot climates". *European Journal of Applied Physiology*, Vol. 103, No. 3, pp. 307–314.

Coquart J.B., Legrand R., Robin S., Duhamel A., Matran R., and Garcin M. (2009). "Influence of successive bouts of fatiguing exercise on perceptual and physiological markers during an incremental exercise test". *Psychophysiology*, Vol. 46, No. 1, pp. 209-216.

Dunbar C.C., Robertson R.J., Baun R., Blandin M.F., Metz K., Burdett R. and Goss F.L. (1992). "The validity of regulating exercise intensity by ratings of perceived exertion". *Medicine and Science in Sports and Exercise*, Vol. 24, No. 1, pp. 94-99.

Fellows, R., and Liu, A. (2008). *Research methods for construction*, 3rd Edition, Blackwell Science, London.

Fleming P. (2004). OSHA launches Stringer probe. ESPN. The Magazine. Online at http://msn.espn.go.com/magazine/fleming_20010802.html. Accessed on June 10, 2008.

Foster C., Florhaug J.A., Franklin J., Gottschall L., Hrovatin L.A., Parker S., Doleshal P. and Dodge C. (2001). "A new approach to monitoring exercise training". *Journal of Strength and Conditioning Research*, Vol. 15, No. 1, pp. 109-115.

Gao C., Kuklane K., and Homer I. (2011). "Cooling vests with phase change materials: the effects of melting temperature on heat strain alleviation in an extremely hot environment". *European Journal of Applied Physiology*, Vol. 111, No. 6, pp. 1207-1216.

Gao, C., Kuklane, K., and Holmer, I. (2010). "Cooling vests with phase change material packs: The effects of temperature gradient, mass, and covering area". *Ergonomics*, Vol. 53, No. 5, pp. 716–723.

Grove, R.W. (1988). "An analysis of the constant comparative method". *Qualitative Studies in Education*, Vol. 1, No. 3, pp. 273–279.

Gotshall R.W., Dahl D.J., and Marcus N.J. (2004). "Evaluation of a physiological strain index for use during intermittent exercise in the heat". *Journal of Exercise Physiology*, Vol. 3, No. 4, pp. 22-29.

Hadid A., Yanovich R., Erlich T., Khomenok G., and Moran D.S. (2008). "Effect of a personal ambient ventilation system on physiological strain during heat stress wearing a ballistic vest". *European Journal of Applied Physiology*, Vol. 104, No. 2, pp. 311-319.

Harrison, M.H., and Belyavin A.J. (1978). "Operational characteristics of liquid-conditioned suits". *Aviation, Space, and Environmental Medicine*, Vol. 49, No. 8, pp. 994–1003.

Haslem, R. (2003). *Focus Groups in Health and Safety Research*. New Fetter Lane, Taylor and Francis, London.

Henderson J.R. and Ruikar K. (2010). "Technology implementation strategies for construction organisations". *Engineering, Construction and Architectural Management*, Vol. 17, No. 3, pp. 309-327.

Hon C.K.H., Chan A.P.C., and Wong F.K.W. (2010). "An analysis for the causes of accidents of repair, maintenance, alteration and addition works in Hong Kong". *Safety Science*, Vol. 48, No. 7, pp. 894–901.

Japan International Center for Occupational Safety and Health (2000). Industrial accidents resulting from heat stroke. Online at http://www.jniosh.go.jp/icpro/jicosh-old/english/statistics/heatstroke/Heat-1.htm. Accessed on April 25, 2013.

Japan Today (2012) 16 dead, 8670 treated for heatstroke July 23-29. National Jul. 31, 2012-07:00PM JST (28) TOKYO. Online at:

http://www.japantoday.com/category/national/view/16-dead-8670-hospitalized-for-heatstroke-july-23-29. Accessed on February 27, 2014.

Li Y and Zhu Q.Y. (2004). "A Model of Heat and Moisture Transfer in Porous Textiles with Phase Change Materials". *Textile Research Journal*, Vol. 74, No. 5, pp. 447-457.

Li Yi and Q.Y. Zhu. (2003). "A model of Coupled Liquid Moisture and Heat Transfer in Porous Textiles with Consideration of Gravity". *Numerical heat transfer*, Vol. 43, No. 5, pp. 510-523.

Mao A.H., Li Y., Wang W.R., and Lou X.N. (2008). "Establishment of Computational Models for Clothing Engineering Design". *WSEAS Transactions on Computers*, Vol. 7, No. 6, pp. 770-780.

Moran D.S., Montain S.J., and Pandolf K.B. (1998). "Evaluation of different levels of hypohydration using a new physiological strain index". *American Journal of Physiology*, Vol. 275, No. 44, R854 -R860.

Muir L.H., Bishop P.A., and Ray P. (1999). "Effects of a novel ics-cooling technique on work in protective clothing at 28 ℃, 23℃, and 18℃ WBGTs". *American Industrial Hygiene Association Journal*, Vol. 60, No. 1, pp. 94-104.

Occupational Safety and Health Council of Hong Kong (OSHC) (2012). "Invitation to tender of contract study on effectiveness of personal equipment for protecting workers from heat stroke while working in a hot environment". Online at: http://www.hkcic.org/files/Document/CIC019052014_web_single%20(1).pdf. Accessed on January 6, 2014.

Rowlinson S., Yunyanjia A., Li B., and Chuanjingju C. (2013). "Management of climatic heat stress risk in construction: a review of practices, methodologies, and future research". *Accident Analysis and Prevention*, Vol. 66, pp. 187-198.

Ryan, G.W., Bernard, H.R. (2000). Data management and analysis methods. In: Denzin, N.K., Lincoln, Y.S. (Eds.), Handbook of Qualitative Research, second ed. Sage Publications, Inc., Thousand Oaks, Calif., pp. 769–802.

Vaughn S., Schumm J.S. and Sinagub J. (1996). *Focus Group Interviews in Education and Psychology*. SAGE, Newbury Park, CA.

Vernieuw, C.R., Stephenson, L.A., and Kolka, M.A. (2007). "Thermal comfort and sensation in men wearing a cooling system controlled by skin temperature". *Human Factors*, Vol. 49, No. 6, pp. 1033–1044.

Xu,Y., Yeung, J.F.Y., Chan, A.P.C., Chan, D.W.M., Wang, S.Q., and Ke, Y. (2010). "Developing a risk assessment model for PPP projects in China — A fuzzy synthetic evaluation approach". *Automation in Construction*, Vol. 19, pp. 929-943.

Xu,Y. and Chan, A.P.C. (2011). "An investigation of heat related incidents on construction workers in Hong Kong". *The 19th Cross-strait conference on occupational safety and health*. Hong Kong Occupational Safety and Health Association.

Yazdi M. M. and Sheikhzadeh M. (2014). "Personal cooling garments: a review". *The Journal of The Textile Institute*. doi: 10.1080/00405000.2014.895088

Yi, W. and Chan, A. (2014). "Optimal Work Pattern for Construction Workers in Hot Weather: A Case Study in Hong Kong". *Journal of Computing in Civil Engineering*, doi:10.1061/(ASCE)CP.1943-5487.0000419.

Zeni A.I., Hoffman M.D. and Clifford P.S. (1996). "Relationships among heart rate, lactate concentration and perceived effort for different types of rhythmic exercise in women". *Archives of Physical Medicine and Rehabilitation*, Vol. 77, No. 3, pp. 237 -241.