IS THE SMART SAFETY VEST A BRUTAL INNOVATION? EVALUATION OF MICROCLIMATE PERFORMANCE USING A THERMAL MANIKIN

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Heat stress is a growing concern in the global construction industry due to its life-threatening consequences. The Smart Safety Vest is a proposed 'internet of things' solution to the heat stress problem in construction. This innovative e-textile monitors the physiological parameters of construction workers in real time, communicates the data to the cloud, then visualises the data on the wearer's smart-phone, and in a web-based management system. Alerts warn of anomalies. The feasibility of this system has been validated through iterative design and by rigorous laboratory tests. This paper reports the experimental procedure used to investigate microclimate variations prior to field testing, which involved a sweating manikin placed in a thermal chamber. Various microclimate scenarios were tested on different layers of protective clothing, and during different activity levels with carefully chosen sweat rates and walking speeds to represent working conditions in construction. These tests showed variations in microclimates under different working and clothing conditions. This research provides initial evidence about microclimate variations, offering useful insights for regulators. The Smart Safety Vest has the potential to improve H&S in construction by addressing a key health risk. The research also significantly contributes to the application of innovations in a poor-performing sector.

Keywords: internet of things, thermal stress, thermal manikin, heat stress, microclimate

INTRODUCTION

The empirical association between ambient temperature and work-related injuries has been investigated globally (Morabito *et al*., 2006; Xiang *et al*., 2014; Rowlinson and Jia, 2014; Chan *et al*., 2015). Due to its potentially life-threatening consequences, heat stress is a growing health and safety concern in the inherently dangerous construction industry. Workers exposed to extreme temperature conditions are at risk of heat stress, manifested in a spectrum of disorders (Lugo-Amador *et al*., 2004), including heat stroke, which can result in serious consequences such as permanent disability or even death. National and international regulatory bodies, such as SafeWork in Australia, the National Institute for Occupational Safety and Health (NIOSH) in the USA, and the Occupational Safety and Health Administration (OSHA) in the UK, are increasingly recognising heat stress

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hazards in the construction industry. Clothing is a key factor determining human thermal environment in the industry (Rowlinson *et al*., 2014).

The Smart Safety Vest is a technological solution to the heat stress problem in construction, and it also represents a timely response to calls for innovation in the industry. The aim of the project reported in this paper is to present the results of experiments on the Smart Safety Vest system conducted in a controlled environment prior to field trials. The contribution of this research is two-fold. Firstly it presents the initial evidence about microclimate variations with different protective garment layers and under different activity loads. Secondly, it contributes to achieving the vision of the smart construction site of the future, addressing perceptions that the construction sector is a poor performer in innovation.

BACKGROUND

Factors affecting heat stress

Fanger (1970) describes the human thermal environment as an interaction of six fundamental factors, categorised as: (i) environmental factors (dry bulb, black globe, wet bulb temperatures, and wind velocity), and; (ii) behavioural factors (metabolic rate, and clothing). The clothing factor includes insulation and moisture permeability (Parson, 1995; Epstein and Moran, 2006).

Attempts to define an accurate heat stress index based on environmental and metabolic variables and zones of discomfort are on-going. Sophisticated indices, such as 'rational indices' (based on calculations involved in heat balance equations), and 'empirical indices' (based on subjective and objective strain) take physiological and environmental factors into account (Epstein and Moran, 2006). Indices, such as the widely used Wet Bulb Globe Temperature Index (WBGT) and Discomfort Index (DI) are based on measurement of basic environmental factors (Epstein and Moran, 2006).

Clothing is a key factor in heat transfer between humans and their surroundings (Qian and Fan, 2006). Unless clothing is skin tight, air gaps exist both between the skin and different layers of clothing; this is referred to as the microclimate. It is important to study microclimate variations in heat stress studies under varying operational set-ups to understand the thermal comfort of the wearer (Qian and Fan, 2006).

Solutions to the heat stress problem in Construction

Parson (2014: 178) suggests three main categories of working practices to address hot environments: (i) engineering controls; (ii) work and hygiene practice and administrative controls, and; (iii) heat alert programmes. Chan *et al*., (2012) developed a nanomaterial-based anti-heat stress uniform for construction workers by reference to measured site temperatures. Some of these indices were trialled in construction. For example, the predictable heat strain index of ISO 7933:2004 (ISO, 2004), has been criticised for its complexity of use (Miller and Bates, 2007) and for its lack of reliability when used with thick protective clothing (Wang *et al*., 2010). In 2014, Rowlinson and Jia trialled this index in the construction context, but, further, accurately measured evidence on reliability is yet to be reported. A study by Miller and Bates (2007) has also validated the use of the Thermal Work Limit (TWL) (Brake and Bates, 2002) with mining workers. In 2016, Jia *et al*., investigated the problem of heat stress in construction to develop a protection logic that made broad use of WBGT measurements. However, the limitations of the WBGT heat index have been widely recognised (see Brake and Bates, 2002; Taylor, 2006; Miller and Bates, 2007). The development of thoroughly validated, accurate environmental indices, combined with data on metabolic and clothing factors, is critical to determining reliable trigger points.

The unrealistic heat stress policy (Jia *et al*., 2016) by the Construction, Forestry, Mining and Energy Union (CFMEU) (CFMEU Queensland and Northern Territory, 2015) for the unionised construction sector suggests work-rest regimen based on daily maximum temperature. It is evident that self-regulation, which is the main practice in the un-unionised sector, is also ineffective. Construction fatalities (Australian Mining, 2013) and serious injuries (Workcover Queensland, 2016) from heat stroke have been reported in Australia. A recent study based on occupational hygienists' perceptions also suggests a need to refine occupational heat management and prevention strategies (Xiang *et al*., 2015).

Innovation in the construction industry

Compared to other industries, the construction industry has not been pioneered in embracing technology, and has often been criticised as poor performer in innovation (Bowden, 2006; Ruddock, 2006; Navon and Sacks, 2007; Hosseini *et al*., 2013). Aligning the construction industry with the global trends of exponentially growing smart technologies, a new vision for the 'construction site of the future' (Bowden, 2006) has emerged, characterised, according to Carbonari *et al*., (2011), by real-time context awareness embedded in construction applications. More recently, the strategic need for research and innovation in smart technologies in the building and construction industry has become apparent. Some examples of attempts to meet this need include the formation of the Task Group on Wearable Sensor Technology (TG 92) in 2015 by the International Council for Building (CIB) to encourage research and innovation in wearable technologies in construction. An innovative E-textile based system by reference to workers' physiological conditions is an example of a technological solution to the heat stress-inducing conditions of construction workers (Edirisinghe and Blismas, 2015).

METHODOLOGY

Smart Safety Vest System

In the recent past, an increasing volume of research has aimed to contribute to the future smart construction site, but research gaps remain in the technology development process due to the lack of use of an appropriate framework to validate such technologies. The Smart Safety Vest project was carefully designed to systematically validate the development process by using the technology readiness levels (TRL) model (Mankins, 1995). The Smart Safety Vest project is ongoing, and followed Mankins' (1995) stages of technology readiness, including: (i) pre-concept refinement/knowledge production, (ii) applied investigation, and (iii) early stages of development and operations.

The pre-concept refinement and proof of concept stage has already been completed, and discussion of that stage is beyond the scope of this paper. The design and functionality of the system were iteratively refined, and then the basic principles of the concept were formulated (Edirisinghe and Blismas, 2015). For example, the sensor circuitry was iteratively redesigned for better response/time of sensors through laboratory tests for thermal conductance/capacitance. The current version of the Smart Safety Vest system is an Internet of Things (IoT) device, and is composed of: (i) textile-attachable, cloud-connected temperature sensors that transmit real-time data of either skin temperature of the wearer or the microclimate between the clothing; (ii) a smart phone mobile app to visualise individual data, and; (iii) a web-based management system to monitor company-, project-, and site-level data, both in abbreviated, dash-board and more comprehensive formats. Both the mobile app and the management system have alert generation mechanisms as per the policy.

An applied investigation of the system was conducted, including functional validation in laboratory and simulated site environments. This paper reports the findings of the applied investigation, which was conducted in a simulated environment using a thermal manikin. This study was done in collaboration with fashion and textiles experts. The objective of these experiments was to validate the system in a controlled environment prior to taking it into the relevant operational environment for real world on-site testing.

Thermal Manikin Test procedure

Thermal sweating manikin

Thermal manikins are useful for bio-physical testing and investigations of functional clothing and living systems under harsh conditions (Fan, 2006) that simulate environmental dynamicity. Such modelling, conducted in a thermal chamber, helps to understand system functionality/response within controlled parameters. Due to the dynamicity of construction activities (Bowden *et al*., 2006), and the highly complex nature of the operational environment and its impact on the six agents of heat stress (Epstein and Moran, 2006), the Smart Safety Vest system was tested with a thermal manikin in a controlled environment to demonstrate TRL5. The Smart Safety Vest prototype was demonstrated using a Newton thermal manikin, model P357, from Measurement Technology Northwest (USA). The model placed in a thermal chamber has dry or sweating skin configurations and a removable wicking fabric skin. The skin of the manikin was saturated with distilled warm water before dressing. The manikin features 20 independently controlled thermal zones, as shown in Figure 2. The sweating systems feature computerised fluid delivery through distributed fluid ports.

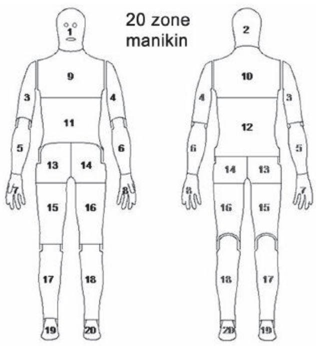

Figure 2: Thermal zones

Test Procedure

Murakami (2004) analysed the microclimate surrounding the human body using the characteristics of the upward airflow generated around the body. In placing Smart Safety Vest sensor patches on the manikin, the factors considered were: (i) the upward airflow and the fact that the upper body is closest to being at the core body temperature; (ii) practical implications (for example, imposing minimal impact on mobility and manoeuvrability during labour-intensive activities), and; (iii) user comfort and convenience. Sensor patches were placed in zones 9 and 10 (Figure 2). The standard manikin skin temperature was set at 35°C. In each test, readings were taken from 15 to 17 minutes after the system reached steady state (thermal balance) with a coefficient of variation (CV) of <5%, which is the manikin standard. A number of test procedures were conducted to investigate the microclimate conditions (thermal characteristics) under two different pieces of clothing and at different activity levels, both of which are significant factors in the creation of heat stress conditions (Epstein and Moran, 2006). The sensor patches were attached to two different commercially available safety garments commonly used in the construction industry: (i) a 100% cotton safety shirt, and; (ii) a 100% polyester safety vest with 100% cotton undergarment. Figure 3 illustrates these tests. For wet tests (with sweating), the thermal chamber temperature was set to 35°C ± 2°C, relative humidity was set to 40% ± 5%, and the water vapour resistance of the garment was recorded. The cover factor was set to 1 for both the garments. Bates and Schneider (2008) report that sweat rates between 0.3 and 1.5 L per hour can be expected for construction workers in hot climates. The manikin simulates different activity levels by varying the rate of double steps per minute (DSPM) and the sweat rate. Three sweat scenarios were tested to simulate low, moderate and high intensity activities as follows: (i) a 20 DSPM and 500mL/hr.m2 sweat rate; (ii) 30 DSPM and 1,000mL/hr.m2 sweat rate; and (iii) 40 DSPM and 1,500mL/hr.m2 sweat rate.

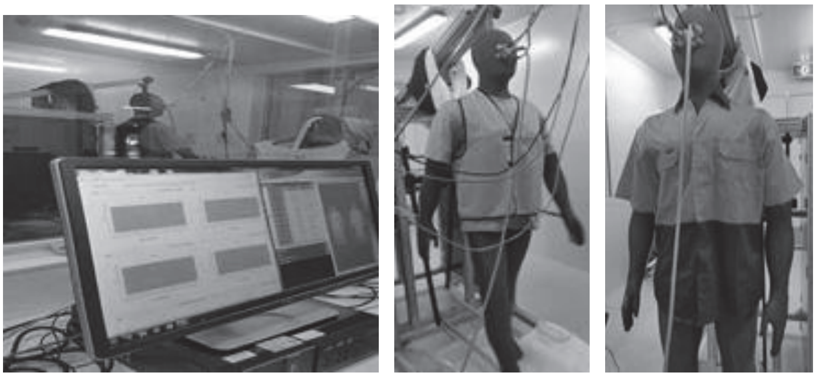

Figure 3: Manikin Tests: left: control room and cloud data; middle: 100% cotton innerwear and polyester safety vest test; right: 100% cotton shirt test

Table 1 shows the experimental configurations. Figure 4 illustrates the arrangement of the clothing layers and positioning of sensors in the microclimates. Sensor placement is depicted at SM1 (F) (sensor for micro-climate 1) in the front zone of the manikin (Figure 2), and SM2 (B) (sensor for micro-climate 2) in the back zone.

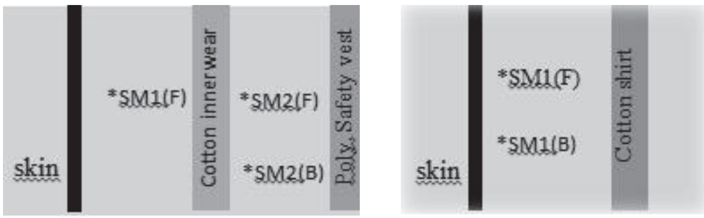

Figure 4: Clothing layers and sensor positioning: left: 100% cotton inner-wear and polyester safety vest; right: 100% cotton shirt

EXPERIMENTAL RESULTS

The manikin's skin temperature, heat flux in the relevant zone, and sweat rate data were recorded during the experiments. The microclimate and/or skin temperature values were recorded to a cloud server during each test through the Smart Vest sensors. Data from the thermal manikin was recorded every minute in the ThermDAC manikin software, and the Smart Vest data was recorded every six seconds. To facilitate better representation and comparison of the two data sets, the average of the sensor data over a minute was calculated. Table 1 summarises the heat flux and water vapour resistance (WVR) values in each experiment. Figure 5(a)-Figure 5(d) graphs the results.

Findings

The water vapour resistance (Ret) of clothing indicates how well it can transport water vapour to the environment, which affects thermal comfort during activity. According to Table 1, the Ret values are higher for the cotton shirt than for the cotton innerwear with polyester vest. This could be due to the thickness of the cotton shirt and the open structure of the polyester vest. In other words, water vapour transmission through the cotton innerwear and polyester vest combination is better compared to the cotton shirt alone. It was observed (Table 1) that as the activity level is increased the Ret is decreased - this could be due to the garment becoming saturated with sweat. Figures 5(a) and (b) shows the variation in the temperatures of the front and back microclimates at low activity levels for the CIV clothing set-up. This could be due to the difference between the boundary air layer thicknesses at both zones.

Table 1: Test procedure and results

Clothing	Experiment	DSPM	Sweat rate (SR) (mL/hr.m2)	Water vapour resistance (Ret) in m2/Pa/W	Heat Flux W/m2
Cotton innerwear and	Exp. 1	20	500	29.60	106.51
polyester safety vest	Exp. 2	30	1000	26.78	122.56
(CIV)	Exp. 3	40	1500	22.25	143.20
100% cotton shirt	Exp. 4	20	500	47.93	68.89
(CS)	Exp. 5	30	1000	38.53	84.18
	Exp. 6	40	1500	34.09	101.55

Note: the water vapour resistance value is the sum of the boundary air layer resistance and the WVR of the clothing. Front Heat flux was considered after stabilisation.

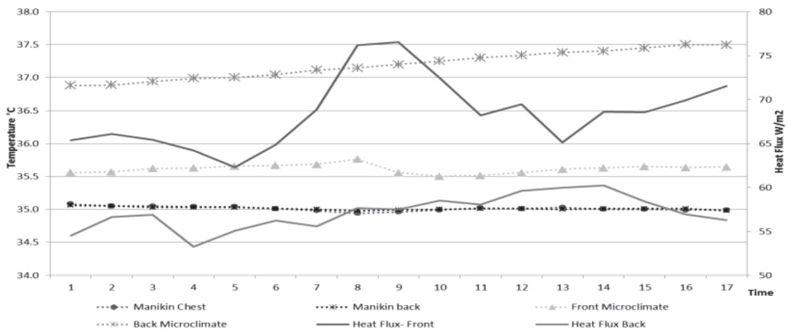

Figure 5(a): Thermal characteristics of CIV, 500 SR

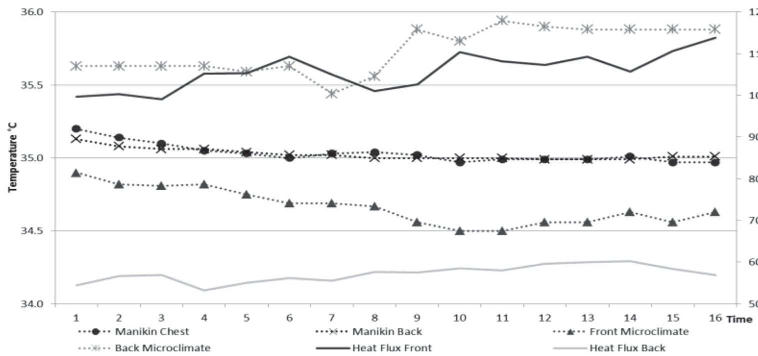

Figure 5(b): Thermal characteristics of CS, 500 SR

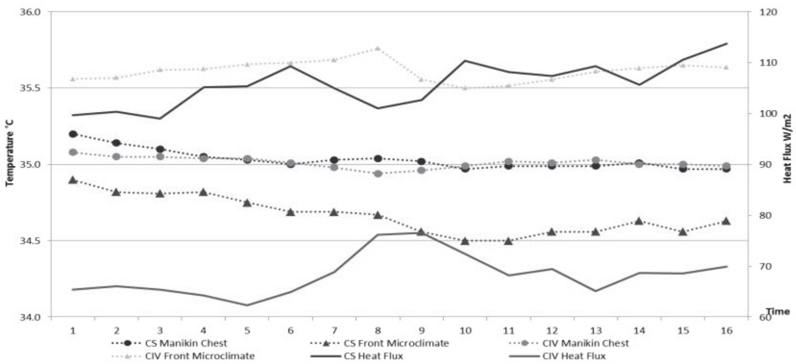

Figure 5(c): Microclimates of CIV & CS, 500 SR

If the boundary air layer is thinner, this means there will be less thermal resistance. Figure 5 (c) shows the variation in the temperature at the front microclimate zone between each garment set-up. A 100% cotton shirt shows a 1°C higher temperature compared to the cotton innerwear + polyester vest garment set-up. Further, variation can also be seen in the heat flux values.

This could be due to the layer assembly of the cotton innerwear + polyester vest garment set-up. The microclimate between the cotton innerwear and the polyester vest is influenced by the light weight and open structure of the polyester vest. Interesting results can be observed in Figure 5 (d); at higher activity rates, the temperature of the microclimate is lower than the manikin's skin temperature.

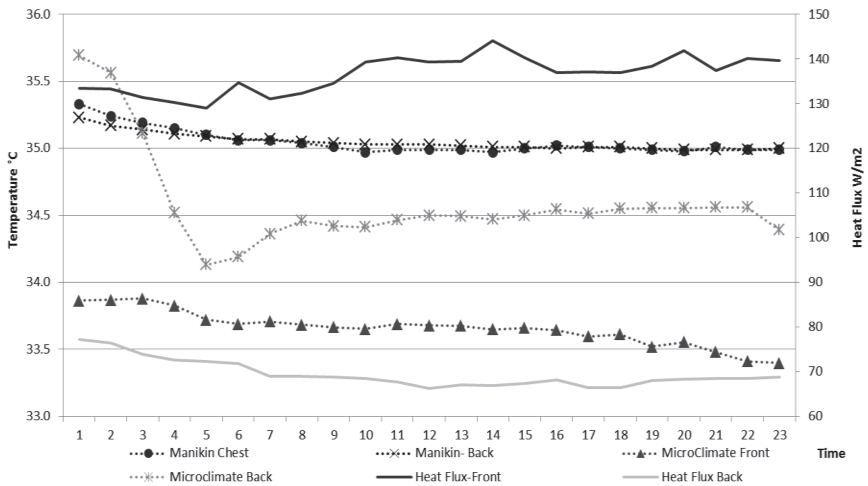

Figure 5(d): Thermal characteristics of CS, 1500 SR

This could be due to the testing of the garments immediately after the previous low level activity rate test. Also, the rise in humidity level between the microclimates could be the key factor in the change in temperatures.

DISCUSSION

Study findings and limitations

This study observed that the layer structure of the cotton innerwear and polyester safety vest plays a significant role in governing microclimatic changes. Along with this, the humidity level and characteristics of the fabrics also play important roles in thermal comfort. The main limitation of the study was the control of variables in the thermal chamber. For example, the wind effect on real construction sites was not modelled;

ventilation is double the wind velocity (Qian and Fan, 2006), and this affects the microclimate.

Another limitation was that non-uniform local thermal environments were not investigated. The findings might not be generalisable to all construction activities, as only three activity levels were experimentally tested.

The multi-variable puzzle, lack of standardisation, and unrealistic regulations
The integration of many of the variables, together with an appropriate regulatory framework that considers the effects of work intensity, acclimation and clothing will be important in real world set-ups. While a standardised heat stress index is a clear gap in research and practice globally, particularly for the construction industry, fundamental issues also exist in using weather forecasts (Jia *et al*., 2016) or even on-site weather data unless an accurate index is used to interpret such data (Brake and Bates, 2002). While some policies are unrealistic (Jia *et al*., 2016), policy gaps exist as far as recommending an accurate measurement protocol in heat stress prevention regime is concerned. Policy variations and urban heat-island effects are also under-researched. Small business accounts for slightly less than one third of the Australian economy (ABS, 2015), and this is mainly un-unionised construction, so it is also important that current practices and policies in both the unionised and un-unionised sectors of the construction industry be investigated.

Is the Smart Safety Vest a brutal innovation?
There is an ongoing and critical debate on brutalism in innovation in the construction industry. The concept of brutal innovation is paradoxical. Symbolising the ambition for the emerging vision of the future 'smart construction site' (Carbonari *et al*., 2011) on one hand, the Smart Safety Vest project can, on the other hand, be perceived as a beastly manifestation to the industry's poor performance in innovation. Innovations embarked upon with good intentions, advancing approaches to solving existing problems or to improving current practice, should also take measures to minimise brutalism. Systematic technology validation through standardised developmental processes, such as TRL (Mankins, 1995), systematic user requirement analysis, and user technology acceptance methods, are critical. It is also paramount that the connections between global, local, construction-specific, and more general or macro-level factors be explored once the technologies are integrated in practice, as, for example, in an industrial product. Challenges exist in technology acceptance, diffusion and standardisation for pockets of innovation like the Smart Vest, while these innovations simultaneously contribute to a paradigm shift in an industry which is far from being a trailblazer of brave new frontiers. However, the Smart Vest has been taken through this incremental process to reduce its potential brutalism, and the aim is to continue with this approach in future work.

CONCLUSIONS

The Smart Safety Vest contributes to the realisation of innovation in the construction sector while moving towards the digital age in order to achieve the vision of the 'smart construction site of the future'. This paper reported the findings of an applied demonstration of the Smart Safety Vest project. The polyester safety vest with a cotton innerwear layer showed better thermal comfort characteristics than a cotton shirt alone. Future work will include testing of the Smart Safety Vest on real construction sites to demonstrate the system under operational conditions, as well as comparison and investigation of the microclimatic conditions of the Smart Vest being linked with existing heat stress indices. Technology acceptance by potential users will also be investigated.

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