# EFFECTS OF UNIFORMS ON FIREFIGHTERS THERMAL STRESSES

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# EFFECTS OF UNIFORMS ON FIREFIGHTERS THERMAL STRESSES

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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

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**______________________________ (Signed)**

**______CHENG CHUN MAN______ (Name of student)**

**TO MY PARENTS, TEACHERS AND FRIENDS**

**For their constant love, support and encouragement**

# Abstract

The purpose of this investigation was to develop and verify a heat stress index called "equivalent effective temperature of clothing microclimate" ($TEE_{cmc}$). $TEE_{cmc}$ was used to identify the thermal stress in firefighter rescue activities when they wore high heat insulated personal protective equipment (PPE). Moreover, a computer simulation, S-smart, was used to verify $TEE_{cmc}$ in different wearing conditions and compare the effects of firefighter uniform's fabric and assemblies on the physiological responses.

The measured physiological responses included core temperature ($T_{core}$), Heart Rate (HR), Skin Temperature ($T_{skin}$), and microclimate Temperature and relative humidity ($T_{cmc}$ & $RH_{cmc}$) between skin and uniform. The wear trial experiments were held in the training facilities in Hong Kong Fire Service Department West Kowloon Rescue Training Centre and climate chamber in Hong Kong Polytechnic University. After experiments, S-smart was also used to simulate the effects of fabric properties and design of uniform on the thermal stress of the firefighters.

The results of the clothing microclimate temperature and humidity indicated that the firefighters had been exposed to the danger category of heat illness during simulated-firefighting training. From the experimental data, a new microclimate index, $TEE_{cmc}$ was developed for the prediction of thermal stress of firefighters. This proposed index was verified in another wear trial conducted in a climate chamber and computer simulation using S-smart. In both wear trials during walking and resting, there was a positive linear relationship between physiological strain index (PSI) and $TEE_{cmc}$. In the S-smart simulation, it also showed a positive linear relationship between the simulated $T_{core}$ and $TEE_{cmc}$ during walking but not resting. This implies that $TEE_{cmc}$ is a useful

index of thermal stress and more convenient to use because the microclimate temperature and humidity can be directly measured.

Based on three pairs of comparison of clothing fabrics and designs revealed that moisture managed fabric, single layer clothing and short-sleeve uniforms caused a lower thermal stress in the climate chamber wear trial. These results matched with that in S-smart simulation.

The Originality of this study is the newly-developed heat stress index $TEE_{cmc}$ in high-risk occupations such as firefighters, this index has been successfully verified by a wear trial and computer simulation of thermal stress in different clothing designs and fabric properties.

# Publication arising from the thesis

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# Chapter 1 Introduction

## 1.1 Background

Firefighters are required to wear thick and heavy multi-layer personal protective equipment (PPE) which is fully encapsulated to protect the firefighters from fire, toxic smoke, and dangerous objects. However, the high insulation properties of PPE resist heat dissipation and moisture transmission. The multi-layered clothing reduces water vapour permeability and increases thermal resistance between the human body and the environment (Finger, 1970) (Qian, 2006) (Cheng, 1994). Wearing PPE increases the metabolic rate of work (Hardy Jr, 1953). Therefore, wearing PPE induces the risk of firefighters in reaching the danger level of thermal stress due to the restricted heat and moisture transfer from the human body. Firefighters always suffer from injuries and danger due to high thermal stress (Kales, 2007). During a rescue operation, the high core temperature experienced by firefighters causes fatigue, heat illness and heart disease especially under repeated exposure to high levels of thermal stress (Rossi, 2003). Rossi found that the environment and work, which bring high radiant heat intensities and flames, pose high levels of thermal stress on firefighters, ultimately affecting their efficiency in carrying out their rescue service (Hatch, 1992). A study reported that from 1994 to 2004 in the US, there were totally 1144 deaths of on-duty firefighters (Ishtiaque, 2001). In 2016, two firefighters in Hong Kong were died during firefighting in a mini-storage house due to the thermal stress induced by the searing heat and sudden rise in temperature inside the building. The PPE with high insulation is one of the fatal reason (Siu, 2016). Therefore, the materials and construction of the PPE and uniform of firefighters are highly important and valuable to safety.

For the indication of thermal stress, heat stress index (PSI) is one of the popular indices calculated by the heart rate (HR) and core temperature ($T_{core}$) (Moran, 1998). Equivalent effective temperature (TEE) is another index of the thermal stress and comfort calculated by ambient air temperature, humidity and wind speed (Krawczyk, 1979) (Teodoreanu, 2007). With the barrier of high insulation PPE as a portable microclimate environment, the actual ambient environment may not affect the firefighters significantly. Therefore, it is anticipated that the equivalent effective temperature of clothing microclimate ($TEE_{cmc}$) calculated from the microclimate temperature ($T_{cmc}$) and humidity ($RH_{cmc}$) may affect the thermal stress of the firefighters, more than the ambient environment outside the protective clothing.

Furthermore, firefighters need to wear uniforms in various situations including rescue operation, non-fire emergencies duties, physical training and rest in the fire station. The uniform should be comfortable, convenient and professional in different situations. They have high metabolic rate activities in a high-temperature environment with PPE during fire suppression, but much lower metabolic rate activities in an indoor room temperature and humidity without PPE when they are taking rest in the fire station. The various metabolic rate of firefighter's activities is shown in Fig. 1.1. However, the microclimate of firefighter uniform was not yet well investigated.

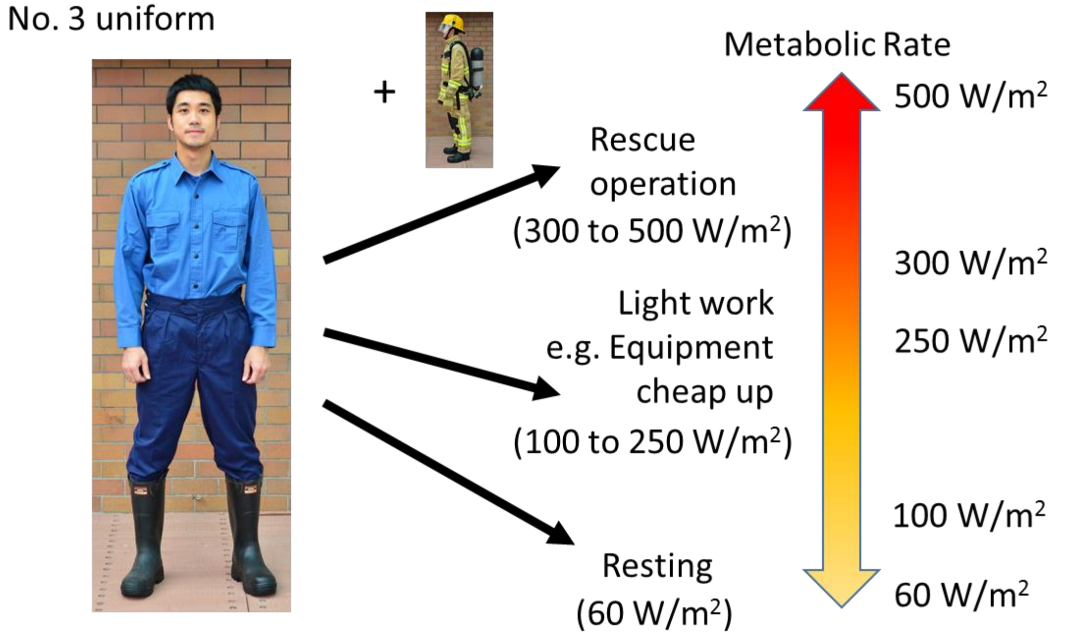



Fig. 1.1 Metabolic rate of firefighter's activity

Previous literature (elaborated in Chapter 2) has focused on the high metabolic work rate of firefighters and fatal problems triggered but there is little scientific focus on the impact of the thermal stress of the firefighters induced by the uniform and PPE. Clothing is an interactive barrier that prevents the sweat evaporation and heat released from the body skin which affects the level of thermal comfort of the wearer (Qian, 2005). The wearers are in a state of comfort when the core temperature of the body is at about 36.5 °C to 37.5 °C and the average skin temperature is around 32 °C to 35 °C (Hardy Jr, 1953)

There are 162 human thermal indices proposed since 1905 to quantify the atmosphere thermal condition (deFreitas, 2015). In order to indicate the level of thermal comfort and thermal stress, thermal stress index such as PSI (Moran, 1998), Equivalent effective temperature in ambient ($TEE_{ambient}$) (Teodoreanu, 2007) and heat illness equation (Anoymous, 2002) can be applied. For PSI, it is necessary to measure the core temperature and heart rate of the subjects. For $TEE_{ambient}$,

ambient temperature ($T_{ambient}$), ambient relative humidity ($RH_{ambient}$) and wind speed (v) are used; For heat illness equation, $T_{ambient}$, $RH_{ambient,}$ and physical work are the parameters.

A multi-layers PPE with high heat insulation creates a portable microclimate environment for the firefighters since PPE prevent the heat and moisture transfer. Studies revealed that the thermal comfort is related to the mechanism of heat released from a clothed human body, but the thermal stress mechanism inside the portable microclimate environment was seldom studied. To date, there is no thermal stress index for the portable microclimate condition.

On the other hand, computer simulation S-smart is valuable in the prediction of thermal stress for simulating the physiological responses based on the properties of the human body, clothing and environmental condition. In this study, the simulated results are used in the analysis of newly TEE. The development of a simulation of heat stress index (HSI) is valuable in the S-smart application. Moreover, the comparison between different designs of uniforms is made in order to investigate the impact of different firefighter uniform design for reduction of thermal stress during firefighting's duties.

## 1.2 Objectives

To fill the knowledge gaps, this study aims to find out an innovative theoretical model to measure the thermal stress of human with a highly insulated clothing such as an encapsulating PPE. Moreover, there is focus on the development of better uniform design by comparison different types of uniform by wear trial and computer simulation. It is important to benefit firefighters from safety during their duties. The following specific objectives included:

1) To measure the physiological responses of firefighters in actual firefighting situation and the climate chamber;

2) To develop a new theoretical index of clothing microclimate to determine the thermal stress in firefighters in various activities;

3) To verify the theoretical index with climate chamber treadmill experiment;

4) To compare the new theoretical index with this index calculated from computer simulation

5) To examine the effects of the clothing design and fabric properties on the thermal stress, based on the wear trial experiments and computer simulation.

1.3 Research Methodology

To achieve the project objectives, a research framework has been built as shown in Fig. 1.2.

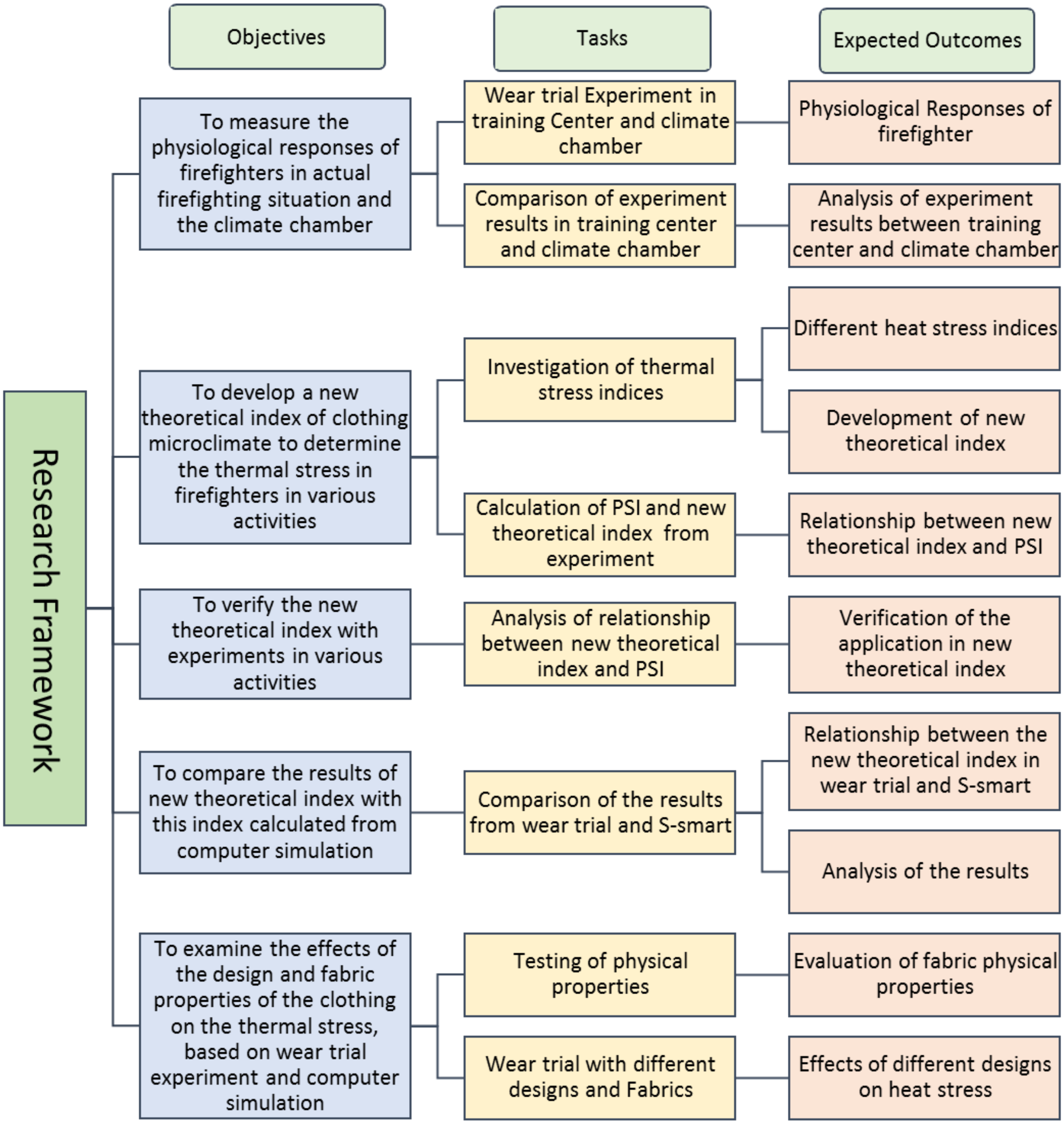



Fig. 1.2 Research framework

For Objective 1, there are two main research tasks.

1) To investigate the physiological responses of a firefighter, a series of wear trials were conducted in the Hong Kong Fire Services Department (HKFSD) training center (Chapter 3) and a climate chamber (Chapter 4) that simulate the work and rest conditions of firefighters according to the firefighter's training protocol of the Hong Kong Fire Services Department. The subjects were selected in HKFSD. During the wear trials, the physiological responses including core temperature ($T_{core}$), skin temperature ($T_{skin}$), heart rate (HR), microclimate temperature ($T_{cmc}$) and microclimate Humidity ($RH_{cmc}$), of subjects were directly measured by instruments and statistically analyzed.

2) To compare the experimental results from the wear trials in the training center and the climate chamber, the same set of firefighter uniform samples and measuring instruments were used in both wear trials.

For Objective 2, a new theoretical index of clothing microclimate has been developed to determine the thermal stress in firefighters in various activities. There are also two main research tasks.

3) To realize different exist thermal stress indices and identify the need for a new theoretical index of microclimate, the theoretical index derived from previous studies were calculated based on the experimental results.

4) The calculated PSI and new theoretical index were compared and their relationship was established.

For Objective 3, the main task is

5) The new theoretical index is applied and verified with another wear trial experiment in a climate chamber with the treadmill (Chapter 4) in various conditions.

For Objective 4, the main task is

6) to compare the results of the new theoretical index from the wear trial and the S-smart simulation program, so as to determine the feasibility of using simulation to predict thermal stress of firefighters.

Objective 5 is to examine the effects of clothing design and fabric properties on the thermal stress. There are two main tasks including

7) to evaluate the physical properties of different fabrics of firefighter uniform according to international standards; and

8) to study the effects of different uniform designs on the heat stress of firefighters based on the results of wear trials and S-smart simulation.

## 1.4 Scope of study

This study included a comprehensive analysis of physiological responses directly measured by instruments in controlled conditions, where the subjects wore different firefighter uniforms in the Spring season in Hong Kong and performed pre-determined resting and training activities. This eliminated the influence of weather and environmental change. There are totally 19 healthy male firefighter participants selected by HKFSD since the male is dominant in this occupation. There are three wear trials including

- The wear trial in field undergo the same protocol according to firefighter's regular training protocol and the location is the Fire Services Department West Kowloon Rescue Training Centre (WKRTC) in Hong Kong.
- The wear trial using a treadmill in a conditioned climate chamber in The Hong Kong Polytechnic University.
- The computer simulation using relevant parameters.

The simulation programme used default parameters such as tortuous gas and maximum distributed capillary diameter since the laboratory did not have such testing instrument. The PPE was not simulated because it was too thick and multi-layer. In order to focus on the performance of thermal stress, only different designs of firefighter uniforms were simulated. About the comparison between the new theoretical index of wear trial and simulation, the experimental results are compared instead of actual value since the protocol and PPE are not totally equivalent.

## 1.5 Research Significance and Value

The originality of this project is to develop a more useful heat stress index in terms of Equivalent Effective Temperature of clothing microclimate ($TEE_{cmc}$). Using this new index, the fabric physical properties and design of firefighter uniform can be evaluated more effectively to benefit the work efficiency and safety of firefighters. The outcome of this study will be valuable to the health and safety of life-risking workers such as firefighters by optimizing the design of their protective clothing in order to reduce their thermal stress.

## 1.6 Outline

In Chapter 1, a general background, objectives, research methodology and research framework are given. In Chapter 2, a comprehensive literature review on the details of thermal comfort including the measurement and the effects of fabric properties is given. Moreover, the characteristics and evaluation of firefighter uniform and PPE are also given. The development of new heat stress index, $TEE_{cmc,}$ with the details of experiment design and the indication of heat illness on firefighter is given in Chapter 3. Chapter 4 shows the effects of fabric assemblies of firefighter uniform on the thermal stress. Chapter 5 demonstrates the application of S-smart simulation with new heat stress index. Finally, Chapter 6 is the conclusions and recommendations of this thesis.

# Chapter 2 Literature Review

This chapter presents a review of literature relevant to the effects of firefighter uniform and PPE on the wearers' thermal stress including the following topics.

i. Thermal comfort and physiological responses
ii. Measurements of thermal stress
    a. Direct measurement of heat stress index (HSI)
    b. Theoretical model and computer simulation
iii. Firefighter uniform and personal protective equipment (PPE)
iv. Evaluation of the performance of PPE and firefighter uniform
v. Effects of fabric properties on thermal comfort

## 2.1 Thermal comfort and physiological responses of wearing firefighter uniform in

### 2.1.1 Thermal comfort

Thermal comfort is primarily related to the efficiency of heat dissipation from a clothed human body and is defined as a "neither too hot nor too cold" feeling of the wearer. Previously work has defined that, the body is in a state of comfort when the core temperature of the body is maintained at 37°C ± 0.5 °C and the average skin temperature is around 32°C to 35°C (Winslow, 1937) (Gagge A. S., 1969)(Cheng, 1994). If a human body's core temperature change significantly, physical threats such as hyperthermia, hypothermia, and cardiac fibrillation may occur if the person's core temperature is increased or decreased more than 2°C from the normal level (Hardy, 1971) (Hensel, 1973) (Gagge A. B., 1941).

Fanger (Fanger, 1970) defined the following three conditions of thermal comfort.

- The body must be in heat balance.
- The sweat rate must be within comfort limits.
- The mean skin temperature must be within comfort limits.

The human body tends to exchange energy with the clothing system and the environmental conditions in different forms including conduction, radiation, convection, and evaporation. The wearers experience thermal comfort when the heat balance of the human body is in a steady state. The steady state is influenced by a sudden change in the environment, for example, from a conditioned indoor environment to a hot and humid outdoor environment. (Fanger, 1970)

Pascoe (Pascoe, 1994) stated that clothing could assist the human body to adjust the rate of energy exchange. Therefore, people tend to design functional clothing that allows the wearers to feel comfortable in the various environment and physical activities. However, thermal comfort is affected significantly by the fabric properties. Previous studies have discussed the effect of clothing on thermal comfort, reviewed the relevant fabric properties, and analyzed other external factors (Hardy, 1971)(Cheng, 1994). The thermal comfort depends mainly on several factors including

- the body's internal metabolism for the production of heat,
- the physical properties of clothing to external elements,
- the air spaces between the skin and the fabric or different layers of inside fabrics,
- the characteristics of the surroundings, such as air temperature, body temperature, relative air velocities, etc.

Furthermore, Sweeney and Branson (Sweeney, 1990) stated that moisture or sweating sensation also had critical impact on the clothing comfort. The skin wetness sensed by a human body affects the feeling of comfort and discomfort (Winslow, 1937). Hollies (Hollies, 1989) confirmed that sweating was a factor associated with the loss of comfort. When more than 50-65% of a body surface is wet, discomfort occurs. Therefore, moisture comfort related to the vapor transmission performance in clothing is also a significant factor contributing to thermal comfort.

### 2.1.2 Heat transfer

Firefighter protective clothing is to provide thermal insulation by a special material to reduce the rate of heat transfer. Since thermal insulation depends on the thermal properties and the type of clothing that affects the heat exchange between the human body and the environment. The heat transfer is both sensible (conduction, convection, and radiation) and latent/insensible (evaporation). The routes of energy transfer and corresponding factors are shown in Table 2.1 and Fig 2.2 presents the pathway of heat loss from the body. (Ingram, 1975) (Dorkin, 1997)

| Route | Environmental Factors | Clothing or intermediate factors | Body factors |
|---|---|---|---|
| Conduction | Temperature difference | Thermal resistance of the material or air layers | Surface temperature |
| Convection | Air temperature; Airflow | Wind penetration | Proportion exposed or covered; surface temperatures |
| Radiation | Temperature of each surface; emissivity of each surface | Emissivity, surface temperature | Proportion exposed or covered; surface temperatures |
| Evaporation | Vapor pressure in air or temperature and relative humidity | Resistance to vapor diffusion and permeability. | Surface temperature and area which is wet |

Table 2.1 Routes of energy transfer and the factors involved

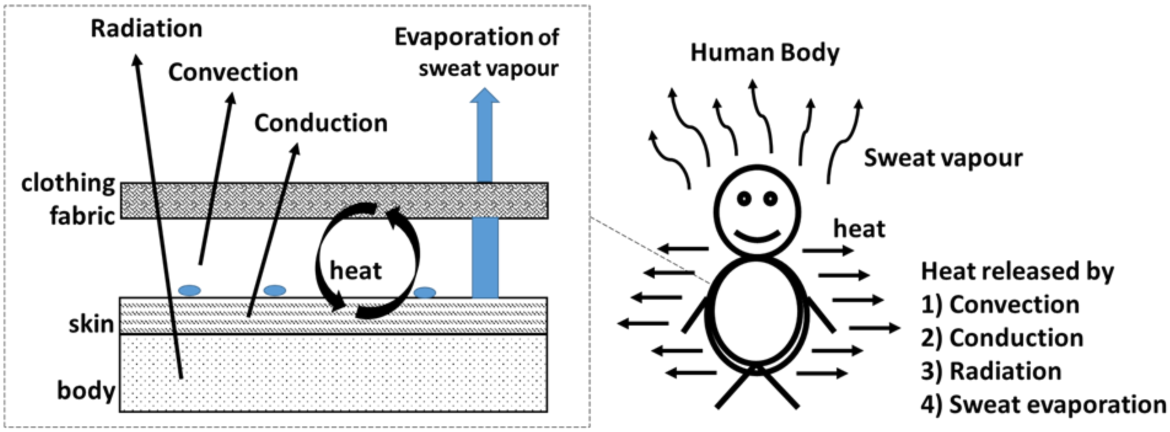



Fig. 2.2 Pathways of heat loss from the body

The body heat moves upward and surrounds the body. The pattern of the heated air rises and forms an air envelope heat dissipation from the body as shown in Fig. 2.3.

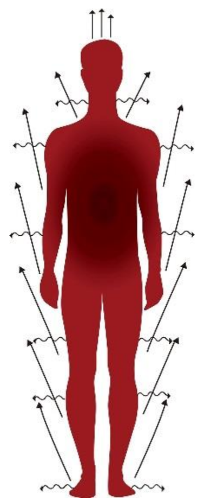


Fig. 2.3 Heat dissipation from an unclothed body (Bejan, 1993)

### 2.1.3 Body thermal regulation system

Equilibrium of body heat refers to a balance between the heat produced and heat loss. For example, shivering generates body heat in the cold air, and sweating reduces heat in order to cool the body. If the body cannot cool or heat itself enough, hypothermia and medical emergency may occur. The function of clothing is to provide insulation to keep the body warm or prevent excessive heat in a hot environment.

In most climates, the body temperature is above that of the external environment so that there has to be an internal source of heat in order to maintain the temperature difference. The required heat comes from the body’s metabolism. The power is provided by burning of calories in the muscles. In order to keep in thermal balance, the metabolic heat generated and the heat received from external sources should be the same as the loss from the body of an equivalent amount of heat. If the heat gain and the heat loss are not in balance then the body temperature will either rise or fall, and life-affecting problems may occur (Webborn., 2005) (Baker, 2000).

If the heat balance cannot maintain equilibrium inside the body, the body thermal regulation system will help the human body maintain a stable thermal condition through different human organs such as muscles, blood vessels, and sweat glands.

An increase in the workload will increase the body core temperature. In a temperature between 37.5 °C and 39 °C, humans will exhibit sweating and breathlessness, feel hot and very uncomfortable and have a fast heart rate. The human body tries to maintain a constant core temperature of about 37°C. The actual core temperature varies between different human bodies, but normally within a narrow range. When the core temperature reaches a dangerous temperature level of 39 °C, the body may experience hyperthermia, fainting, dehydration, vomiting, headache, and dizziness. Having a core temperature higher than 41 °C is considered a medical emergency.

A human body can function well if the thermoregulation can keep the core temperature within the acceptable limits. The thermoregulatory control system depends on the climate conditions, the clothing, and workload (i.e. metabolic rate). (Laing, 2002) (George, 1998) The fabric of the clothing acts as an important tool to maintain the core temperature of the wearer's body.

The heat that comes from the body's metabolism arises from the necessary burning of calories to provide power to the muscles and other organs. However, the metabolic heat generated together with the heat received from external colder sources is normally equal to the heat loss from the body. If the heat gain and the heat loss are not in balance, the core temperature will increase or decrease and may lead to a threat to life.

Vasodilation and Vasoconstriction are the mechanisms of the body for controlling the heat loss and keep the body in a heat balance by changing the flow of blood near the skin. Vasodilation is a thermal function that the skin blood vessels was controlled to allow more blood to pass under the skin for heat dissipation when the core temperature is higher than the normal level by intense dilation of the blood vessels. The heat loss to the surrounding is increased due to the heat conduction between the cooler environment and the warm skin. If the vasodilation is not enough to bring the core temperature back to normal, the anterior hypothalamus in the thermoregulatory system triggers the sweating process by sending sweat-promoting signals to all the sweat glands in the body through the sympathetic nerves. Sweating occurs and increases the heat loss by evaporation of sweat. A large amount of heat is released by the vaporization of liquid sweat. Every gram of water evaporated is equivalent to the loss of 24 kJ (Laing, 2002).

On the other hand, when the core temperature is lower than its normal level, the posterior hypothalamic sympathetic centers in the thermoregulatory system cause the blood vessels of the skin to constrict to reduce the flow of warm blood under to the skin surface and reduce the heat loss. Such thermal function is called vasoconstriction. Moreover, body shivering is a body and muscle reflex that increases metabolic heat production (George, 1998) (Whelan, 1995).

## 2.2 Measurement of thermal stress

To identify the thermal stress in various conditions, experiments were conducted to record the physiological responses of human subjects. Barr et al. summarized the experiment settings for measuring the firefighter's physiological profile. Most studies proposed using the treadmill in a laboratory in testing the physiological responses of the subjects (Barr, 2010). Others used field-based experiments to measure the thermal stress. For example, Petruzzello et al. collected the physiological parameters of thermal stress in the treadmill experiments and field study that simulated the firefighting activities, such as hoisting a rolled-up section of hose and dragging a dummy to a particular distance (Petruzzello, 2009).

Different thermal stress indices have been developed based on the estimation of thermal stress inflicted by the different metabolic rate of work in different environmental conditions, but there is no simple universal heat stress index. (Epstein, 2006) Generally, the thermal stress indices are divided into the following three groups.

- Rational indices are the indices that are based on calculations involving the heat balance equation,
- Empirical indices that are based on objective and subjective strain and
- Direct indices based on direct measurements of environmental variables.

Rational indices and empirical indices are difficult to apply since they evolve many variables and difficult-to-measure parameters. Direct indices are more friendly and applicable since these indices are based on monitored environmental variables (Epstein, 2006) (Parsons, 2014). Table 2.2 shows a comprehensive review of the heat stress indices (HSI) by Epstein et al. (Epstein, 2006).

| Year | Index | Author(s) |
|---|---|---|
| 1905 | Wet-bulb temperature ($T_w$) | Haldane[19)] |
| 1916 | Katathermometer | Hill *et al.*[47)] |
| 1923 | Effective temperature (ET) | Houghton & Yaglou[23)] |
| 1929 | Equivalent temperature ($T_{eq}$) | Dufton[48)] |
| 1932 | Corrected effective temperature (CET) | Vernon & Warner[24)] |
| 1937 | Operative temperature (OpT) | Winslow *et al.*[49)] |
| 1945 | Thermal acceptance ratio (TAR) | Ionides *et al.*[50)] |
| 1945 | Index of physiological effect ($E_p$) | Robinson *et al.*[51)] |
| 1946 | Corrected effective temperature (CET) | Bedford[52)] |
| 1947 | Predicted 4-h sweat rate (P4SR) | McArdel *et al.*[53)] |
| 1948 | Resultant temperature (RT) | Missenard *et al.*[54)] |
| 1950 | Craig index (I) | Craig[55)] |
| 1955 | Heat stress index (HIS) | Belding & Hatch[7)] |
| 1957 | Wet-bulg globe temperature (WBGT) | Yaglou & Minard[25)] |
| 1957 | Oxford index (WD) | Lind & Hellon[34)] |
| 1957 | Discomfort index (DI) | Thom[36)] |
| 1958 | Thermal strain index (TSI) | Lee & Henschel[56)] |
| 1959 | Discomfort index (DI) | Tennenbaum *et al.*[39)] |
| 1960 | Cumulative discomfort index (CumDI) | Tennenbaum *et al.*[39)] |
| 1960 | Index of physiological strain ($I_s$) | Hall & Polte[57)] |
| 1962 | Index of thermal stress (ITS) | Givoni[58)] |
| 1966 | Heat strain index (corrected) (HSI) | McKarns & Brief[59)] |
| 1966 | Prediction of heart rate (HR) | Fuller & Brouha[60)] |
| 1967 | Effective radiant field (ERF) | Gagge *et al.*[61)] |
| 1970 | Predicted mean vote (PMV)<br>Threshold limit value (TLV) | Fanger[9)] |
| 1970 | Prescriptive zone | Lind[62)] |
| 1971 | New effective temperature (ET*) | Gagge *et al.*[63)] |
| 1971 | Wet globe temperature (WGT) | Botsford[64)] |
| 1971 | Humid operative temperature | Nishi & Gagge[65)] |
| 1972 | Predicted body core temperature | Givoni & Goldman[66)] |
| 1972 | Skin wettedness | Kerslake[67)] |
| 1973 | Standard effective temperature (SET) | Gagge *et al.*[68)] |
| 1973 | Predicted heart rate | Givoni & Goldman[69)] |
| 1978 | Skin wettedness | Gonzales *et al.*[70)] |
| 1979 | Fighter index of thermal stress (FITS) | Nunneley & Stribley[71)] |
| 1981 | Effective heat strain index (EHSI) | Kamon & Ryan[72)] |
| 1982 | Predicted sweat loss ($m_{sw}$) | Shapiro *et al.*[73)] |
| 1985 | Required sweating ($SW_{req}$) | ISO 7933[74)] |
| 1986 | Predicted mean vote (modified) (PMV*) | Gagge *et al.*[75)] |
| 1996 | Cumulative heat strain index (CHSI) | Frank *et al.*[76)] |
| 1998 | Physiological strain index (PSI) | Moran *et al.*[77)] |
| 1999 | Modified discomfort index (MDI) | Moran *et al.*[78)] |
| 2001 | Environmental stress index (ESI) | Moran *et al.*[79)] |
| 2005 | Wet-bulb dry temperature (WBDT) | Wallace *et al.*[80)] |
| 2005 | Relative humidity dry temperature (RHDT) | Wallace *et al.*[80)] |

Table 2.2 Proposed systems for HSI by Y. Epstein et al (Epstein, 2006)

### 2.2.1 Direct measurement of thermal comfort

#### 2.2.1.1 Heat stress index(PSI)

Human thermophysiological responses in terms of heat stress indices can quantify the physiological thermal stress that human body experiences in different environments, with different clothing and activities. Robinson developed a formula to calculate the physiological thermal stress based on four different components including core temperature, heart rate, skin temperature and sweat rate (Roninson, 1945). The thermal stress can be quantified by the formula and the heat stress index for a comparison between different situations.

The heat stress index(PSI) was used to evaluate the thermal stress of the subjects in certain climatic conditions, types of clothing, the intensity of exercise, gender, and age (Moran, 1998). The PSI can be calculated by the HR and $T_{core}$. The mathematical expression for PSI is given by Equation 2.1 (Moran, 1998)

$$\mathrm{PSI} = 5\left(\frac{\mathrm{T}_{\mathrm{ret}} - T_{re0}}{T_{\max} - T_{re0}}\right) + 5\left(\frac{HR_t - HR_0}{HR_{\max} - HR_0}\right) \qquad \text{(Equation 2.1)}$$

where $T_{ret}$ and $HR_t$ are the $T_{core}$ and HR at any time t; $T_{re0}$ and $HR_0$ are the minimum $T_{core}$ and HR during the rest periods. $T_{max}$ = 39.5 and $HR_{max}$ = 192 bpm are the standard maximum $T_{core}$ and maximum HR corrected by the mean age of the subjects in this study, respectively. A value of zero PSI means no physiological strain, 2 to 4 represents a mild strain, 4 to 6 is a moderate strain, 6 to 8 means a heavy strain and 10 indicates an extremely high thermal stress.

2.2.1.2 Equivalent effective temperature (TEE)

Another useful index is Effective Temperature Equivalent (TEE) that is commonly used to determine the bioclimatic thermal stress level based on the ambient temperature, moisture content, and the wind speed of the environment (Aizenshtat, 1974). The ambient equivalent effective temperature, $TEE_{ambient}$ is calculated by Equation 2.2:

$$TEE_{ambient} = 37 - \frac{37 - T_{ambient}}{0.68 + 0.00014RH_{ambient} + \frac{1}{1.76 + 1.4v_{ambient}^{0.75}}} - 0.29T_{ambient}\left(1 - \frac{RH_{ambient}}{100}\right) \quad \text{(Equation 2.2)}$$

where $T_{ambient}$ is the air temperature (ºC); $RH_{ambient}$ is relative humidity (%) and $v_{ambient}$ is the wind speed of air flow (m/s) in the ambient environment. Agostini and Baibakova et al. suggested that a value of TEE from 16.8˚C to 20.8˚C is a comfortable environment, a TEE under 16˚C is too cool and over 20.8˚C is too hot. Both the value too cool or too hot causes discomfort (Agostini, 2005) (Baibakova, 1964).

Because of the high insulation of PPE, the microclimate temperature ($T_{cmc}$) and relative humidity ($RH_{cmc}$) inside PPE is highly different from the $TEE_{ambient}$. $TEE_{ambient}$ is not suitable for describing the thermal stress of human body wearing high-insulated clothing such as PPE.

2.2.2 Indirect measurement of thermal comfort

2.2.2.1 Computational simulation

Computational simulation is an important research tool to create a virtual space (Eberhardt, 1996) (Baraff, 1998) for evaluating complex clothing designs using the thermoregulatory model to predict the physiological responses of firefighters (Kim, 2013) (Yokota, 2008). Based on the results of the simulation, designers can quickly preview the functional thermal performance of a clothing without making the actual sample (Volino, 1995) (Carignan, 1992).

In addition to fitting and appearance, the thermal functional performance of clothing is a critical aspect related to safety and comfort of the wearers, especially in a difficult environment. Previous literature has focused on the development of mathematical models, computational algorithms and numerical solutions for the simulation of the heat and moisture transfer between clothing materials and the human body (Henry, 1939) (Farnworth, 1983) (Li, 2003).

2.2.2.2 Human-clothing-environment system in S-smart

Li's research team has designed and developed a CAD system called S-smart, with user-friendly interfaces for pre-processing, computational simulation and post-processing modules (Li, 2006). As mentioned in 2.1.3, the thermal regulation system of human body is supposed to maintain a stable thermal condition of the human body by adjusting the skin, muscles, blood vessels and sweat glands. Fig. 2.4 shows the body thermoregulation system involving the thermal sensors and responses of the skin, brain and internal organs.

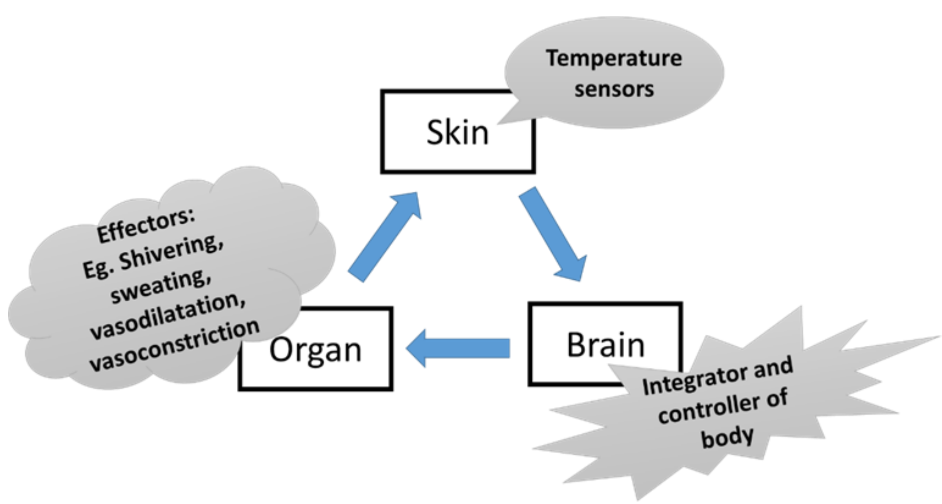



Fig. 2.4 Human body thermoregulation system

In S-smart, the human-clothing-environment (HCE) system, in particular, the body thermoregulation system is applied to simulate the core temperature of human body. The input parameters include the clothing properties and environmental condition (Fig. 2.5). The thermal mechanism of HCE system is predicted by three sets of mathematical models of the following processes (Li, 2006).

- the thermoregulation processes of the human body,
- the heat transfer processes, and
- the moisture transfer processes in clothing and external environment.
- Then the thermal performance of clothing and the thermal physiological responses of the human body can be predicted.

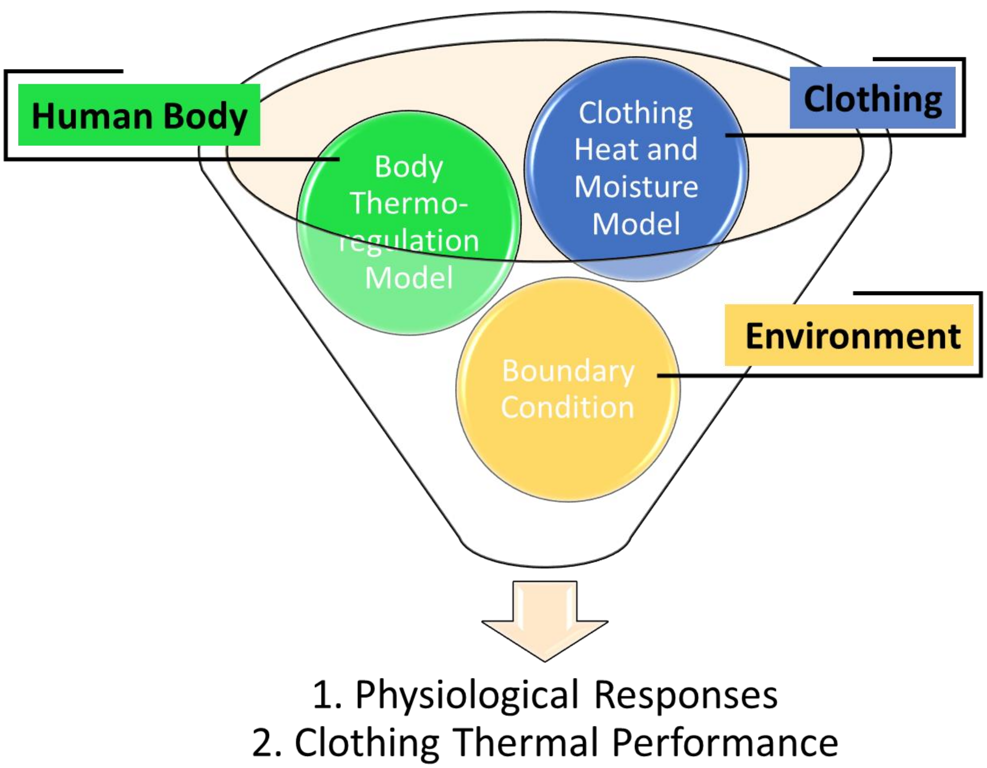



Fig. 2.5 Key elements in the S-smart system

## 2.3 Firefighter uniform and PPE

Firefighters are exposed to different hazards such as fire flash, high-temperature steam, toxic chemical and biological hazard during operation. Apart from direct contact with dangerous, firefighters may suffer from high thermal stresses when the body temperature rises significantly due to the workload and environmental conditions of the rescue location which is high temperature and humid. (Sun, 2000) (Robinson, 1945)

During the rescue operation, firefighters need to wear a uniform and a multilayer PPE with high fire-resistance properties for thermal protection. They are also responsible for the equipment maintenance and preparation in the fire station. It is important to ensure their comfort and convenience when wearing a uniform with and without PPE for a wide range of applications. Previous studies have investigated the importance, performance and the design of PPE (Mell, 2000) (Holmér, 1995) (Lawson, 1998), but seldom studied the firefighter uniforms. Fig. 2.6 shows the firefighter uniform and PPE provided by Hong Kong Fire Services Department.

Firefighter uniform + PPE

Firefighter uniform only

Fig. 2.6 Firefighter Uniform and Personal Protective Equipment (PPE)

### 2.3.1 Firefighter and uniform

Previous studies have investigated the appearance and image of firefighter uniform (Martin, 2001). McLellan studied the effect of shorts and long pants inside PPE on the TPP and thermal stress (McLellan, 2004). Smith evaluated the firefighter uniform with a cotton underwear T-shirt (Smith, 2013). Wilmoth suggested that the firefighter uniform should meet the performance requirement of heat and thermal shrinkage resistance, thermal stability, and seam strength (Wilmoth, 2014) (Merkel, 1987).

Although researchers have studied the design and protective performance of PPE (Perkins, 1979) (Ukponmwan, 1993), limited work has investigated the effects of firefighter uniform design and fabric properties on the physiological change of the wearers.

### 2.3.2 Thermal protection

Since the fabric is composed of fiber and air that has low thermal conductivity, so it can provide protection from the radiant heat of fire and sunlight. The total resistance is the sum of the resistance provided by the fabric itself, the boundary layer of air between the skin surface and the back of the fabric, as well as the air inside the fabric. The control of heat transfer let the person maintain a thermal balance in a hot or cool environment.

Studies have revealed that fabric insulation was a barrier to interfere with the heat release from a human body in a hot environment (Li, 2001). Accumulation of heat in the boundary layer between the skin surface and the fabric can also make a person feel hot in a tight clothing.

### 2.3.3 Firefighter and personal protective Equipment

Personal Protective Equipment (PPE) is designed to protect the firefighter body from hazards of electricity, heat, chemicals, and infection. They need to wear an outer coat with breathing apparatus on duty for fire suppression or another emergency rescue. Protective clothing for firefighters consists of highly insulated and inflammable fabrics to prevent burning and/or contact with all hazards (Perkins, 1979). The protective clothing requires a thermal protection performance (TPP) rating 35 or above according to the National Fire Protection Association (NFPA) standard. At this level of protection, firefighters have approximately 17.5 seconds to escape from a flashover exposure before sustaining second-degree burns (Anonymous, 2013). Protective clothing can be an interactive barrier that creates a layer of air between the skin and clothing. This air gap of microclimate maintains the body temperature at a relatively stable state compared to the surface of clothing, especially in an extremely high-temperature environment.

Previous studies also examined the effect of PPE design in terms of thermal protection performance (TPP). For example, the effect of air gap entrapped inside multilayer fabric of PPE related to TPP has been studied by Wang et. al. (Wong, 2012). Although PPE can protect the firefighters from the danger surroundings, the heavy and thick multilayered clothing may significantly decrease the heat release by conduction, convection, and evaporation of sweat from the firefighter body through PPE to ambient (Sun, 2000).

## 2.4 Effects of fabric properties on thermal stress

The importance of thermal protection and reduction of thermal stress for the development of protective clothing is well reported (Sun, 2000). The fabric properties of a firefighter uniform essentially include the thermal insulation properties, inflammability, water vapor permeability and moisture management properties.

### 2.4.1 Heat and Moisture transfer from a clothed body

The modes of heat transfer from a clothed body and an unclothed body are the same. They include conduction, convection, and radiation. Heat loss is due in part to the conduction of heat along the fibers having direct contact with the skin, and in part to the fiber-to-fiber contact. Heat may also be conducted through a boundary layer of air near the skin. The mechanisms of heat transfer include

- conduction through the fibers and air,
- convection of air through the fabric interstices,
- conduction through the air near the fabric face and then by convection, and
- radiation to the cooler environment.

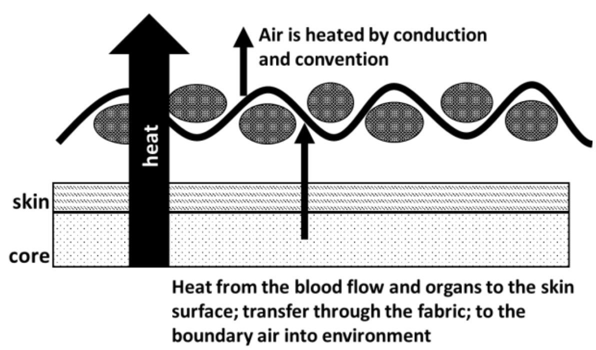



Fig. 2.7 Heat flow through a fabric when the skin is hotter than the environment

According to Hatch, the heat release happens when the blood flows through the capillaries under the skin surface and dissipates to the boundary air between the skin and fabric. The heat is transferred to the boundary air (microclimate) inside the fabric and transferred to the outside air in contact with the fabric by conduction, or transferred through the fabric and the boundary air (microclimate) between the fabric and the skin by convection, or dissipated by radiation to cooler surfaces from the skin and the fiber of the fabric (Hatch, 1992).

The heat dissipation can be aided by the moisture transfer from the skin. Moisture is transferred by diffusion, sorption, wicking, evaporation and mechanical interactions in the forms of pressure, friction and dynamic irregular contact.

Insensible perspiration is described as a loss of water from the human body that is not felt during respiration, where the moisture exhaled from the lungs is lost into the air. Sweating contains water that evaporates from the skin. During this evaporation, the skin is cooled since the heat is transferred to the moisture that escapes. When the vapor pressure on the fabric is higher on one side than on the other, a vapor pressure gradient exists and the moisture moves out. When the vapor pressure on the skin surface is high, the heat loss due to insensible perspiration is high. Then, the person feels comfortable. If the vapor pressure on the skin is lower than another side of the fabric, or the rate of evaporation is not high enough, the heat transfers slowly and sensible perspiration occurs. The type of perspiration is dependent on the atmospheric temperature and humidity in the air. Therefore, the choice of clothing is important for the thermal stress. Clothing should not block the flow of insensible perspiration. This perspiration should freely flow from the body. When the fibers prevent this air movement, the skin can feel the wetness and become uncomfortable.

When there is a fabric on the skin during perspiration, the wetness will move into the fabric. If the fabric is water vapor permeable, the vapor will move from or through the fibers into the atmosphere. This type of fabric is considered to be “breathable and helps to keep, the skin and the fabric to stay dry. Fabrics are, ideally, supposed to have a certain amount of water vapor permeability especially in a hot or humid environment.

Water is moved through the fabric through a capillary action or wicking. This movement can either be vertical or horizontal. It can also occur down the length of the fiber and through the capillaries formed between the fibers in the cloth. The wicking property of a fabric causes the absorption of moisture from the air and enables the distribution of the water inside the fibrous assemblies. The wicking away of moisture will keep the skin dry to prevent the wet fabric from sticking to the skin and causing fungal infections (Hatch, 1992). Wicking of sweat through and across a fabric are illustrated in Fig. 2.8.

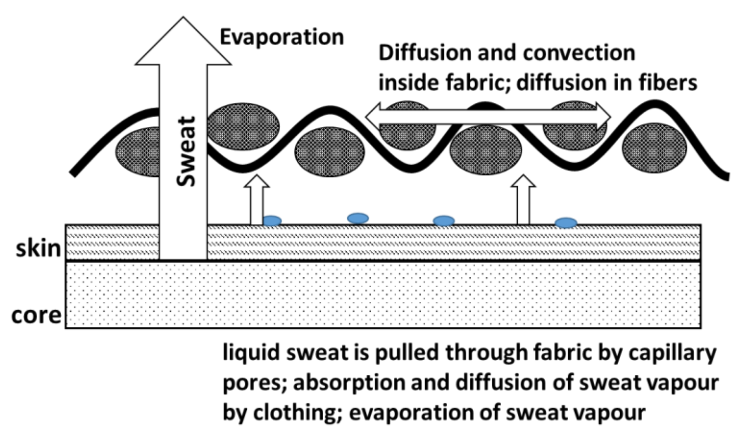



Fig. 2.8 Wicking of liquid water (sweat) through and across the fabric

According to Mecheels and Umbach, the thermal properties of a clothing system are determined by its resistance to heat transfer and its moisture transfer. The integration of moisture and heat transfer in textile materials has been analyzed widely as a very important parameter of dynamic thermal stress during wear. Fabrics made from cellulosic fibers are generally thought to be more comfortable than synthetics in warm weather. The greater comfort of the cellulosic is almost universally attributed to their hydrophilic properties and greater ability to transport moisture (Chen, 2003) (Umbach, 1977). Since thermos-physiological comfort is related to the heat balance of the body in different levels of activity. Improving moisture management in clothing to increase heat and moisture transfer from skin side to fabric outside can benefit the thermal comfort (Rengasamy, 2011).

A Moisture Management Tester (MMT) was developed to measure and quantify the behavior of dynamic liquid and moisture transfer in clothing materials. It can also be used to characterize the moisture management properties of textiles. The overall moisture management capacity (OMMC) is an index to indicate the overall ability of a fabric to allow liquid moisture transportation inside a fabric. A high value of OMMC is usually desirable (Hu, 2005). The overall moisture management capacity of the new fabric increases the rate of liquid sweat transformed from the skin side to the opposite side of fabric. The overall moisture management capacity (OMMC) is an index to indicate the overall ability of a fabric to allow liquid moisture transportation inside a fabric. A high value of OMMC is usually desirable (Guo, 2008).

In conclusion, heat from the body can be transferred and dissipated by conduction, convection, radiation and moisture transfer by diffusion, sorption, wicking, and evaporation of water from the skin. Clothing is a barrier to this heat and moisture transfer from the body to the environment. The clothing insulation, water and windproof and the water vapour permeability are the factors related to the rate of heat and moisture transfer. In order to have a better thermal comfort sensation, the most suitable contributions from each of these factors should be investigated. Moreover, the thermal stress can be reduced when the heat is effectively released from body to the environment if the insulation value of the fabric is low; the breathability and water vapour permeability of the fabrics are relatively good.

### 2.4.2 Reduction of thermal stress

The thermal stress of firefighters increases with a high workload, high temperature, and humid condition. Although protective clothing provides thermal protection to the wearer, it prevents good ventilation and heat dissipation from the body so that the thermal stress increases (Sun, 2000). The high insulation of PPE prevents heat and moisture transmission and cause a reduction in the "breathability" of a fabric, so it induces high thermal stress experienced by the wearers (Smith, 1995). The performance of clothing in both physiological and psychological terms is influenced by the fabric selection and clothing design. Studies have reported the effect of the fabric and style of firefighter uniform on the thermal stress reduction (Malley, 1999). Guo et al. revealed the impact of physical properties on physiological responses of healthcare workers when wearing protective clothing (Guo, 2008).

## 2.5 Summary of knowledge gaps

This chapter reviews the major areas of human physiological heat balance, measurement of thermal stress, the performance of firefighter uniform and PPE, and the effects of uniform designs on the thermal stress. The following conclusion is drawn.

The human physiological response of firefighters has been recorded and analyzed in many studies. Experiments were designed to record the physiological responses including laboratory treadmill and field simulated firefighting activities. Therefore, in this study, experiments were conducted in both the actual firefighting situation and the climate chamber, for comparison. It is the first time for such experiments of firefighter uniform in the training center in Hong Kong.

Among many thermal stress indices developed in previous studies, the equivalent effective temperature (TEE) is most useful because it refers to direct climatic parameters associated with the thermal stress. In the situation of firefighters with PPE, the space between the high insulated thermal barrier of PPE and the firefighter's body acts like a portable microclimate environment. However, the new theoretical index about TEE on this microclimate situation has not been systematically developed and verified.

Computer simulation is an important tool for evaluating the fitting, appearance, and thermal functional performance of clothing. However, the simulated results should be applied to derive a meaningful heat stress index, for a holistic and systematic analysis of the thermal performance of a functional clothing.

Previous studies have widely and deeply investigated the heat stress index such as PSI and TEE. However, the relationship between PSI (empirical index) and TEE (direct index) was still unknown.

Even the effects of fabric properties on thermal stress were investigated, there is a lack of understanding of the effects of the design and fabric properties of the clothing with PPE on the thermal stress of Hong Kong firefighter uniform.

## 2.6 Conclusion

Firefighters need to work in different harsh conditions of high temperatures, humidities and often full of toxic irritators. The safety of the firefighter is important in their duty. It is valuable to evaluate the design and fabric properties of the uniforms under PPE, in terms of human physiological responses of firefighters in various activities, for a reduction in their thermal stress.

Moreover, a new theoretical index should be used to determine the thermal stress of firefighters more effectively and accurately. For higher efficiency, computer simulation can quickly predict the thermal stress. In the simulation program, S-smart, the heat stress index should also be applied to predict the overall thermal stress in terms of TEE inside microclimate.

# Chapter 3 Clothing microclimate and heat stress index of firefighters

## 3.1 Introduction

Firefighters need to undertake various duties at work. These tasks cover routine technical rescue work up to unpredictable, highly dangerous firefighting. The most demanding firefighting tasks include rescue work, searching in a building, and rescue of the victims (Romet, 1987). Firefighters are required to wear “turnouts”, comprising multi-layer personal protective equipment (PPE) and heavy self-contained breathing apparatus (SCBA) weighing 25–28 kg (Elsner, 2008) that can reduce evaporative cooling capacity within those environments encountered during rescue operations (Cheung, 2000) (Ftaiti, 2001). The thermal barrier function of their protective clothing can critically protect them from burns. However, the heat stress within such a clothing microclimate has seldom been considered or reported on in previous studies. Heat stress is a major problem for the firefighters when they are wearing heat-insulated clothing and PPE that cannot shed the heat arising from their physical exertion (Frank, 2001) (Petruzzello, 2009) when performing firefighting tasks in an extremely high heat loading. This heat loading is generated from intensive direct heat radiation and heat fluxes caused by both heat convection and conduction (Havenith, 1999). The physical demands and the high-temperature clothing climate created due to the wearing of the encapsulating turnouts including Polybenzimidazole (PBI), Matrix fire protective suit, waterproof boots, hood, helmet with face shield, gloves, and SCBA further adds to the overall heat load (Smith, 2001).

Studies on the thermal and cardiovascular strain of structural firefighters during rescue training have found markedly high heart rates and core temperature (Bennett, 1993) (Smith, 1997). Some studies have indicated that, although the mean core temperature and heart rate of some firefighters remained within the acceptable limits of 38.5 °C and 138 beats per minute (bpm) respectively, the core temperatures exceeded 39 °C in other subjects, and the maximum heart rate exceeded 90% of the subjects' heart rate reserve during many exercises (Eglin, 2004). At core temperatures over 39 °C, humans may experience hyperthermia and heat-related disorders, as well as heat exhaustion, fainting, dehydration, vomiting, headache, and dizziness.

According to the US Department of Labor Occupational Safety and Health Administration (Anoymous, 2002), heat illness = high temperature + high humidity + physical work. Based on this equation, heat illness in firefighters is caused by the high temperature and high humidity in the environment in which the firefighters experience great physical demands. The equivalent effective temperature (TEE) is a useful index to indicate the thermal stress associated with climatic parameters including the ambient temperature, moisture, and wind speed (Aizenshtat, 1974). The space between the thermal barrier of protective clothing (PPE) and the firefighter's body acts like a portable microclimate environment, analogous to a condition that the nude body is in when in an ambient environment. It is therefore anticipated that the equivalent effective temperature within the clothing microclimate ($TEE_{cmc}$), calculated from the microclimate temperature ($T_{cmc}$) and relative humidity ($RH_{cmc}$) may affect the heat stress of the firefighters, more than the actual ambient environment outside the protective clothing.

The full turnout is designed to significantly reduce the heat stress by lowering the rate of heat build-up on the human skin whilst maintaining the highest level of protection against burn injuries.

The clothing microclimate including temperature and humidity needs to be considered in order to maintain the core temperature ($T_{core}$) within the body, and thus prevent the firefighter from suffering heat stroke or a heart attack. However, there is a dearth of studies on the clothing microclimate for firefighters who are performing physically demanding tasks.

Therefore, the aim of this study was to develop a new index of the equivalent effective temperature within the clothing microclimate ($TEE_{cmc}$) and use it to predict the heat stress index of firefighters experienced during four different simulated fire training activities. The training was held at the Fire Services Department West Kowloon Rescue Training Centre (FSDWKRTC) in Hong Kong. The physiological data was measured regularly during the training activities. The data included the subject's skin temperature ($T_{skin}$) at four body parts, body core temperature ($T_{core}$), plasma oxygen saturation ($SpO_2$) and blood pressure (BP). The heat stress index(PSI) was calculated from the heart rate and $T_{core}$. The clothing microclimate data included the temperature and humidity on the skin of the subject's chest and back. The physiological risk was then assessed by the equation for heat illness.

## 3.2 Method

### 3.2.1 Subjects

In collaboration with the local Fire Services Department, 19 healthy Chinese male firefighters (27.4 ± 2.3 years of age, 174.4 ± 4.4 cm height, 70.7 ± 6.0 kg body mass, and 1.85 ± 0.08 $m^2$ body surface area) volunteered to be the subjects in this study. Each subject was fully informed of the purpose and the procedure of the study. All of them signed an informed consent form indicating that they understood the risks and benefits of participation prior to engaging in this study, approved by the Hong Kong Fire Services Department and the Human Subject Ethics and Sub-Committee of the Hong Kong Polytechnic University.

### 3.2.2 Physiological responses

Six types of physiological responses were measured for the subjects regularly during the training sessions. These were heart rate (HR), BP, $T_{core}$, clothing microclimate temperature, $T_{cmc}$ and humidity, $RH_{cmc}$, $T_{skin,}$ and $SpO_2$. Table 3.1 shows the instruments used for measuring these physiological responses.

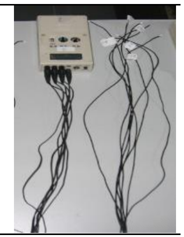
| Instrument | Heart rate monitor & belt with sensor | Vital signs monitor | Intestinal temperature capsule & monitor | Thermal probe | Temperature sensor |
|---|---|---|---|---|---|
| Picture |  |  |   |  |  |
| Dimensions | Sensor: 7cm x 4cm. Belt: 70-150cm | H24xW17x D17cm <3.5kg weight | Capsule: 1.6g ϕ8.7mm x23mm | H58xW78xD 26mm | H100xW60 xD20mm |
| Physiological response | HR | BP | $T_{core}$ | $T_{cmc}$ and $RH_{cmc}$ | $T_{skin}$ |
| Value | A factor of heat stress | Data of physiological stress | A factor of heat stress | Two parameters of heat illness | Mean skin temperature ($T_{mean\ skin}$) |

Table 3.1 Instruments to measure the physiological responses

The HR of the subjects was measured every minute using a Heart Rate Monitor (Polar Electro Oy, Kempele, Finland). The HR monitor was a watch worn by the subjects connected to a sensor in a belt worn around their chest throughout the experiment for continuously recording the HR.

The BP and $SpO_2$ were measured using a Vital Signs Monitor (VS-800, Shenzhen Mindray Bio-Medical Electronics Co., Ltd., China) after every training and rest session.

The $T_{core}$ was measured using a sterile, disposable intestinal temperature capsule (Jonah™, VitalSenses, Mini Mitter Co., Inc, Bend, OR, USA), which was ingested with a small meal by each subject approximately four hours before the start of the experiment in order to avoid the influence of liquid and food intake on the measured temperature. The wireless monitor connected to the capsule, recorded the $T_{core}$ of each subject every 30s after the start of each training session.

The clothing microclimate, including the temperature and humidity on the chest skin under the clothing, was measured using a thermal probe (Especmic, Japan). The thermal probe was attached to the chest and the back of each subject. The temperature and humidity data were recorded every 30s.

The $T_{skin}$ was monitored using skin temperature sensors (Nikkiso-YSI, Japan). The sensors were attached to four body parts of each subject, namely, the chest, upper arm, upper leg, and lower leg. The data was recorded every 30s.

The physiological responses (HR, $T_{core}$, $T_{skin}$, clothing microclimate) were recorded continuously as they fluctuated with time. It takes time for the body to accommodate the climate change during different activities. Therefore, only the average value of the data during the final 5 minutes of each session was extracted for data analysis. On the other hand, BP and $SpO_2$ were only measured after each activity, thus the actual data was used.

Before each experiment, calibration of the temperature probes and skin temperature sensors was performed. The probes and sensors were put in a climate chamber which was set at 3 levels of temperature and relative humidity combinations that were likely to be encountered within the clothing microclimate including 20°C/60%, 25°C/70% and 30°C/80% respectively. After 30 minutes, when the temperature and humidity of the climate chamber reached a stable status at each respective level, the measurements were taken using the temperature probes and skin temperature sensors for 30 mins. The measured errors in the mean temperature and humidity recorded from the temperature probes and the humidity sensors ranged from 0.06 to 0.12 °C and 2.1 to 2.8% RH. These errors were within the required accuracy for the measurement of temperature (± 0.3 °C) and humidity (± 5% RH).

### 3.2.3 Heat stress index

The heat stress index(PSI) was used to evaluate the heat stress of the subjects, which was believed to be related to the climatic conditions, types of clothing, the intensity of exercise, gender, and age. The PSI can be calculated by the HR and $T_{core}$. The mathematical expression for PSI is given by Equation 3.1(Moran, 1998) (Moran, 2000):

$$\mathrm{PSI} = 5\left(\frac{\mathrm{T}_{\mathrm{ret}} - T_{re0}}{T_{\max} - T_{re0}}\right) + 5\left(\frac{HR_t - HR_0}{HR_{\max} - HR_0}\right) \qquad \text{(Equation 3.1)}$$

where $T_{ret}$ and $HR_t$ are the $T_{core}$ and HR at any time t; $T_{reo}$ and $HR_0$ are the $T_{core}$ and HR during the rest periods in the controlled room prior to the fire training. $T_{max}$ = 39.5 and $HR_{max}$= 192 bpm are the standard maximum $T_{core}$ and maximum HR corrected by the mean age of the subjects in this study, respectively. A PSI level of 0 represents no heat stress, 2 to 4 represents a mild strain, 4 to 6 is a moderate strain, 6 to 8 means a heavy strain and 10 indicates an extremely high thermal stress.

### 3.2.4 Equivalent Effective Temperature

Effective Temperature Equivalent (TEE) is commonly used to determine the bioclimatic thermal stress level based on the ambient temperature, moisture content, and the wind speed (Aizenshtat, 1974) of the environment. The ambient equivalent effective temperature, $TEE_{ambient}$ is calculated by Equation 3.2 (Aizenshtat, 1974):

$$TEE_{ambient} = 37 - \frac{37 - T_{ambient}}{0.68 + 0.00014RH_{ambient} + \frac{1}{1.76 + 1.4{v_{ambient}}^{0.75}}} - 0.29T_{ambient}\left(1 - \frac{RH_{ambient}}{100}\right)$$

(Equation 3.2)

where $T_{ambient}$ is the air temperature (ºC); $RH_{ambient}$ is relative humidity (%) and $v_{ambient}$ is the wind speed of air flow (m/s) in the ambient environment. Previous studies suggested that a value of TEE from 16.8˚C to 20.8˚C signifies a comfortable environment, a TEE under 16˚C is too cool and over 20.8˚C is too hot. Both the latter temperatures cause discomfort (Teodoreanu, 2016).

### 3.2.5 Clothing Microclimate Equivalent Effective Temperature

TEE is determined by temperature, humidity and air velocity, as defined and accepted in literature. This concept/definition can be applied for large scale of environment for outdoor when a human being worn very little clothing like on the beach, or in a controlled environment where people does not wear clothing like in Sauna rooms, or clothing microclimate, which is defined as the microclimate between the underwear and skin. In clothing microclimate, air velocity varies depending on the fitting, movement and openings of clothing. As the concept is the same, there is no need to change the definition and considering other factors.Using the same equation 3.2, the clothing microclimate equivalent effective temperature ($TEE_{cmc}$) experienced by the firefighters can be defined as in Equation 3.3:

$$TEE_{cmc} = 37 - \frac{37 - T_{cmc}}{0.68 + 0.00014RH_{cmc} + \frac{1}{1.76 + 1.4{v_{cmc}}^{0.75}}} - 0.29T_{cmc}\left(1 - \frac{RH_{cmc}}{100}\right) \quad \text{(Equation 3.3)}$$

where $RH_{cmc}$ is the relative humidity (%) and $v_{cmc}$ is the speed of air flow (m/s) which is assumed to be zero in the clothing microclimate in this study. In fact, different clothing designs will give different microclimate conditions depending on the material used and the covered surface areas. Therefore, future studies may need to consider the clothing construction that affects the $TEE_{cmc}$ in particular body regions.

3.2.6 Overall mean skin temperature

The $T_{mean\ skin}$ at the chest, upper arm, upper leg, and lower leg was calculated using Equation 3.4 as defined by Ramanathan (Ramanathan, 1964):

$$T_{mean\ skin} = 0.3\left(T_{chest} + T_{upper\ arm}\right) + 0.2\left(T_{upper\ leg} + T_{lower\ leg}\right) \quad \text{(Equation 3.4)}$$

where $T_{mean\ skin}$ is the mean skin temperature.

3.2.7 Experimental protocol

The experimental protocol is shown in Table 3.2 with pictures and descriptions of the training performed in one day. The experiment was conducted according to the guidelines and procedures of the formal training in the FSDWKRTC actually in practice. The subjects wore the encapsulating turnouts including PBI Matrix fire protective suit, waterproof boots, hood, helmet with face shield, gloves, and SCBA (shown in Fig. 3.1) and participated in four training sessions in an environment set to simulate the real firefighting and rescue conditions. Each session lasted for 15 to 30 minutes. After every two sessions, they took a rest and removed the encapsulating turnouts. Both the physiological data and clothing climate were directly measured as indicated in Fig. 3.1.

Fig. 3.1 Encapsulating turnout of firefighters

| Session no. | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|---|---|---|---|---|---|---|---|---|---|
| Session | Briefing | Real fire training 1 | Real fire training 2 | Lunch | Tunnel training | Maze training | Rest | 15th minute rest | 30th minute rest |
| Start time | 10:30 | 11:00 | 12:00 | 13:00 | 15:00 | 14:00 | 16:00 | 16:15 | 16:30 |
| End time | 11:00 | 12:00 | 13:00 | 14:00 | 16:00 | 15:00 | 16:15 | 16:30 | 16:30 |
| Picture |  |  |  |  |  |  |  | | |
| - Max $T_{ambient}$<br>- Mean $T_{ambient}$<br>- Max $RH_{ambient}$<br>- Mean $RH_{ambient}$<br>- Workload | 24.9ºC<br>22.6ºC<br>77%<br>65.6%<br>Low | 27.2ºC<br>25.4ºC<br>75%<br>65.6%<br>High | 29.4ºC<br>24.9ºC<br>99%<br>64.9%<br>High | 23.1ºC<br>20.9ºC<br>76%<br>76.7%<br>Low | 30.1ºC<br>25.3ºC<br>99%<br>75.8%<br>High | 25.6ºC<br>22.9ºC<br>87%<br>71.3%<br>High | 23.3ºC<br>20.2ºC<br>80%<br>71.6%<br>Low | 23.1ºC<br>20.2ºC<br>82%<br>71.1%<br>Low | 30.1ºC<br>22.6ºC<br>82%<br>73.4%<br>Low |
| Clothing | T-shirt & uniform | encapsulating turnouts | encapsulating turnouts | T-shirt & uniform | encapsulating turnouts | encapsulating turnouts | T-shirt & uniform | T-shirt & uniform | T-shirt & uniform |
| PPE | No | Yes | Yes | No | Yes | Yes | No | No | No |
| Activities | rest | extinguished a fire in hotel & domestic office | extinguished a fire in industrial & karaoke | control meal | train in a simulated tunnel and chute | search breathing apparatus in a maze | rest | rest | rate comfort & strain |
| Physiological data measured | $T_{skin}$ /30s<br>$T_{core}$/30s<br>HR | $T_{skin}$ /30s<br>$T_{core}$/30s<br>HR | $T_{skin}$ /30s<br>$T_{core}$/30s<br>HR | $T_{skin}$ /30s<br>$T_{core}$/30s<br>HR | $T_{skin}$ /30s<br>$T_{core}$/30s<br>HR | $T_{skin}$ /30s<br>$T_{core}$/30s<br>HR | $T_{skin}$ /30s<br>$T_{core}$/30s<br>HR | $T_{skin}$ /30s<br>$T_{core}$/30s<br>HR | $T_{skin}$ /30s<br>$T_{core}$/30s<br>HR |
| After activity | BP<br>$SpO_2$ | BP<br>$SpO_2$ | BP<br>$SpO_2$ | BP<br>$SpO_2$ | BP<br>$SpO_2$ | BP<br>$SpO_2$ | BP<br>$SpO_2$ | BP<br>$SpO_2$ | BP<br>$SpO_2$ |
| Clothing microclimate | T & H every 30s at chest & back | T & H every 30s at chest & back | T & H every 30s at chest & back | T & H every 30s at chest & back | T & H every 30s at chest & back | T & H every 30s at chest & back | T & H every 30s at chest & back | T & H every 30s at chest & back | T & H every 30s at chest & back |

Caption: HR: heart rate; BP: blood pressure; $SpO_2$: plasma oxygen saturation; $T_{core}$: core temperature; $T_{skin}$: skin temperature, T: temperature; H: humidity

Table 3.2 Experimental protocol.

Before 10:30, the subjects were asked to empty their bladders to reduce their needs to urinate during the experiment. They wore a T-shirt as underwear and a uniform (blends of cotton and polyester) equipped with sensors to measure their $T_{skin}$ at the four body parts previously defined. The clothing microclimate temperature and humidity, as well as the subjects' HR, BP, $T_{core}$, and $SpO_2$, were measured regularly.

At 10:30, a 30-minute brief meeting was conducted with the subjects in a rest condition. At 11:00, the real fire training sessions 1 and 2 started. The subjects wore the encapsulating turnouts, searched a building and extinguished a fire in the controlled-climate chamber. At 13:00, they removed the encapsulating turnouts and had lunch for 60 minutes, with the same set lunch provided. The control of equal calorie and liquid intake prevents the different physiological impact of firefighters by food. At 14:00, the subjects trained inside a simulated tunnel and a chute training chamber without a fire. At 15:00, the subjects searched for a breathing apparatus in a maze inside the controlled climate chamber. At 16:00, they removed the encapsulating turnouts and had a 30-minute rest.

### 3.2.8 Statistical analysis

The data for HR, BP, $SpO_2$, $T_{skin}$, $T_{core}$, and clothing microclimates ($T_{cmc}$ and $RH_{cmc}$) for the 19 subjects were analyzed by analysis of variance (ANOVA) with repeated measures. When ANOVA revealed a significant effect of time (activity), multiple Bonferroni tests were applied to identify the significant differences amongst the different sessions, with a 95% confidence level, using statistical analysis SPSS V.17.0 statistical software (Chicago, Illinois, USA). The significance level was set at $p < 0.05$.

### 3.3 Results and Discussion

#### 3.3.1. Heart rate

In monitoring the subject's cardiovascular responses, HR is the most important data (Lusa, 1993) (Eglin, 2004). Fig. 3.2 shows the time series for the mean and standard error of the HR for all subjects in the experiment. Unsurprisingly, the mean HR was significantly higher in the real fire training sessions 1 and 2 and the tunnel and maze training than in the briefing, lunchtime and final rest sessions ($p$ <0.001). Time also had an effect on the HR response during the 30-min rest session ($p$ <0.001). HR decreased by 17.1% when the rest started, by 36.8% after 15 minutes, and by 44.1% after 30 minutes, respectively.

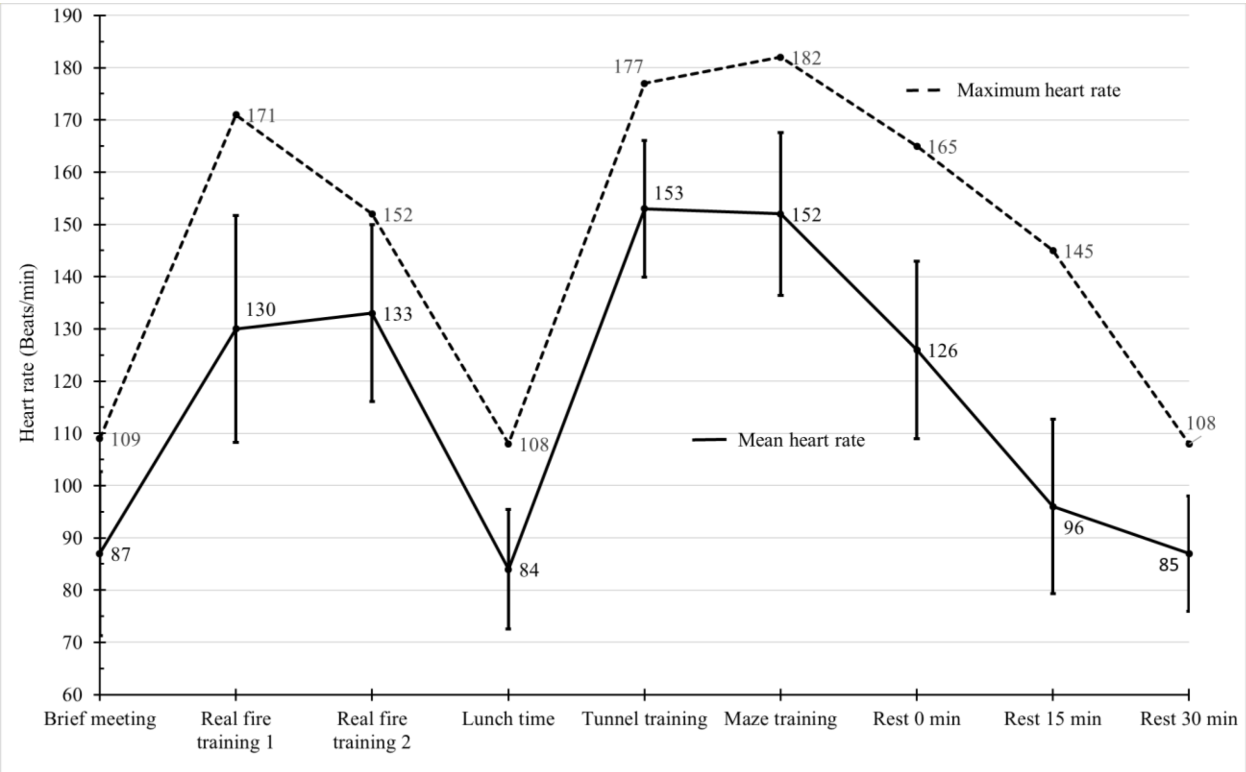



Fig 3.2. Mean heart rate during the training-rest schedule.

For the mean age of 27, the maximum recommended heart rate ($HR_{max}$) = 220 –27 = 193 bpm, during moderately vigorous activities (Yao, 2005). However, during the fire training session, the $HR_{max}$ values recorded were up to 182 bpm which reached 90% of the $HR_{max}$. Considering the high $T_{core}$ together, this indicated that the firefighters had undergone a high-risk vigorous physical activity. This finding is in agreement with the results from Lusa et al, and Eglin et al. They also found that the HR of the firefighters was approaching the maximum levels. In this study, the mean HR of the subjects significantly decreased from 152 bpm during the maze training to 85 bpm in the 30 mins final rest. This shows the importance of a work-rest schedule.

### 3.3.2. Blood pressure

As shown in Fig. 3.3, the mean systolic blood pressure (SBP), the mean and standard error of the arterial pressure (MAP) and mean diastolic blood pressure (DBP) for all the subjects during the training sessions were all significantly higher ($p < 0.001$) than that in the rest sessions. Relatively few studies have investigated the BP of firefighters when they perform moderately to severely intense physical activities. In the present study, the mean SBP ranged from 151–156 mmHg during the training sessions (Fig. 3.3), which is regarded as the hypertensive stage 1 (140–159 mmHg) (Kahan and Ashar, 2009). The subjects' SBP increased because of their hearts needed to work harder to pump more blood to continue supplying the muscles with oxygen. The more strenuous the task was, the greater was the rise in systolic pressure.

However, throughout the entire fire training, the mean DBP changed only slightly in a range between 60 to 75 mmHg which is below the 80 mmHg that is considered normal (Kahan, 2009). This was probably because the blood vessels in the working muscles were widened to decrease the peripheral resistance to blood flow. The mean MAP of the subjects was between 80 and 106 mmHg, which is also considered to be normal (Yao, 2005).

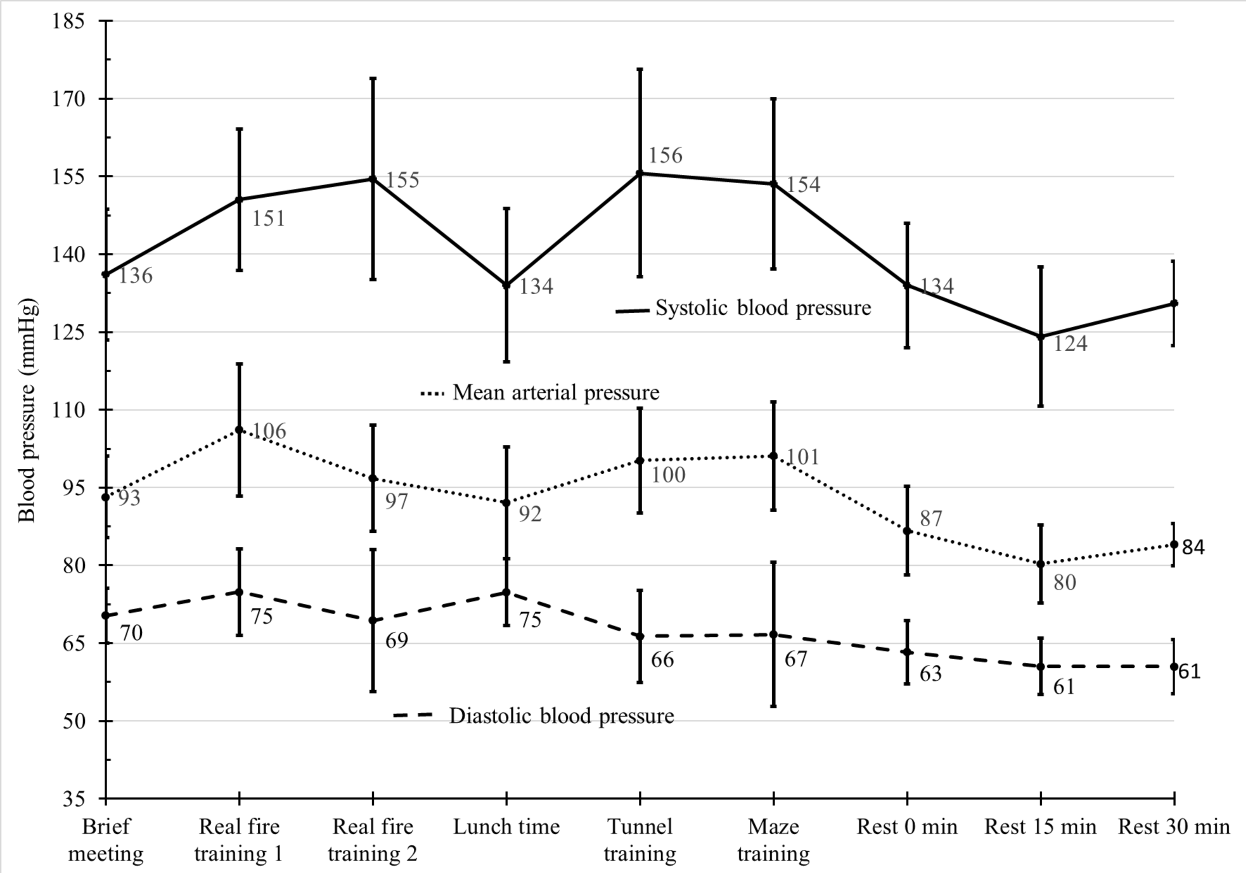



Fig. 3.3 Mean blood pressures during the training-rest schedule

3.3.3 Blood oxygen saturation

Fig. 3.4 shows the mean, standard error, and maximum and minimum values for $SpO_2$ during the nine sessions. $SpO_2$ measures the percentage of hemoglobin binding sites in the bloodstream occupied by oxygen. A value of SpO2 higher than 95% is considered to be normal. The experimental minimum ($SpO_{2\,min}$) value in the period of real fire training session 1 dropped rapidly to 92%, then increased to 95% in fire training session 2, and further increased to 98% during the lunch break. However, the decrease in blood oxygen level did not necessarily indicate a health risk because it was over 90%, so it was not considered to be hypoxemic (Yao, 2005). The hood, helmet and face shield did not cause a significant effect on the $SpO_2$ level because the subjects had self-contained breathing apparatus to provide them with oxygen continuously. The lunch break contributed to an increase in their $SpO_2$ levels because oxygen molecules can travel from the fresh air into the blood during rest and after a meal. Blood is oxygenated in the lungs, thereby increasing the blood oxygen levels and keeping the $SpO_2$ level within a normal level.

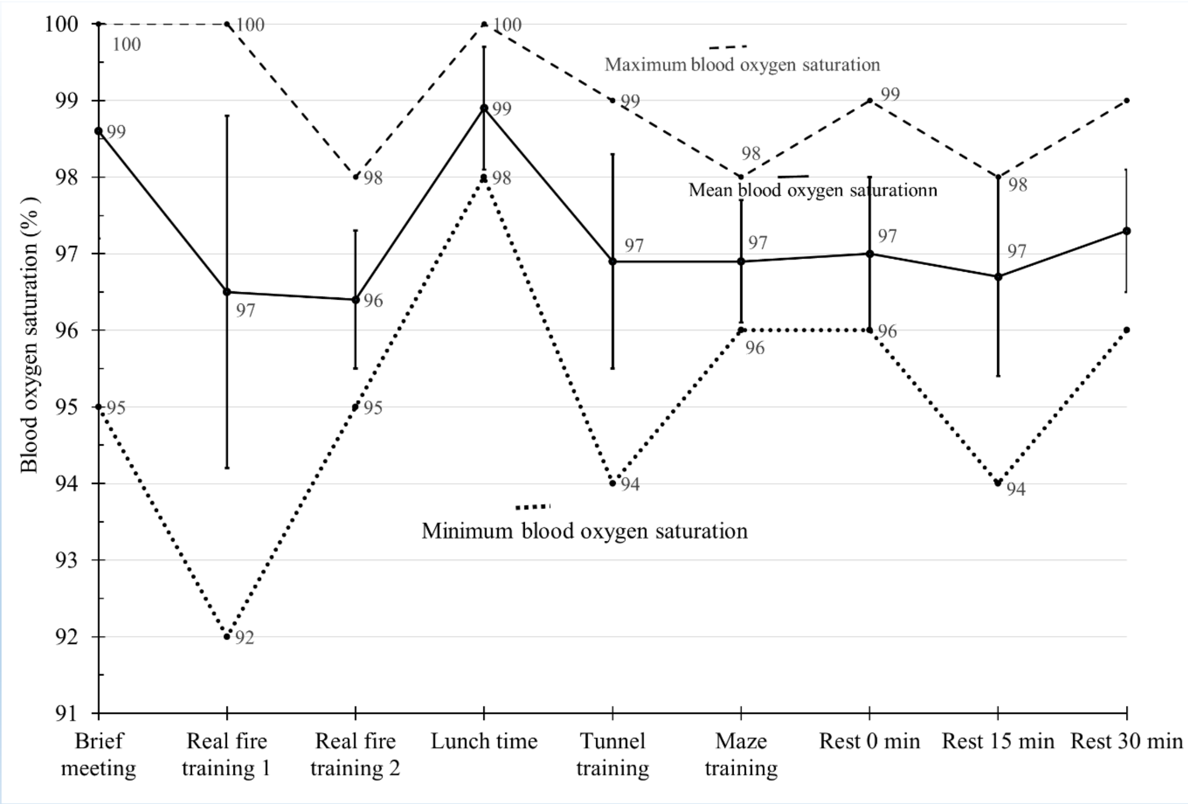



Fig. 3.4. Blood oxygen saturation levels during the training-rest schedule.

### 3.3.4. Core temperature and skin temperature

The safe upper limit for $T_{core}$ is 38.5 °C (Parsons, 1993) and the acceptable limit for work is 38 °C as recommended by (Dukesdob, 1973). Fig. 3.5 shows that the mean $T_{core}$ reached the limit of 38 °C during the training sessions. Firefighting tasks are very demanding. Any single case of over 38 °C $T_{core}$ can cause heat illness and even death. It is alarming to observe that 7 out of the 19 subjects (Fig. 3.6) were either borderline or fell into the dangerous and emergency conditions during the training sessions. Such high $T_{core}$ values may decrease their performance, especially for the tasks that firefighters are unacquainted with, or may even make them feel more stressful when rescuing a collapsed firefighter (Hancock, 1982).

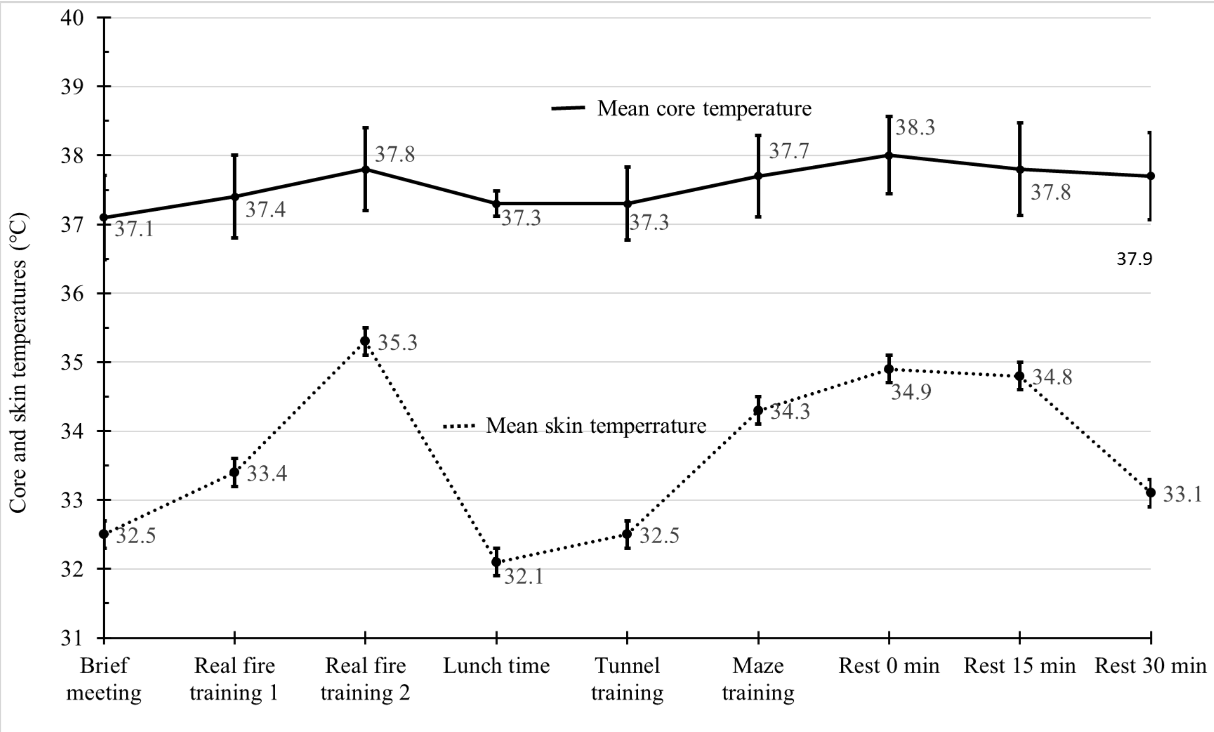



Fig. 3.5 Core temperature and skin temperature during the training-rest schedule

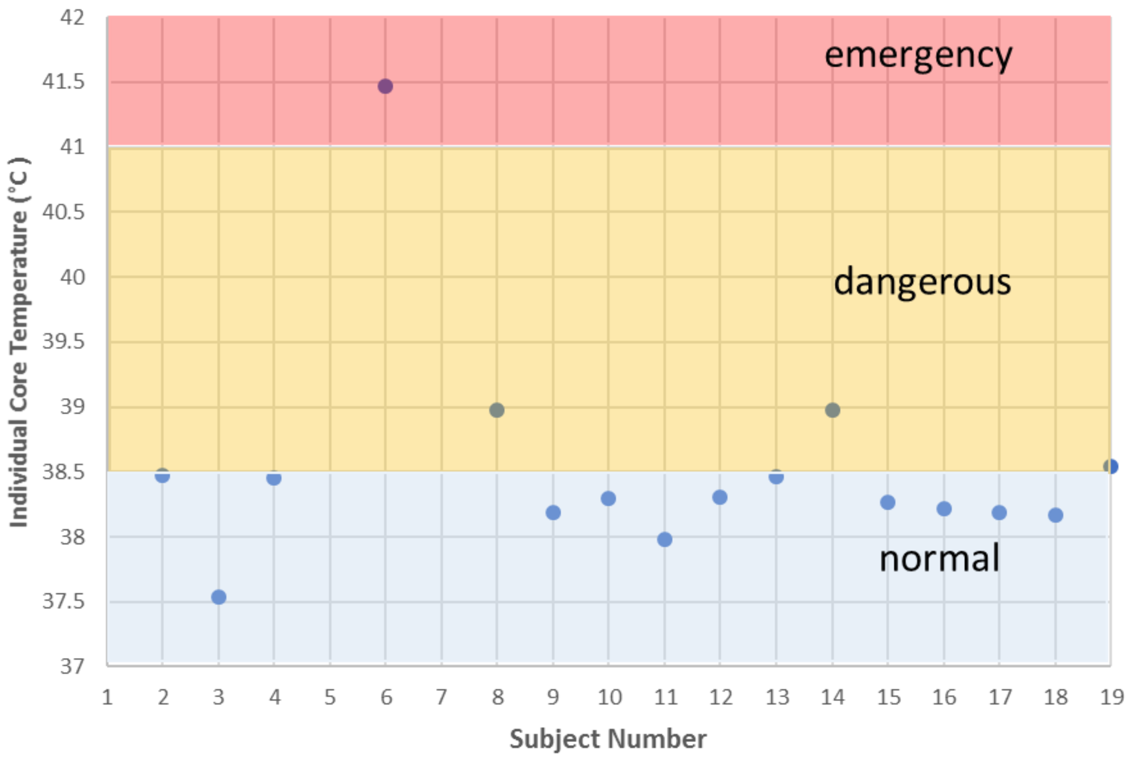



Fig. 3.6 Maximum core temperatures of individual subjects during the training sessions

These findings are in agreement with the results of Eglin et al. (Eglin, 2004), whereby the HR values for the firefighters increased significantly when the mean $T_{core}$ reaching a value of 38.3°C at the end of the exercise. In the danger region for $T_{core}$, heat exhaustion and heatstroke may develop suddenly, and the person may suffer from fainting, headache, breathlessness, thirst, fatigue, nausea, transient loss of consciousness, and muscle cramps.

A dangerously high $T_{core}$ value could have been attained during the two fire training sessions. Fortunately, there was a lunch break between the morning and afternoon training. Consequently, the $T_{core}$ sharply declined to a safe level that prevented the danger of heat exhaustion. Therefore, a work-rest schedule (60~80 min work, 30 min rest) at the FSDWKRTC of Hong Kong is considered reasonable for the health and safety of firefighters. This schedule is also a useful reference for wildfire firefighting.

The mean skin temperature showed a greater increase during the training sessions. Particularly, in the second tasks during the morning and afternoon, $T_{skin}$ rose quickly (from morning: 32.5 °C at rest to 33.4 °C during real fire training 1 and 35.3 °C during real fire training 2; from afternoon: 32.1 °C at rest to 32.5 °C in the tunnel and 34.3 °C in the maze). The results suggested that the duration of tasks markedly influenced the value of $T_{skin}$ ($p < 0.001$), and the aforementioned work–rest schedule was necessary for keeping both $T_{core}$ and $T_{skin}$ within the normal region.

3.3.5. Microclimate temperature and humidity on the chest and back

The comfortable clothing microclimate temperature is between 30°C and 32°C in a rest state, and 15°C during a physical activity; the comfortable relative humidity is between 35% and 60% (Parkova, 2011). Fig. 3.7 shows that the mean microclimate temperature and mean relative humidity values were extremely high in the training sessions.

The chest/back microclimate temperatures in all the four training sessions were significantly higher than those in the rest sessions ($p < 0.001$). The chest microclimate temperature was lower than that on the back in all the four training sessions, probably because more heat could transfer from the skin to the environment by convection through the garment's front openings.

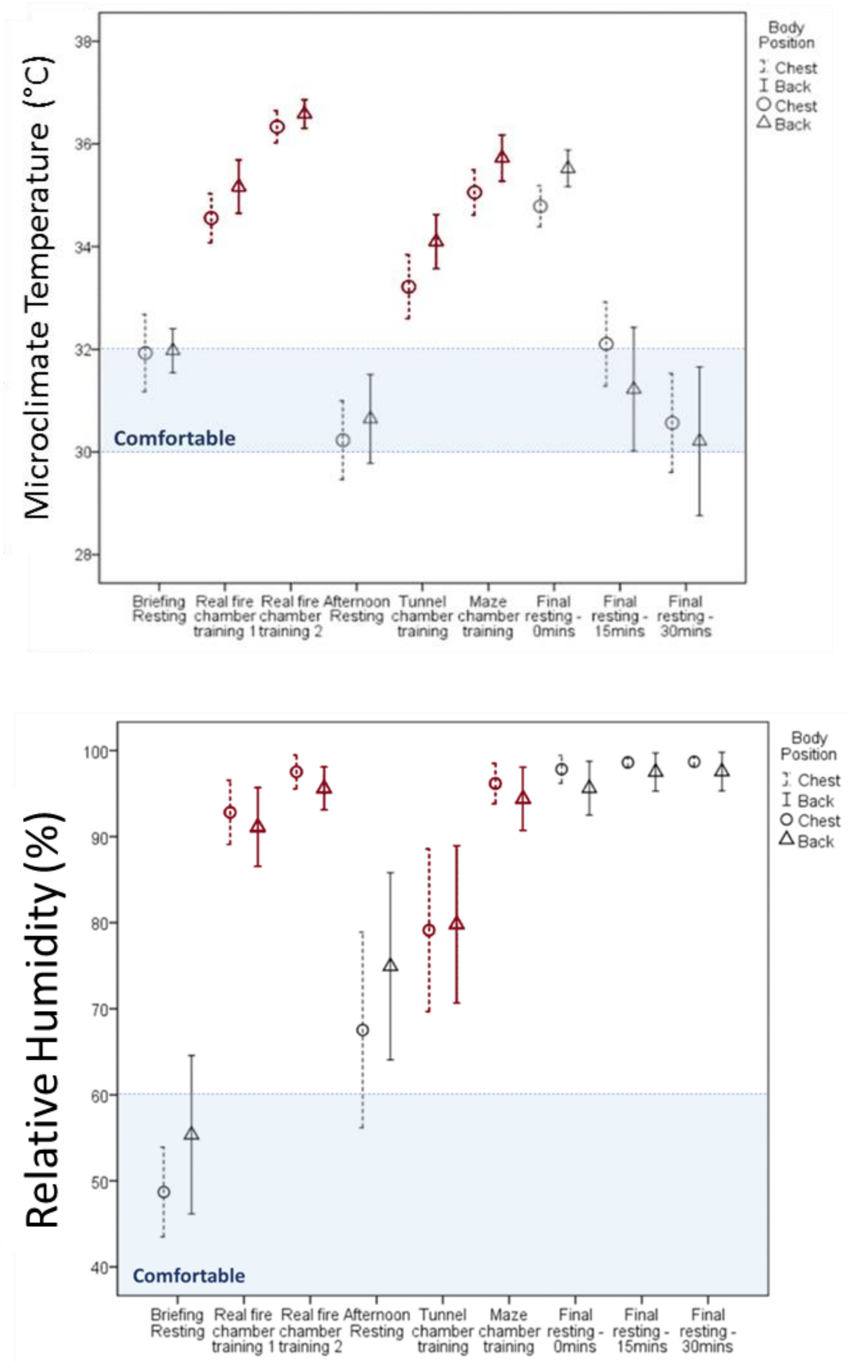



Fig. 3.7 Mean microclimate temperature and humidity on the chest and back during different activities

Fig. 3.7 shows that the chest and back microclimate humidity in all the four training sessions and the final rest session were significantly higher than those in the brief rest session (chest: *p* <0.001; back: *p* <0.001). In the lunchtime sessions, the mean microclimate humidity on the chest was lower than that on the back. The sweating was less on the chest during the rest periods, probably because more heat had been transferred from the chest during the training sessions. The values for the microclimate humidity were similar in the consecutive final rest sessions.

The results indicate that the microclimate condition of the firefighter's backs was exposed to the Danger category of heat illness (Fig. 3.8), during their fire training activities 1 and 2 and maze searching training whilst wearing the PPE. To prevent heat illness of the firefighters, there must be appropriate rest sessions that allow them to remove the encapsulating turnouts in a lower temperature and humidity environment.

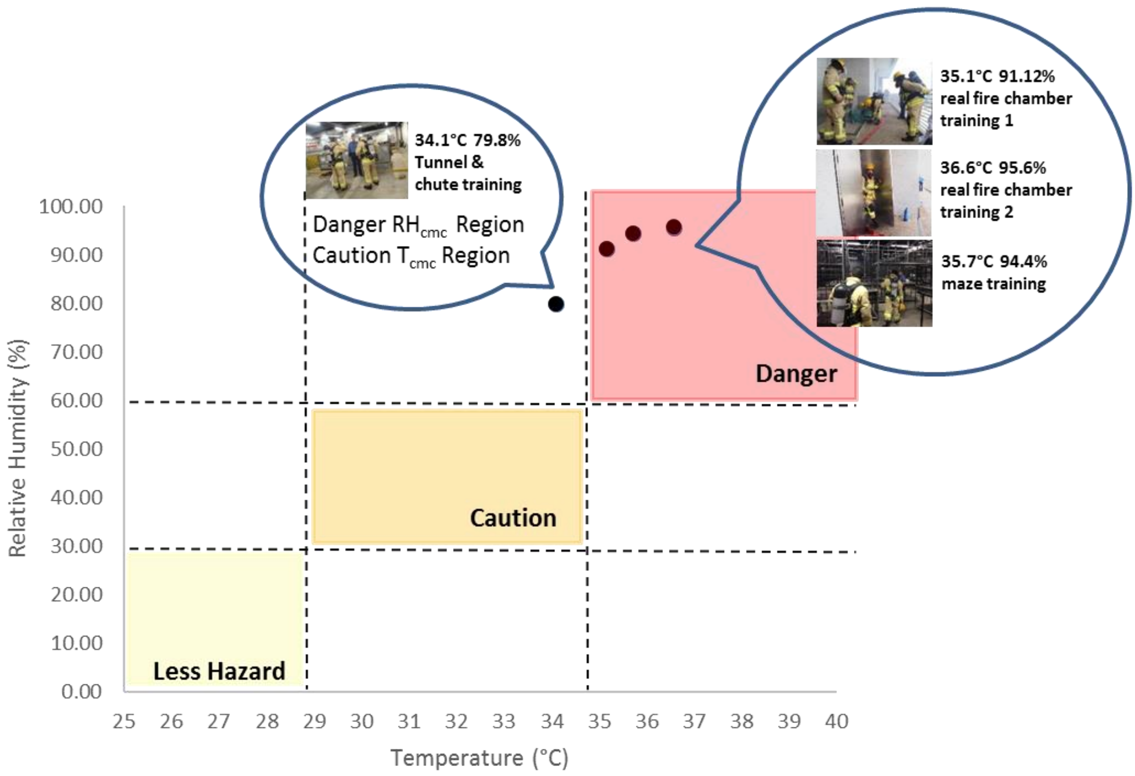



Fig. 3.8 The microclimate levels of heat stress during the rescue training (Anoymous, 2002)

3.3.6 Heat stress index (PSI)

The PSI is a reasonable indication of the cumulative cardiovascular and thermal stress associated with short-term to medium-term (about 60~80 min) severely intense firefighting tasks for the firefighters garbed in their firefighting PPE. Fig. 3.9 shows the mean and standard deviation of the PSI for the subjects during the different activities.

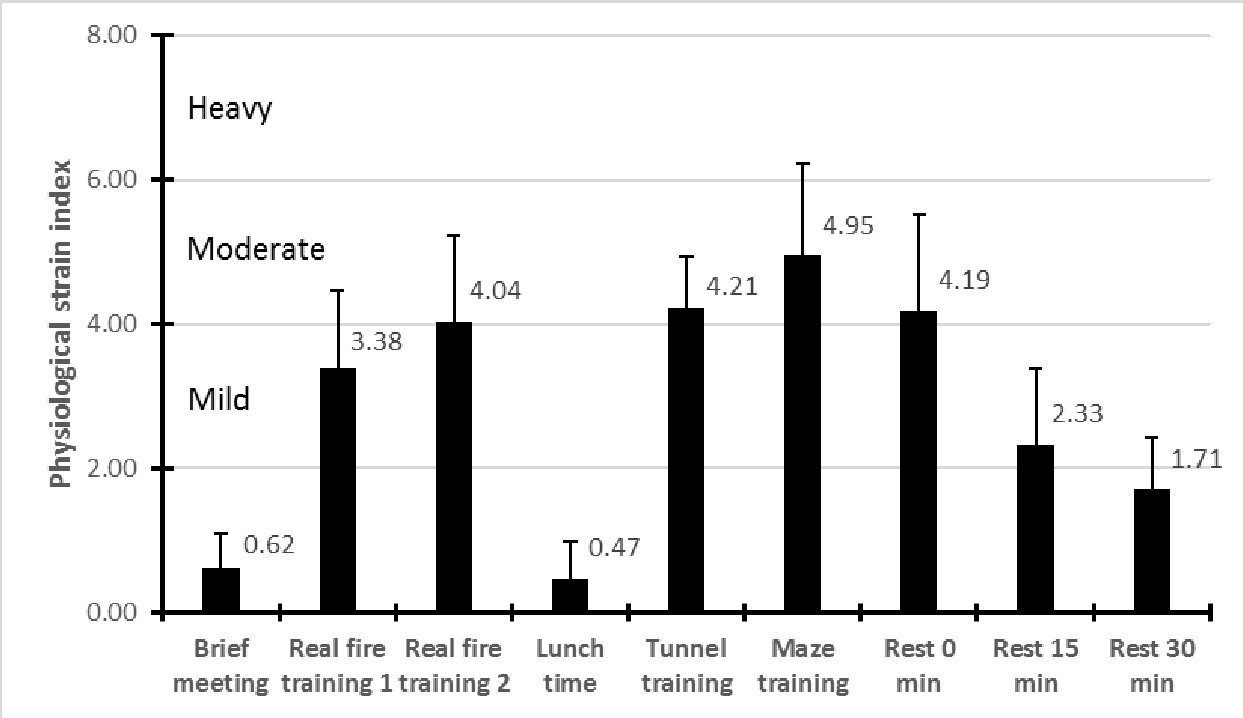



Fig. 3.9 mean heat stress index during the rescue training.

These mean values indicate moderate levels of heat strain (PSI = 4.04 to 4.95) produced during the real fire training session 2, tunnel training, maze training (a total of 60-80 minutes of firefighting in the morning and afternoon) and at the beginning of the final rest session. In the briefing meeting, at lunchtime, and at the end of the resting period, the mean PSI was maintained at a very low level (PSI = 0.62, 0.47 and 1.71, respectively). Despite the fact that heat strain was induced among the firefighters when they were wearing the full set of uniform and PPE in the simulated high temperature and humid conditions, the fire training was still considered to be safe because the PSI was generally below the region of heavy heat strain. The evidence shows that the PSI will decline if the firefighters have enough resting between and after firefighting activities. Therefore, a reasonable resting time should be offered for the health and safety of firefighters.

3.3.7 Comparison of TEE and PSI

According to Fig. 3.10, the mean $TEE_{cmc}$ in the chest region has a positive strong linear relationship with the mean $TEE_{cmc}$ in back region, meaning that the $TEE_{cmc}$ in the chest is associated with and predictable by the microclimate TEE in back.

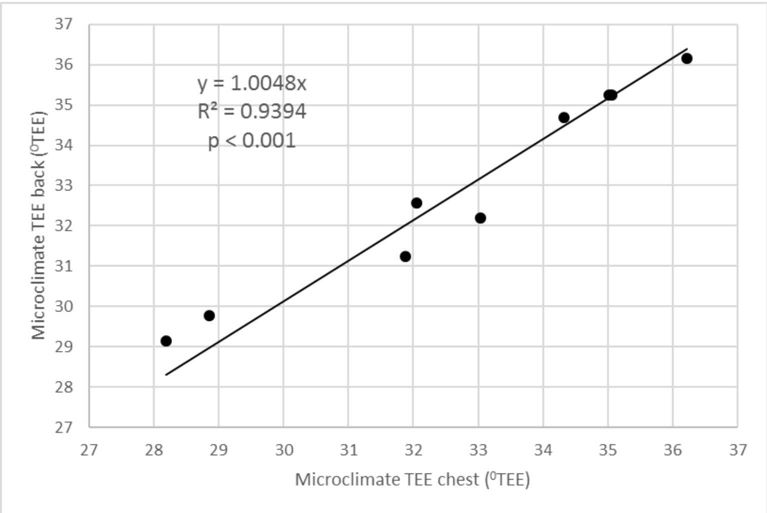



Fig. 3.10 Relationship between values for $TEE_{cmc}$ in chest and back during different activities

The space between the thermal barrier of the PPE and the firefighter's body is, in effect, a portable microclimate environment, analogous to the condition that a nude body is in when in an ambient environment (Fig. 3.11) Therefore the $TEE_{cmc}$, calculated from the $T_{cmc}$ and $RH_{cmc}$, may affect the heat stress of the firefighters more than the actual ambient environment outside the protective clothing.

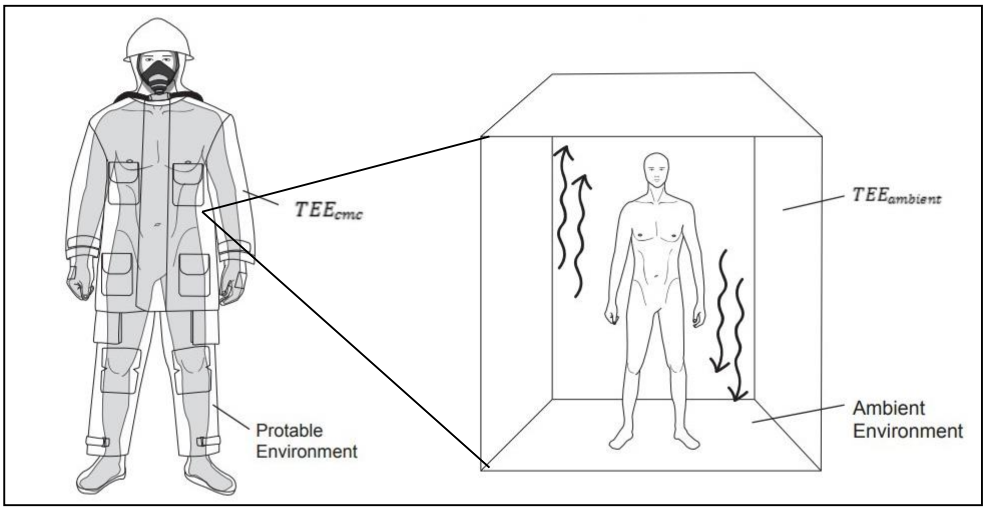
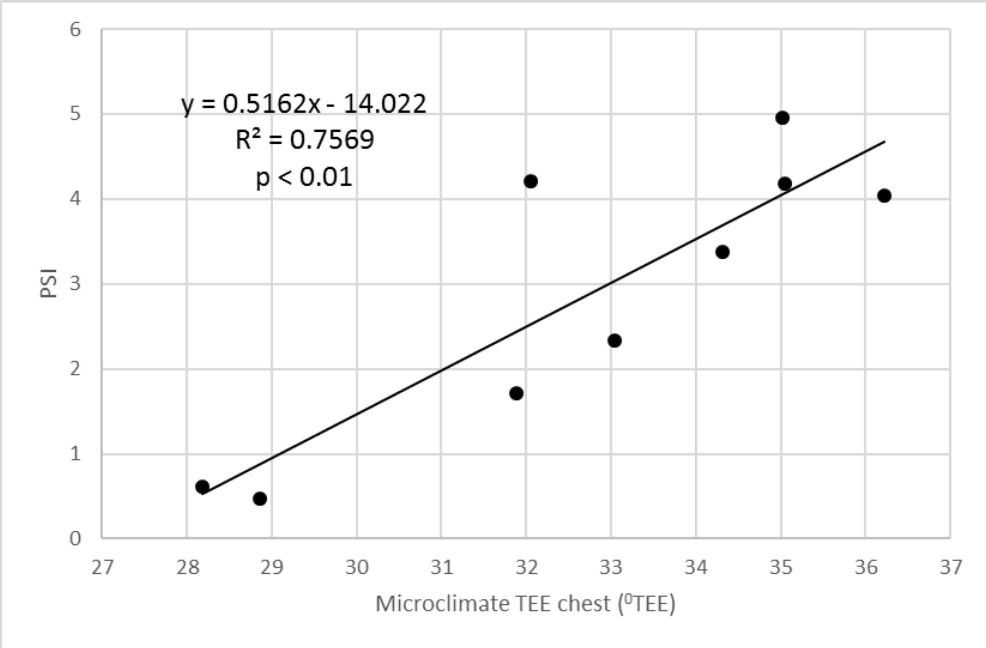



Fig. 3.11 Portable environment within a firefighter clothing, considered as a nude body in a similar ambient environment

The microclimate can be considered for each space between different layers including 1st layer (between firefighter's body and undergarment) and 2nd layer (between undergarment and PPE). As no airflow was assumed inside encapsulated PPE, heat and sweat tends to stay in 1st layer than 2nd layer. Therefore, the heat stress influence of microclimate in 1st layer was more significant than that of 2nd layer. Addition of microclimate sensors were suggested for further investigation about the relationship between 1st and 2nd layer.

Fig. 3.12 shows that there is a positive linear relationship between the mean $TEE_{cmc}$ in the chest/back regions ($r^2 = 0.757$ for the chest and $r^2 = 0.8137$ for the back) and the equivalent means PSI for the investigated 19 subjects during the various activities. However, Fig. 3.13 shows that the mean $TEE_{ambient}$ is not significantly ($p > 0.05$) related to the mean PSI.



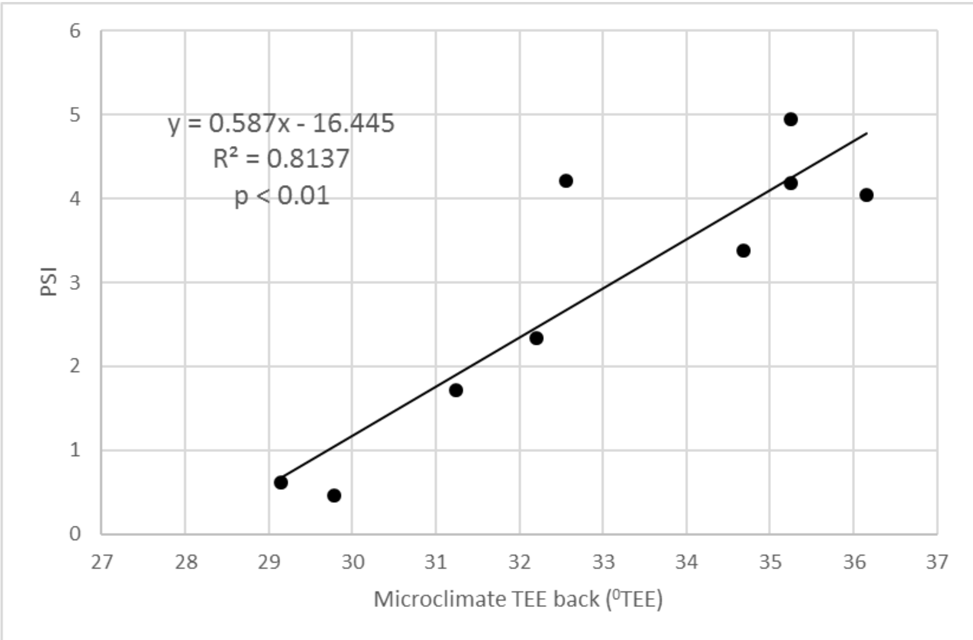




Fig. 3.12 Relationship between microclimate mean $TEE_{cmc}$ and mean PSI values

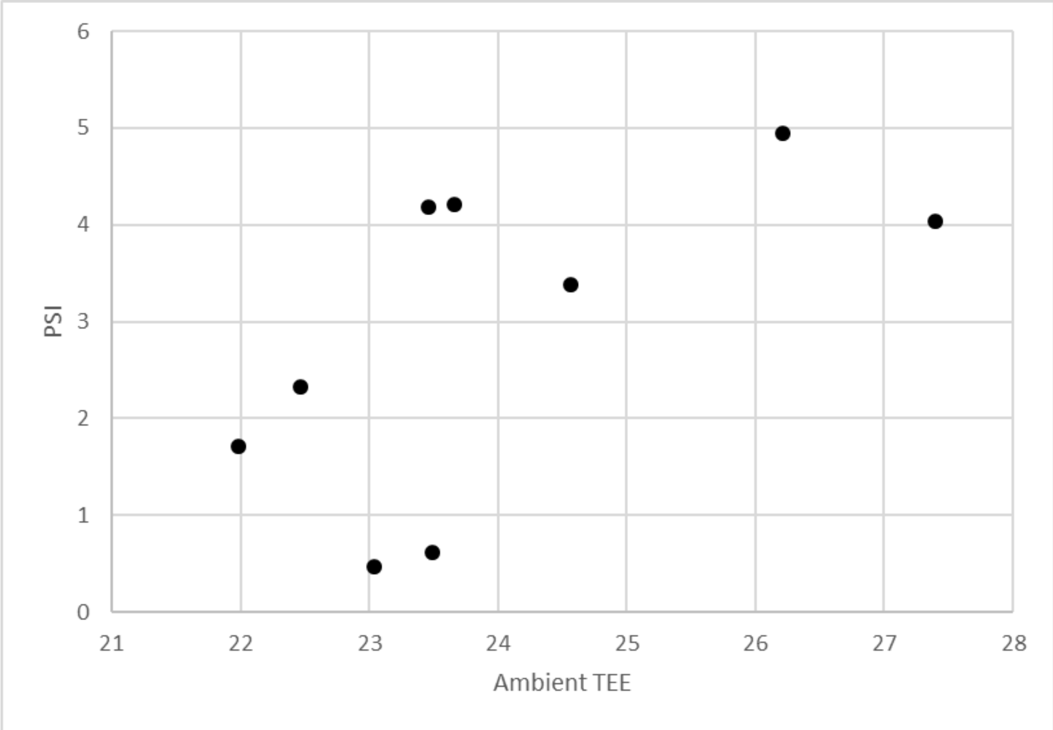



Fig. 3.13 Relationship between mean $TEE_{ambient}$ and mean PSI values

To conclude, the $TEE_{cmc}$ is a useful and more practical index to predict the PSI in portable environment conditions (such as that within a firefighter's protective clothing system), and is a better indicator of psychological strain, than the traditional reliance on the ambient temperature, moisture and wind speed (Aizenshtat, 1974).

### 3.4 Conclusions

This study comprehensively measured the physiological responses of firefighters when they undertook firefighting simulated training in the training center. The major findings are that:

1) the vigorous physical activity in the firefighting training-induced high values of $T_{core}$, HR, and SBP in the firefighters; however, their $SpO_2$ values were normal or almost normal because they wore the PPE assemblies;

2) the clothing microclimate temperature and humidity indicated that the firefighters had been exposed to the danger category of heat illness during the training sessions;

3) a schedule of 60 to 80minute work and 30 minutes rest was reasonable for dissipating heat loads and preventing heat illness. This provides evidence to support the occupational safety guidelines for firefighters;

4) a newly proposed microclimate index, $TEE_{cmc,}$ has a higher impact on and is a better predictor of the PSI than the TEE of the ambient environment.

# Chapter 4 Effect of fabric assemblies of uniform on the thermal stresses of firefighters

## 4.1 Introduction

In Chapter 3, the importance of reducing thermal stress and the heat stress index for the firefighters were identified. This chapter focuses on the impact of different designs and fabric properties of firefighter uniforms on thermal stress in a climate chamber. Twelve firefighters participated in the experiment, wore different sets of uniform under the PPE and walked on a treadmill. Their physiological responses were directly measured. The new index of microclimate TEE was applied and verified in the analysis of experimental data.

## 4.2 Research Design

In order to identify the effect of fabrics and assemblies on the thermal stress of firefighters wearing different sets of uniforms in a control ambient condition, the experiments were conducted in a climate chamber. All the firefighter participants were recruited from the Hong Kong Fire Services Department.

### 4.2.1 Garment Assemblies

For fabric sourcing, a total of 33 pieces of fabrics have been tested.

A questionnaire about firefighter uniform have been finished by 40 frontline firefighters, they suggested the uniform should be focus on the comfort, movement allowance, wear convenience and enhancement of the sweat absorption and heat dissipation. The functional fabrics included TenCate Defense & Tactical's fabric with high protective properties, Nano-tex Asia's fabric with moisture management properties and Esquel's stretch knit fabric were selected future work for the development of new uniform.

Since this thesis was focused on the investigation of new thermal stress index, only 6 samples including fabrics in existing uniform and fabrics with high OMMC were used for comparison. As shown in Fig. 4.1, there are five different sets of uniform to be worn under a set of PPE including a self-contained breathing apparatus (SCBA) during the experiment.

Set 1: Existing short-sleeve T-shirt, existing shirt, and existing trousers

Set 2: Existing short-sleeve T-shirt and existing trousers

Set 3: New short-sleeve T-shirt, new shirt and new trousers made of moisture management fabrics.

Set 4: New short-sleeve T-shirt and new trousers made of moisture management fabrics.

Set 5: New long sleeve T-shirt and new trousers made of moisture management fabrics.


Fig. 4.1 Uniforms used in the wear trial

The existing uniform was mainly made of cotton and polyester. However, Spandex was used to make the new uniform including a new T-shirt and new trousers. In the experiment, the OMMC of new uniform is higher than those of existing uniform. The water vapour permeability (WVP) of new shirt is slightly higher than the existing shirt. The construction details and physical properties of the fabrics are shown in Tables 4.1 and 4.2 respectively.

| Uniform | Fabric type | Fiber contents |
|---|---|---|
| Existing Uniform | | |
| Existing T-shirt | Jersey Knit | 100% cotton |
| Existing shirt | Plain weave | 35% Cotton/65% Polyester |
| Existing trousers | Plain weave | 35% Cotton/65% Polyester |
| New Uniform | | |
| New T-shirt (long and short sleeve) | Jersey Knit | 95% Cotton/5% Spandex |
| New shirt | Plain weave | 35% Cotton/65% Polyester |
| New trousers | Plain weave | 98% Cotton/2% Spandex |

Table 4.1 Characteristics of the fabrics used in the wear trial

| Sample | | Weight (g/m$^2$) | Thickness (mm) | OMMC | WVP (g/m$^2$day) |
|---|---|---|---|---|---|
| Existing Uniform | | | | | |
| T-shirt | Mean<br>SD | 195.2<br>0.7 | 0.55<br>0.02 | 0.52<br>0.04 | 1164<br>61 |
| Shirt | Mean<br>SD | 198.3<br>1.3 | 0.94<br>0.03 | 0.61<br>0.04 | 1002<br>28 |
| Trousers | Mean<br>SD | 211.3<br>2.3 | 0.4<br>0.00 | 0.58<br>0.08 | 1263<br>58 |
| New Uniform | | | | | |
| T-shirt (Long and short sleeve) | Mean<br>SD | 193.1<br>1.9 | 0.66<br>0.01 | 0.82<br>0.06 | 1165<br>13 |
| Shirt | Mean<br>SD | 150.4<br>1.0 | 0.32<br>0.00 | 0.83<br>0.10 | 1176<br>34 |
| Trousers | Mean<br>SD | 187.7<br>0.7 | 0.46<br>0.02 | 0.73<br>0.05 | 1242<br>23 |

Table 4.2 Physical properties of the existing uniform and the new uniform

### 4.2.2 Experimental protocol

In the morning or afternoon sessions of the wear trials, participants were asked to refrain from taking exercise, alcohol, caffeine, and tobacco during the previous 24 hours. The participants arrived at the laboratory at 09:30 or 14:30 h. At the midnight of the evening prior to each trial, the firefighter ingests an ingestible temperature sensor in order to facilitate the transit of the pill into the gastrointestinal tract (Kolka, 1997). Each firefighter ingests 5 ml kg/body mass of water prior to arriving to reduce the likelihood of dehydration prior to exercise. The randomized trials are conducted at least 1 week apart. All trials are conducted at the same time of the day to avoid the circadian variation in internal body temperature (Reilly, 1986).

The firefighters are conditioned for 30mins in an environmental chamber controlled at 30 °C and relative humidity 75 % ± 2%. The nude body mass with underwear is measured using an electronic scale (Seca 704, Germany). The detailed method to attach the following equipment has been mentioned in Chapter 3.

- temperature and humidity sensors on chest and back,
- heart rate chest strap
- core temperature data logger

The experimental procedure and the task of each subject is as follows

i. put on the firefighter uniform
ii. body mass is measured again
iii. drink a controlled amount of water (5 ml per kg body mass) at 19°C
iv. first rest for 10 minutes
v. put on their PPE and SCBA
vi. start the first 20-min bout of walking at a treadmill speed of 5 km $h^{-1}$ and gradient of 7.5% (Graveling, 1999)
vii. body mass with a full set of protective clothing and nude body is measured.
viii. remove PPE and SCBA
ix. middle rest for 15 minutes, and drink a controlled amount of water (5 ml $kg^{-1}$ body mass) stored at 19°C.
x. don their PPE and SCBA
xi. start the second 20-min bout of treadmill walking at the same intensity and duration as the first bout (speed of 5 km $h^{-1}$ and gradient of 7.5%)
xii. body mass with a full set of protective clothing and nude body is measured.
xiii. remove their PPE and SCBA
xiv. final rest in 3 sessions each of 10 minutes.

The detailed protocol is shown in Fig. 4.2. The subjects don PPE during all walking sessions and remove PPE in all resting sessions. The loss in body mass corrected for fluid intake is taken to determine the fluid loss of subjects in the experiment.

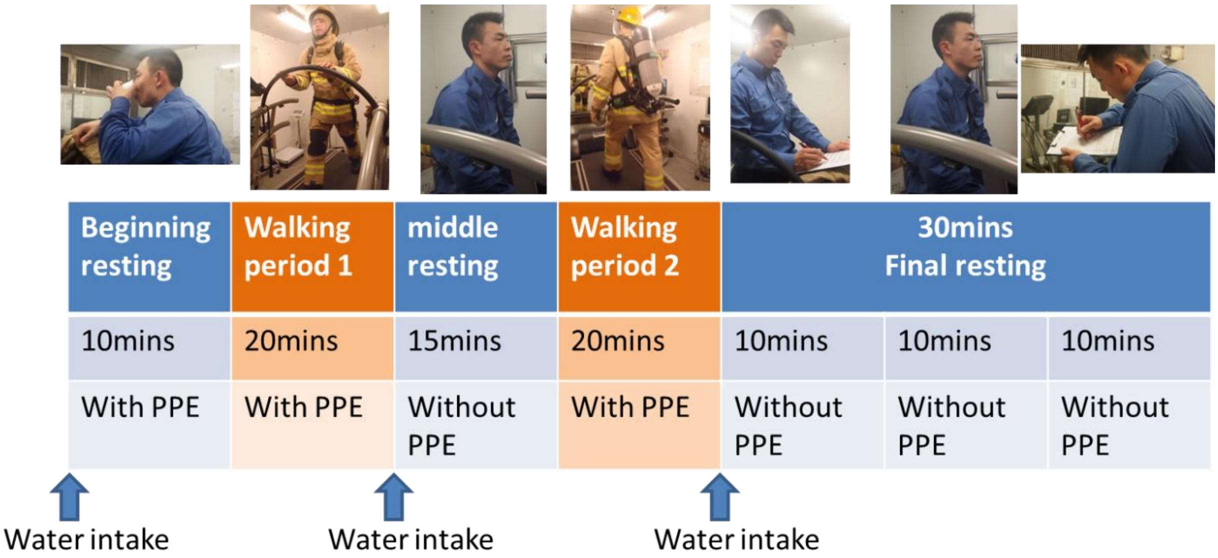



Fig. 4.2 Experimental protocol of wear trial

4.2.3 Sample size of human subjects

The sample size was calculated based on the results of Webborn et al. (Webborn, 2005) who examined the effects of two cooling strategies on the thermoregulatory responses of tetraplegic athletes during repeated intermittent exercise in the heat and found that the difference (δ) in core temperature is approximately 0.8°C and standard deviation (σ) is around 0.45°C (Webborn, 2005). As the probability of falsely rejecting a true null hypothesis ($\alpha$) = 0.05 and the probability of failing to reject a false null hypothesis (β) = 0.80. So, $\mu_\alpha$ is 1.65 with a probable error p<0.05 and $\mu_b$ is 1.28 with a statistical power of 90% respectively. The sample size (*N*) can be estimated by Equation 4.1.

$$\mathrm{N} = 2[\frac{(\mu_\alpha+\mu_\beta)\sigma}{\delta}]^2 \qquad \text{(Equation 4.1)}$$

$$\mathrm{N} = 2[\frac{(1.65 + 1.28) * 0.45}{37.3 - 36.5}]^2 = 5.43$$

It is revealed that 6 participants will achieve a result with a probable error of <5% and a statistical power of 90%. In case of the possible drop out, the sample size was increased to 12 in this study.

4.3 Results

This section compares the effects of uniform sets on the physiological responses in terms of PSI (calculated from heart rate and core temperature) and microclimate TEE (calculated from temperature and relative humidity).

4.3.1 PSI

According to Fig. 4.3, the results and possible reasons are listed in Table 4.3.

| Phase | Result | Possible reasons |
|---|---|---|
| a) rest - walk | PSI rose for a range between 2.06 and 2.63 | The metabolic rate increased during walking. |
| b) walk - rest | PSI did not decrease except Set 5 | Sweat on extra forearm area was absorbed by long-sleeve moisture managed T-shirt. More sweat absorbed and evaporated from the skin. Heat release increased during resting. |
| c) rest - walk | PSI further increased by a rate similar to Phase 1, but PSI of Set 5 increased faster than Sets 2 to 4. | The increase of metabolic rate remains similar during the same walking speed. The clothing becomes a key factor of PSI change. Set 5 was saturated with sweat, and the high cover ratio of long sleeves reduced the heat release from subjects. |
| d) walk - rest | PSI did not decrease, except Set 4 in the first 10-min rest, but sharply decreased in the 2nd 10-min rest. | The regulation of core temperature and heart rate needs time to accommodate the rest condition. Therefore, the effect of uniforms should be examined after the first 10-minute final resting without PPE. |
| e-f) final resting | The PSI was the highest in Set 1, and the lowest in Set 4. | PSI is affected by $T_{core}$ and HR of the human body. The moisture-managed fabric increased the heat and sweat evaporated from body skin. Moreover, Set 1 uniform had two layers clothing (shirt and T-shirt) that made heat release more difficult. |

Table 4.3 Results of the mean PSI

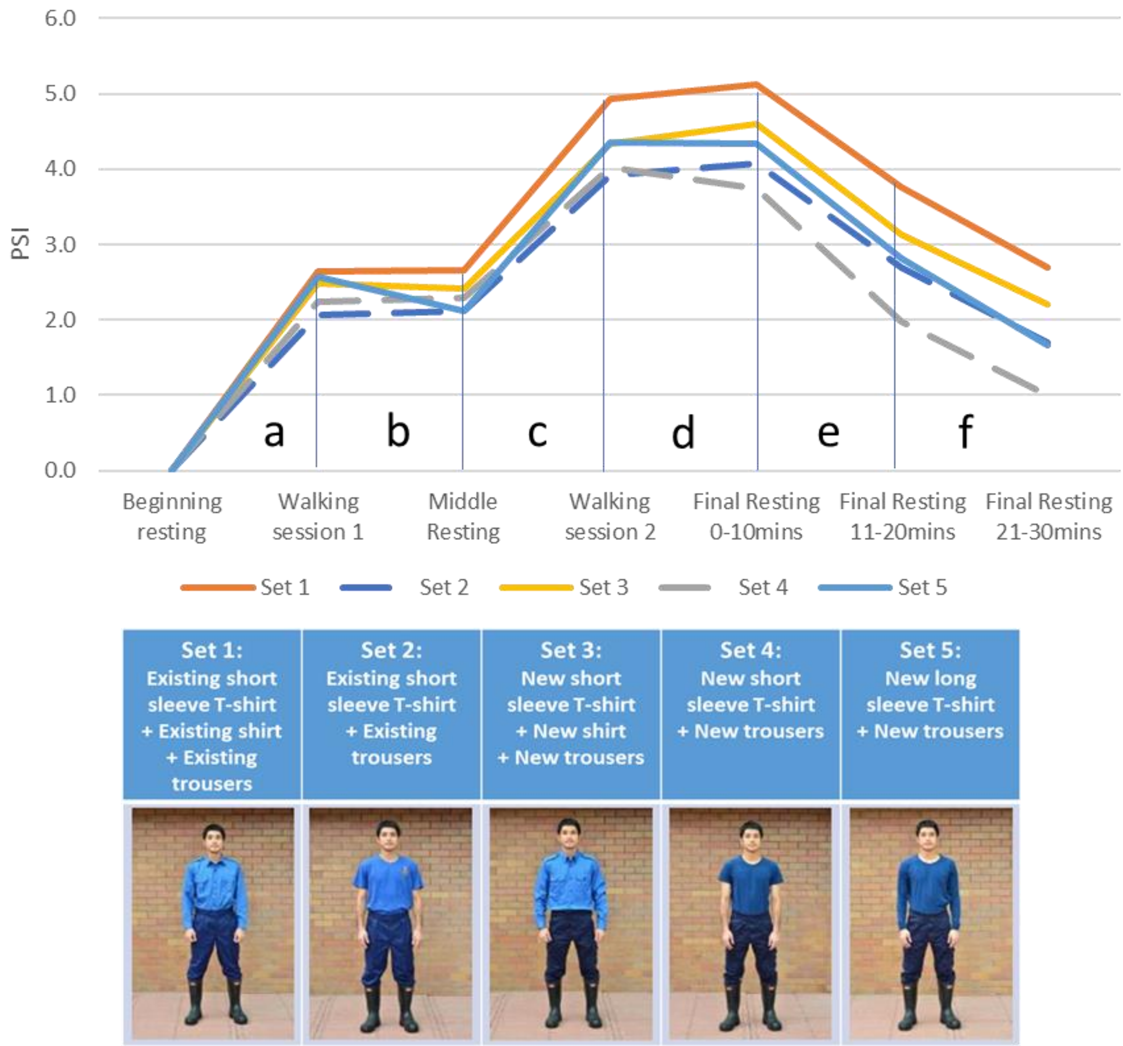



Fig. 4.3 Mean PSI in 5 sets of uniform in all activities

According to Fig. 4.4, the results and possible reasons are listed in Table 4.4.

| Phase | Result | Possible reasons |
|---|---|---|
| All | $T_{core}$ increased continuously until final resting. | Body thermoregulatory system takes time to reduce $T_{core}$ to the normal state. |
| All | $T_{core}$ when wearing Set 3 was initially the lowest. | Moisture-managed fabric provides a portable environment condition with lower $T_{core}$ by evaporating sweat and heat effectively. |
| a) rest - walk | $T_{core}$ rose to about 0.2°C | $T_{core}$ increased due to the increase of metabolism during walking with uniform in 30°C and 75% RH |
| b) walk - rest | $T_{core}$ kept rising for 0.5 to 0.7°C | Body organs takes time to increase $T_{core}$ Therefore, the increase of $T_{core}$ in resting period was higher than that at the beginning. |
| c) rest - walk | Sets 2 & 4 kept $T_{core}$ unchanged, but $T_{core}$ in other sets continued to rise. | Short-sleeve T-shirts have the less covered area, so allow more heat release to reduce $T_{core}$. |
| d) walk - rest | $T_{core}$ increased to 0.5 °C in Set 2 but only 0.25 °C in Set 4. | The moisture-managed fabric of Set 4 allows easier heat release from the body due to better absorption of sweat. |
| e) final rest | Set 4 reduced to 0.6°C, but Set 1 reduced to 0.3°C. | Short-sleeve T-shirt made of moisture-managed fabric can speed up the reduction of $T_{core}$. |

Table 4.4 Results of the mean core temperature

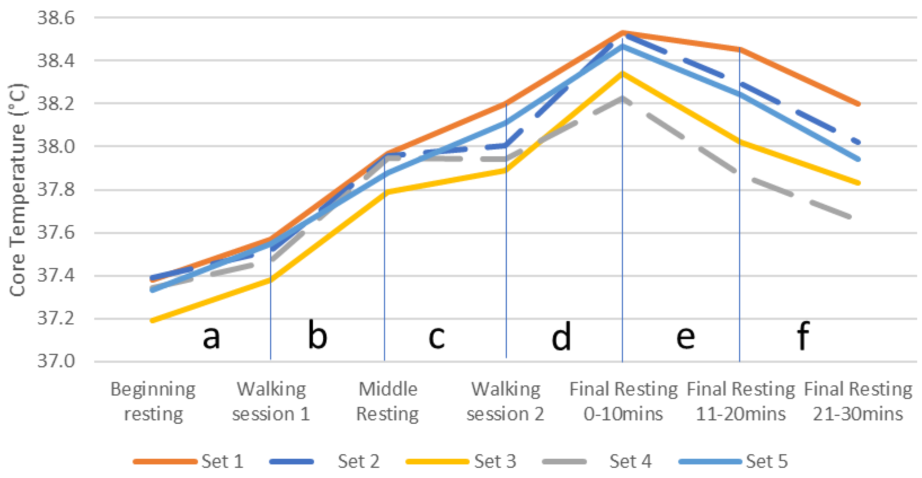



Fig. 4.4 Mean $T_{core}$ in 5 sets of uniform in all activity sessions

According to Fig. 4.5, the results and possible reasons are listed in Table 4.5.

| Phase | Result | Possible reasons |
|---|---|---|
| All | HR is a more sensitive response to the activities than $T_{core}$.<br>HR decreased for 13-18% during resting and increased for 29-37% during walking. | The blood circulatory system responsively regulates the heart rate. For $T_{core}$, more time is required for the skin to release heat. |
| All | HR in Set 1 was the highest. | Set 1 has two layers of clothing of conventional fabric. |
| b)<br>walk – rest | All HR decreased with similar rate except that Set 5 decreased faster | Metabolism of resting is lower than walking so the mean HR decreased. Long sleeves allow more sweat absorption, comfort from drier feeling let the HR of firefighter decrease (Taelman, 2008) (Huang, 2013) |
| d) walk - rest | HR in Set 1 decreased the least | Two layers of clothing without moisture management increase the fatigue of body, so HR kept high. |
| e) final rest | HR in Sets 2 and 4 were lower than the others. | Short sleeve uniforms expose the forearm, so allow more heat release. |

Table 4.5 Results of the mean HR

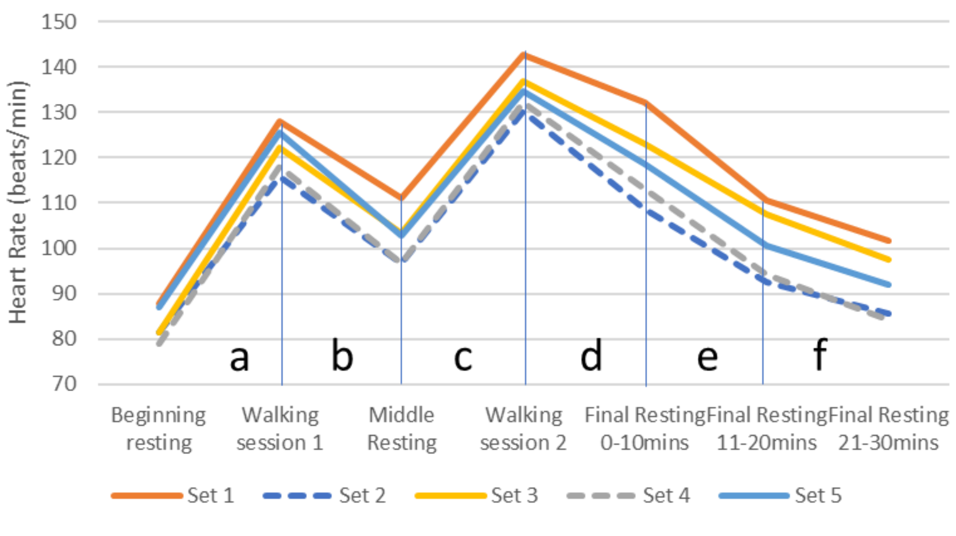



Fig. 4.5 Mean HR with 5 sets of uniform in all activity sessions

4.3.2 $TEE_{cmc}$

According to Fig. 4.6, the results and possible reasons are listed in Table 4.6

| Phase | Result | Possible reasons |
|---|---|---|
| All | $TEE_{cmc}$ was mainly affected by $T_{cmc}$ and $RH_{cmc}$ | Since the mean $RH_{cmc}$ was nearly 99% in all phases, $TEE_{cmc}$ was mainly dependent on $T_{cmc}$. |
| b) walk - rest | In middle resting, $TEE_{cmc}$ decreased with all sets of uniform except set 1. | Heat released during resting period but heat release from set 1 was hard due to two layers and lower moisture management properties |
| b) walk – rest | Set 2 decreased more core temperature, that was 1.11°C, from walking session 1 to middle resting. Set 1 decreased 0.52°C. It is relatively low compared to 0.89°C for Set 2, for Set 4 and 0.99°C for Set 5. | Moisture managed fabric with short sleeve provides better performance in relieving thermal stress. |
| c) rest - walk | In walking session 2, Set 1 was still the highest $TEE_{cmc}$. Other four sets of uniform increased with similar value and slope (rate). | During walking with PPE, the difference between 4 sets of uniform was not obvious. |
| e & f) final rest | The value and the slope of Set 2, 4 & 5 in final resting were similar | The impact of Set 5 with long sleeve was similar to short sleeve uniforms<br>The heat release from sweat absorbed by moisture managed fabric > heat directly release from body to uncovered forearm skin |

Table 4.6 Results of the $TEE_{cmc}$

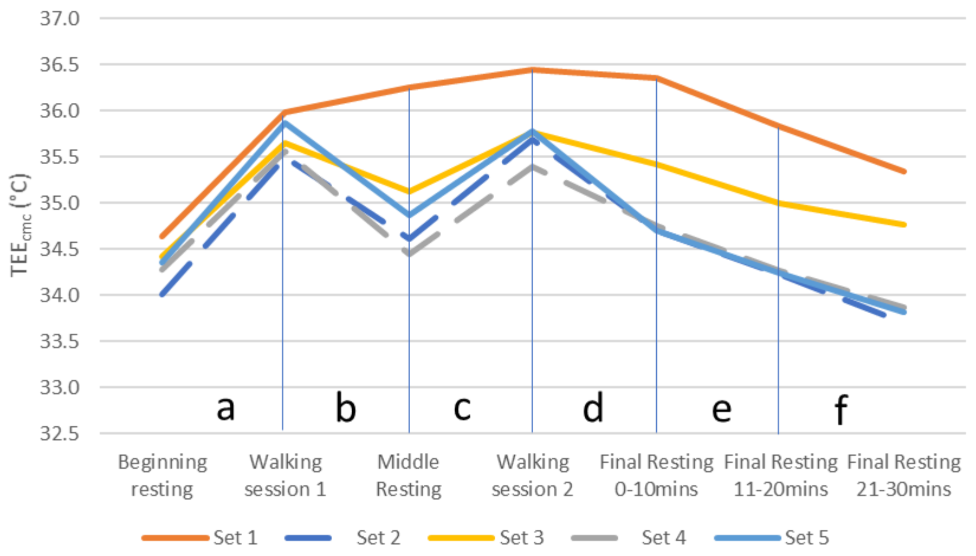



Fig. 4.6 Mean $TEE_{cmc}$ with 5 sets of uniform in all activity sessions

According to Fig. 4.7, the results and possible reasons are listed in Table 4.7

| Phase | Result | Possible reasons |
|---|---|---|
| All | The $RH_{cmc}$ of five sets of uniform was about the maximum relative humidity - 99% | Swearing from the beginning of the experiment. 30°C and 75% controlled chamber condition<br>At the beginning, subjects were started to perspire and the evaporation of sweat inside portable environment between skin and uniform was started to absorb by uniform fabric. |

Table 4.7 Results of the $RH_{cmc}$

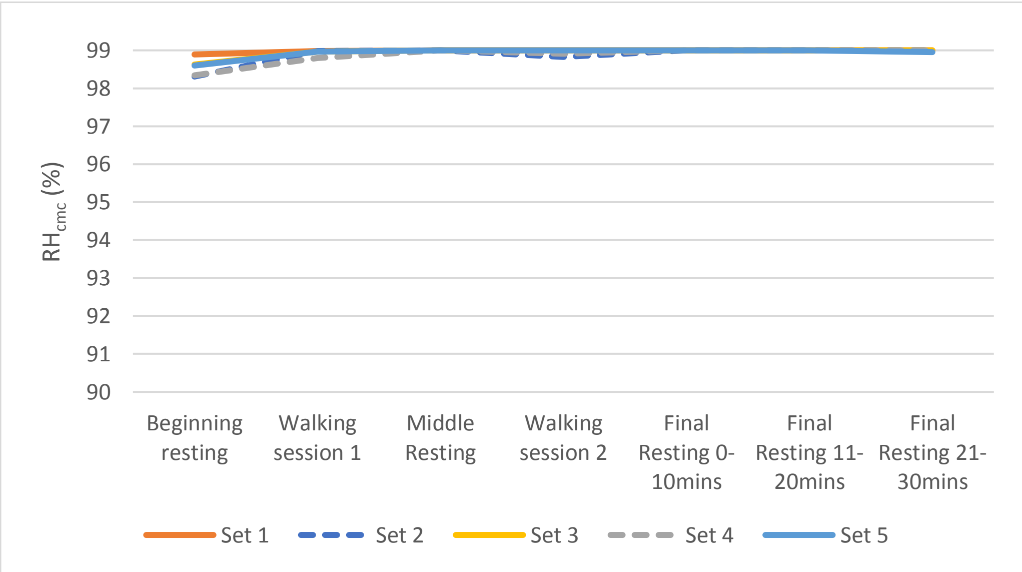



Fig. 4.7 Mean $RH_{cmc}$ with 5 sets of uniform in all activity sessions

According to Fig. 4.8, the results and possible reasons are listed in Table 4.8

| Phase | Result | Possible reasons |
|---|---|---|
| All | The $RH_{cmc}$ of all sets were similar (nearly the same), $TEE_{cmc}$ was mainly affected by $T_{cmc}$. | Sweat started from the beginning of the experiment. The 30°C and 70% chamber condition was simulated Hong Kong summer weather. |
| b) walk - rest | Set 5 decreased the largest amount in middle resting and first part of final resting | The long sleeve of set 5 was higher heat accumulated during walking sessions with PPE. After taking off the PPE, the high rate of sweat evaporated from moisture managed fabric provided largest amount of $T_{cmc}$ decreased |
| e & f) final rest | The value and the slope of Set 2, 4 & 5 in final resting are similar | The heat release from sweat absorbed by moisture managed fabric of set 5 > heat directly release from body to uncovered forearm skin |

Table 4.8 Results of the $T_{cmc}$

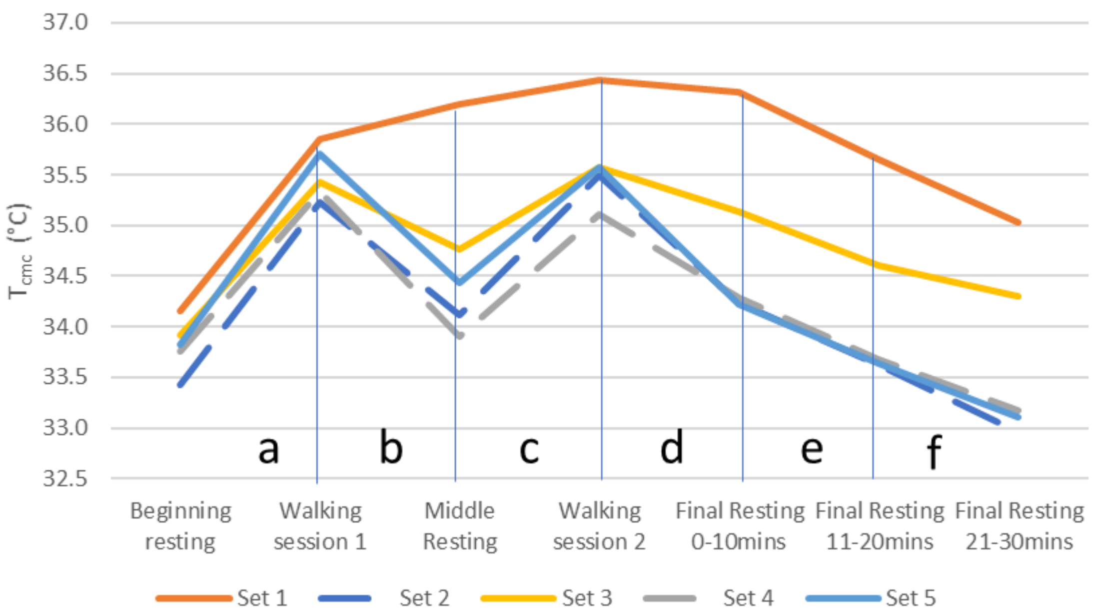



Fig. 4.8 Mean $T_{cmc}$ with 5 sets of uniform in all activity sessions

4.3.3 PSI

In Fig. 4.9, the mean PSI of 5 sets uniform in all sessions, including walking and resting, was shown. The PSI order was Set 1 > Set 3 > Set 5 > Set 4 > Set 2. Set 1 was the highest PSI in five sets of uniform. Unexpectedly, the lowest PS uniform was Set 2. Set 2 was better performance than moisture managed uniform Set 4 for thermal stress.

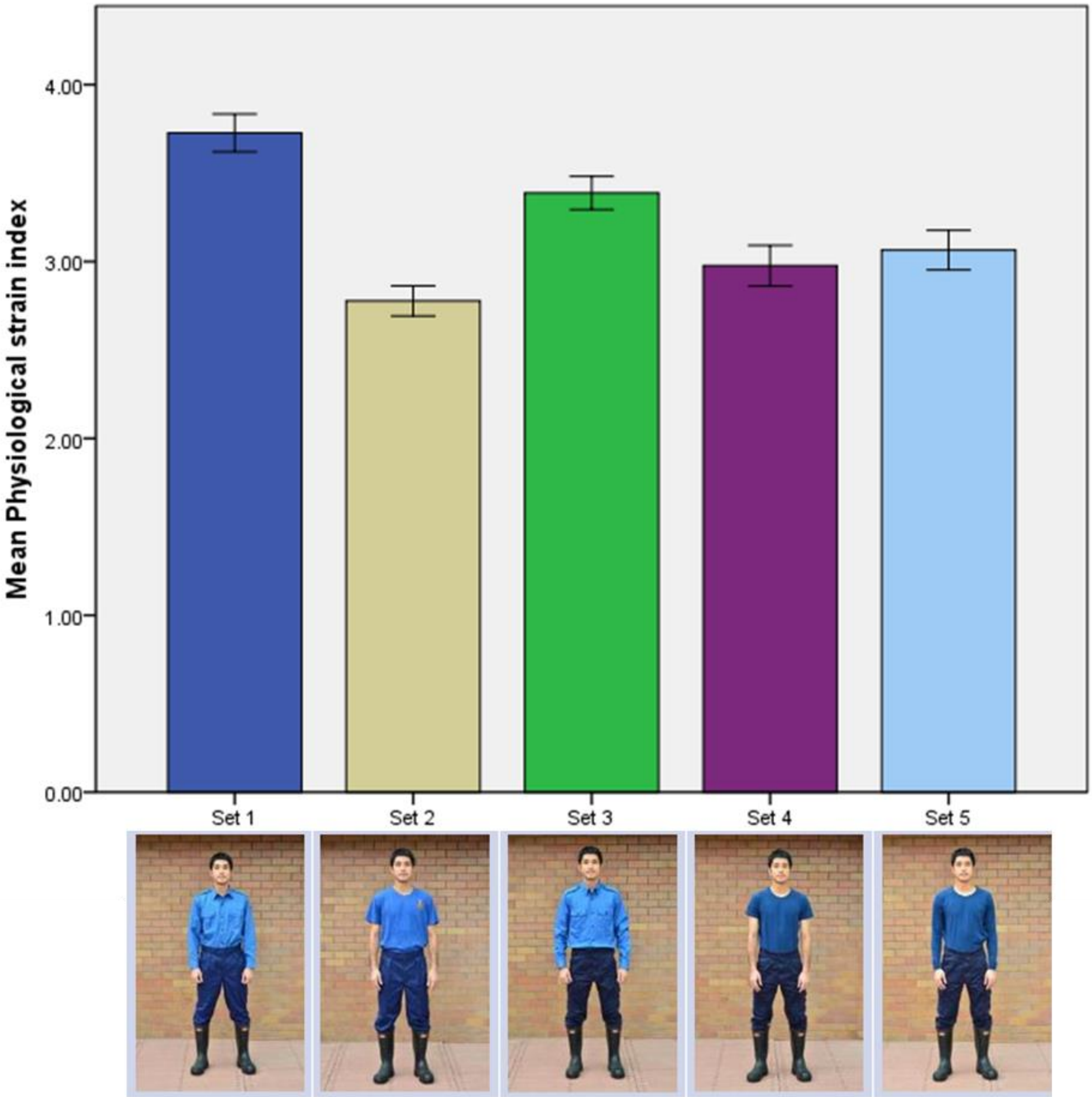



Fig. 4.9 Comparison of Mean PSI of 5 sets uniform in all sessions

In Fig. 4.10, the mean PSI of 5 sets uniform in all walking sessions. Set 2 was obviously lower than Set 4 that was equivalent to mean PSI in all sessions showed in Fig 4. 10. Set 3, 4 and 5 were similar. During walking sessions, firefighters were worn PPE that high insulation impeded heat release and moisture evaporated. The sweat was accumulated inside the portable environment created. The sweat was absorbed by T-shirt, shirt, and trousers. Thickness of T-shirt and trousers (0.55mm + 0.4mm) in Set 2 was thinner than T-shirt (0.66mm + 0.46mm) in Set 4. The total thickness of Set 1 (T-shirt + Shirt + trousers) was 1.89mm and that of Set 3 was 1.44mm. The thickness order was Set 1 > Set 3 > Set 4 > Set 2. It is the same as the mean PSI order. It showed that thinner fabric provided better thermal stress performance to firefighters in the experiment.

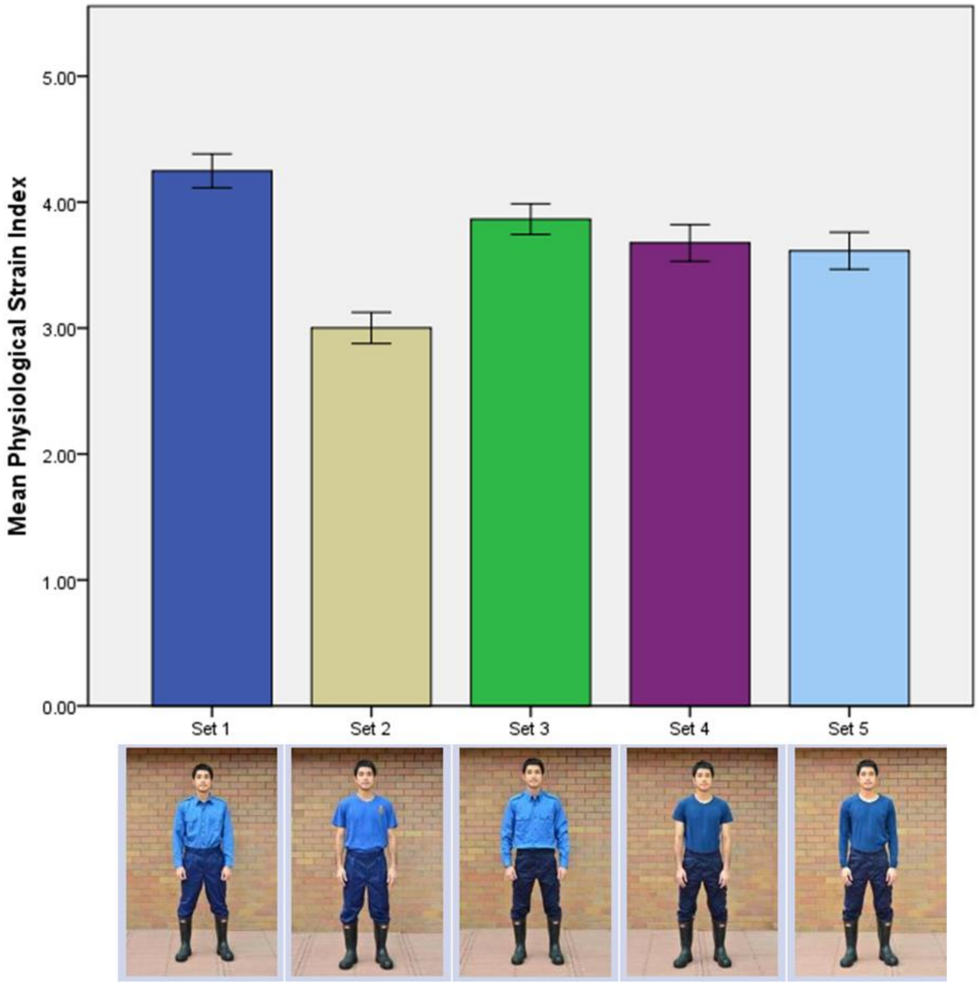



Fig. 4.10 Comparison of Mean PSI of 5 sets uniform in all walking sessions

In Fig. 4.11, it showed the mean PSI of 5 sets uniform in all resting sessions. PPE was taken off. The impact of high insulation from PPE was eliminated. The result showed single layer moisture managed T-shirt was lower mean PSI than existing T-shirt. Moisture managed uniform Set 3 was lower mean PSI than existing uniform Set 1. Single layer long sleeve uniform Set 5 was lower than double layers uniform and higher than single layer short sleeve T-shirt. In concluded, moisture managed fabric performed better and provided a lower mean PSI of firefighters, but the two layers fabric gave a higher mean PSI.

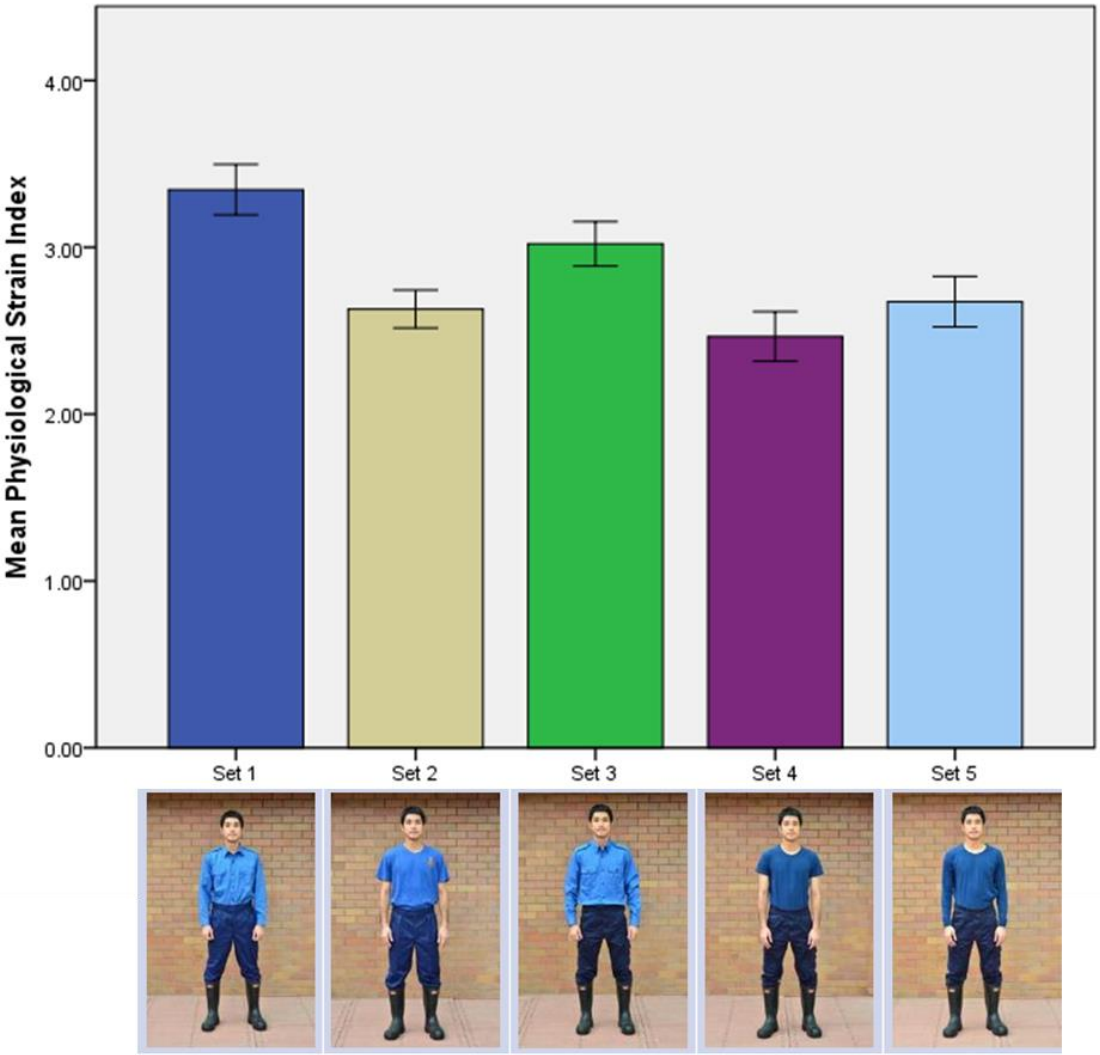



Fig. 4.11 Comparison of Mean PSI of 5 sets uniform in all resting sessions

4.3.4 Impact of Fabric with moisture managed fabric

Fig. 4.12 showed the mean PSI between Set 1 and Set 3 in different activities. The mean PSI of existing uniform Set 1 was higher than moisture managed Set 3 in every activity session.

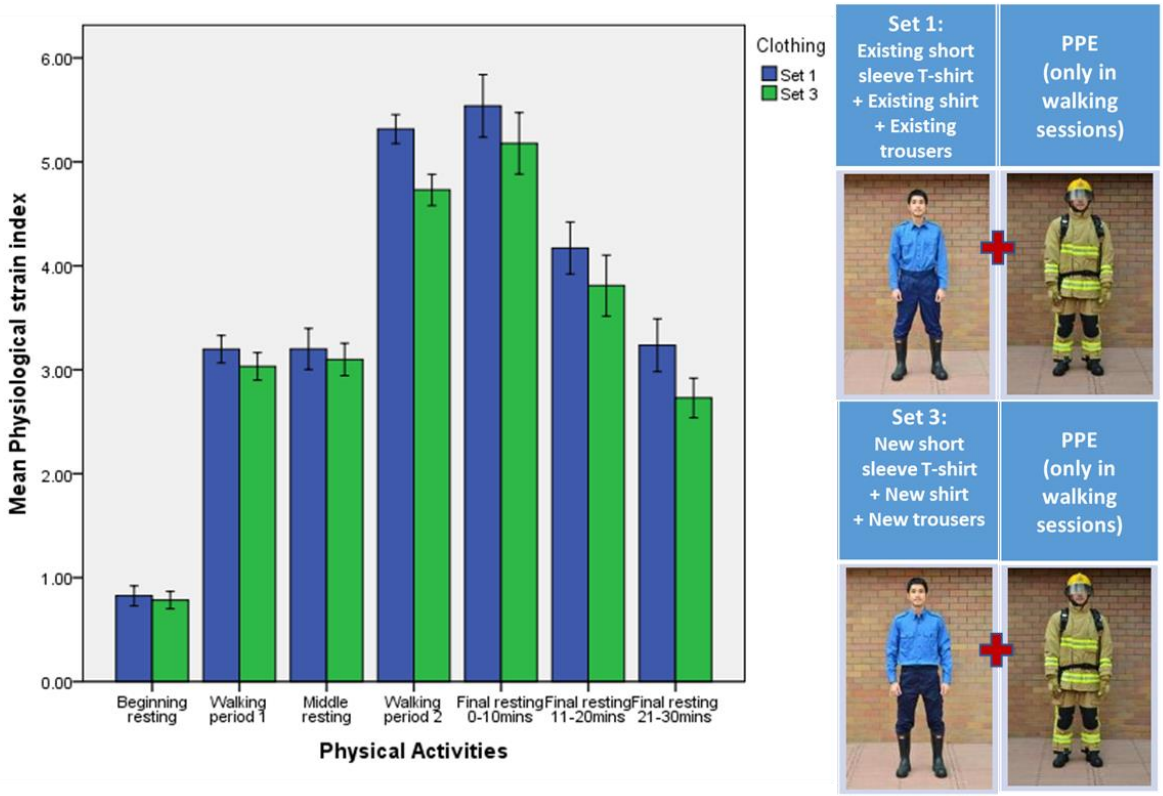



Fig. 4.12 The mean PSI between Set 1 and Set 3 in different activities

Fig. 4.13 shows the mean PSI between Set 2 and Set 4 in walking sessions that firefighters wore their PPE. The same case as Fig. 4.11 and mentioned before. The thickness of T-shirt and trousers had significant impacts when wearing PPE with high heat insulation. In walking period, the effect to thermal stress from fabric thickness was greater than moisture management properties.

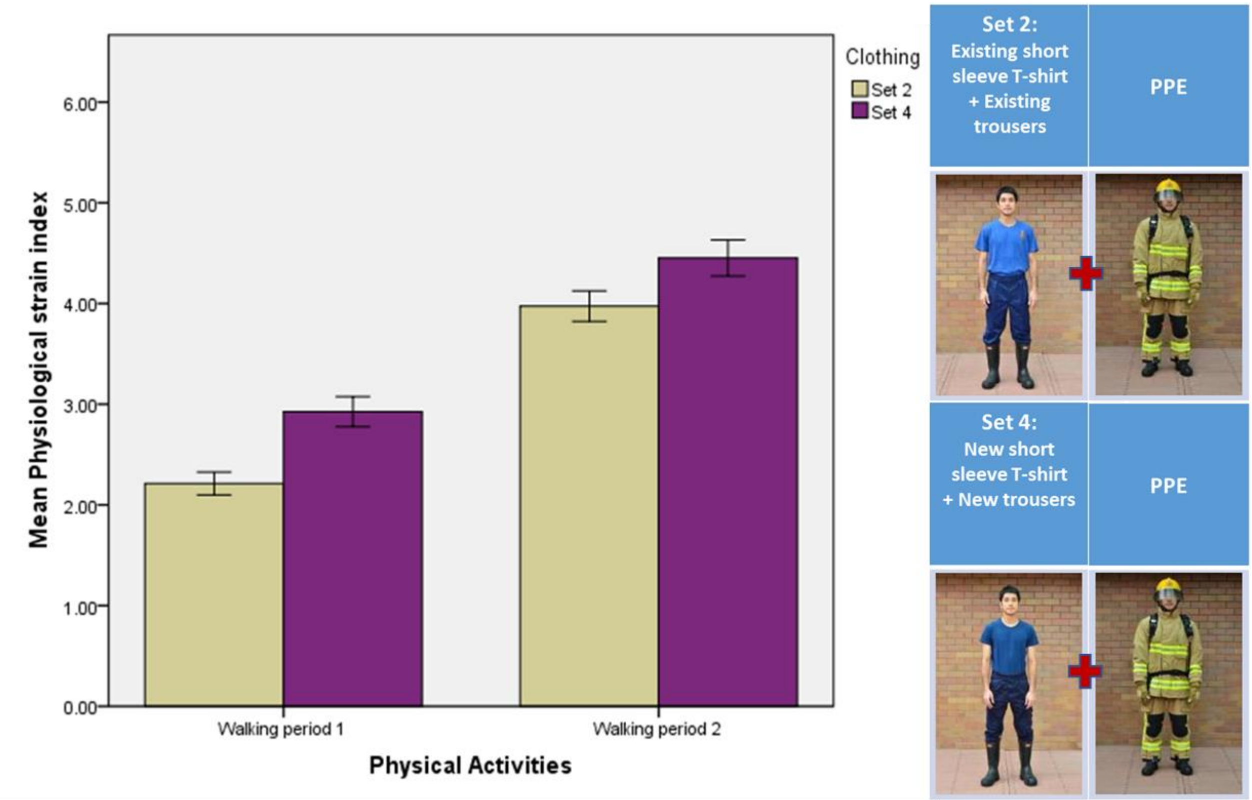



Fig. 4.13 Comparison of Mean PSI between Set 2 and Set 4 in walking sessions

Fig. 4.14 shows the mean PSI between Set 2 and Set 4 in resting sessions that firefighters were taken off their PPE. Set 2 was lower mean PSI than Set 4 in briefing resting and middle resting. In Final resting, Set 4 was lower mean PSI and performed better thermal stress. In briefing resting and middle resting, the impact of uniform thickness was greater than moisture management properties since the sweat amount was little in beginning resting and resting time was limited during middle resting. Therefore, longer time should be provided to show the benefit from moisture managed fabric.

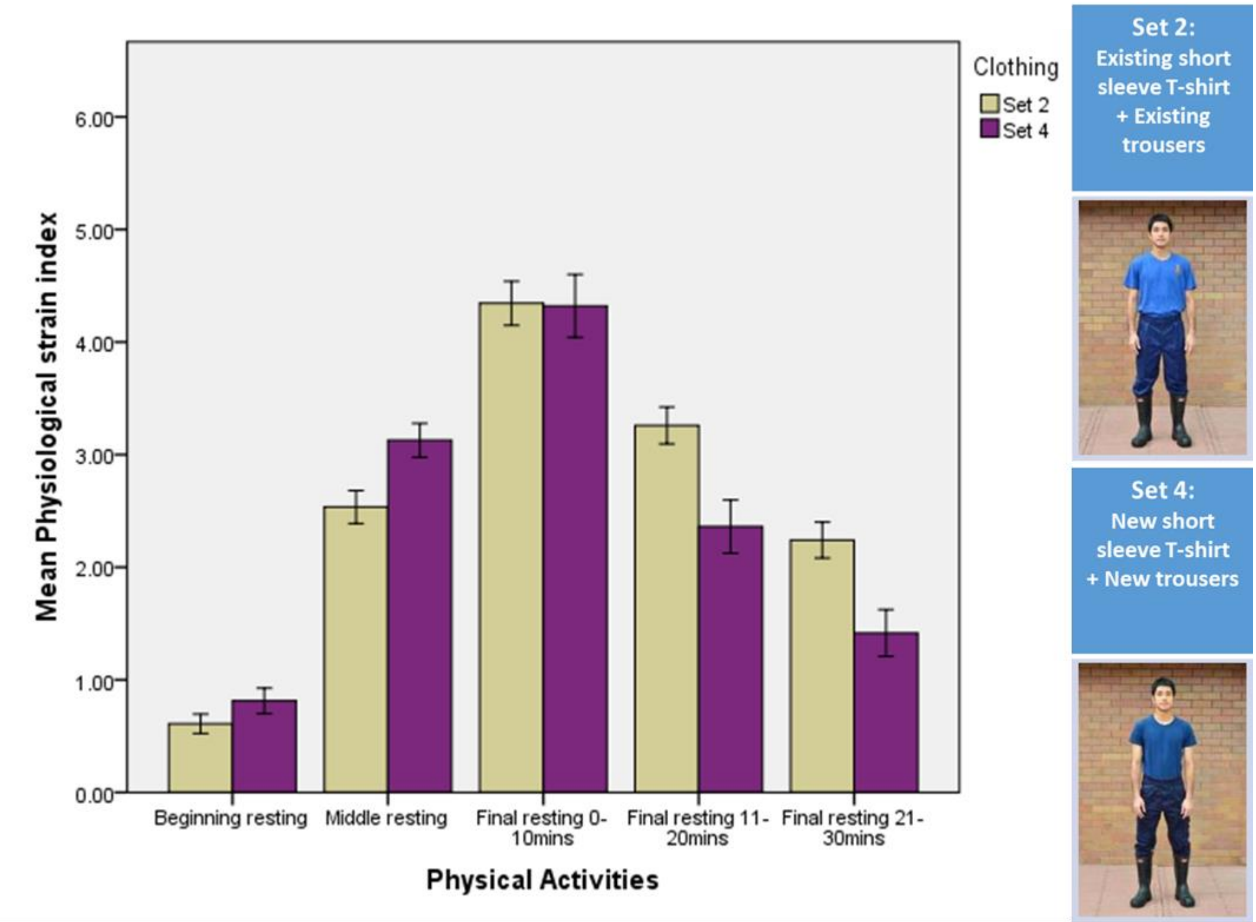



Fig. 4.14 Comparison of Mean PSI between Set 2 and Set 4 in resting sessions

4.3.5 Impact of uniform with long or short sleeve

Fig. 4.15 showed mean PSI between Set 4 and Set 5 in 2 parts of walking sessions. Short sleeve T-shirt Set 4 and long sleeve T-shirt Set 5 were made of the same moisture managed fabric and with the same trousers. The PSI was similar during the walking session. The impact of long sleeve T-shirt inside highly insulated PPE was not obvious.

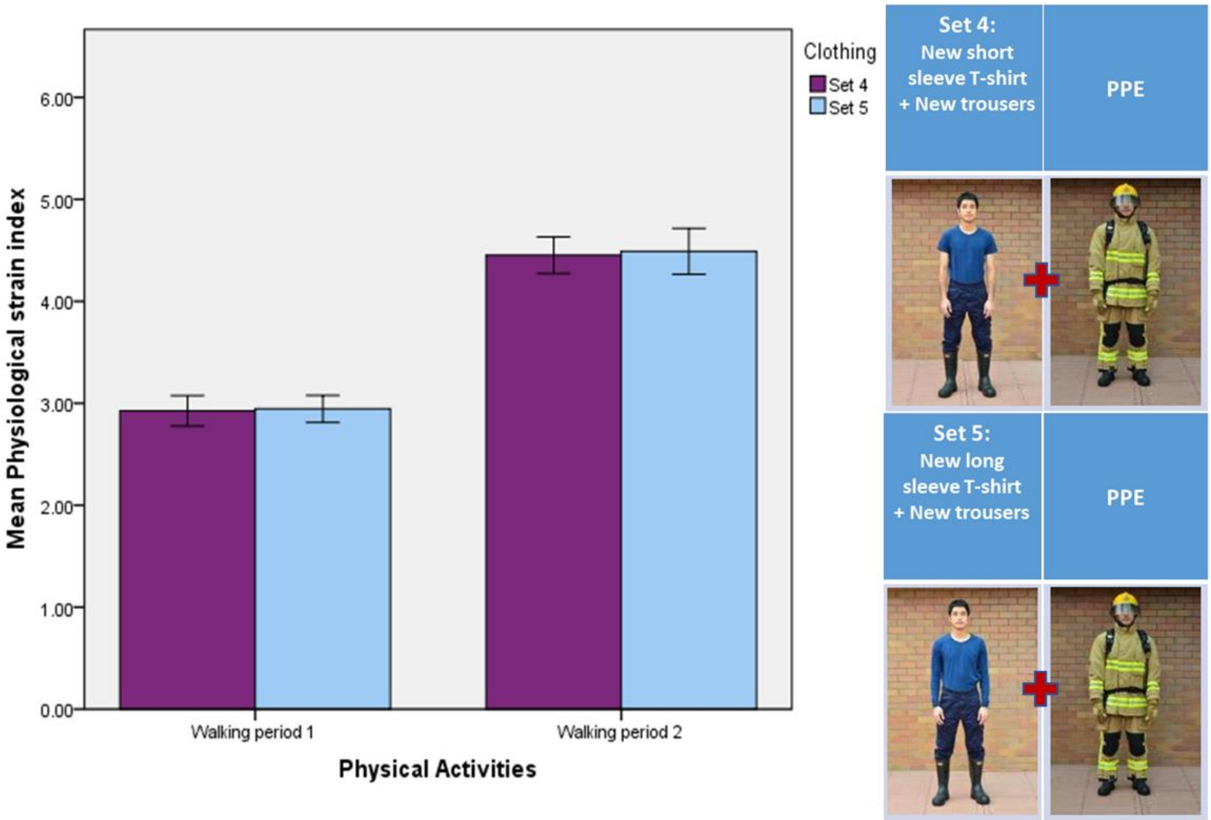



Fig. 4.15 Comparison of Mean PSI between Set 4 and Set 5 in walking sessions

Fig. 4.16 showed mean PSI between Set 4 and Set 5 in resting session. Set 4 showed the lower mean PSI in 3 parts of final resting. In beginning resting, PSI of Set 4 and Set 5 was similar. In middle resting, uniform set 5 was surprisingly lower mean PSI than Set 4. since long sleeve provided more cover ratio to the firefighters, it was able to absorb more sweat release from the body after walking session. At the start of final resting After walking session 2, the high volume of sweat was accumulated inside fabric. The rate of sweat evaporation from fabric was not fast enough. Therefore, long sleeve T-shirt with higher cover ratio prevent the sweat evaporation and heat release that compared to the forearm can be directly contacted by the environment (Set 4 uniform). Therefore, the result showed that long sleeve T-shirt benefits the thermal stress if liquid sweat release was not too much. After the fabric was saturated with liquid sweat, short sleeve T-shirt with uncover area of forearm skin was better in thermal stress.

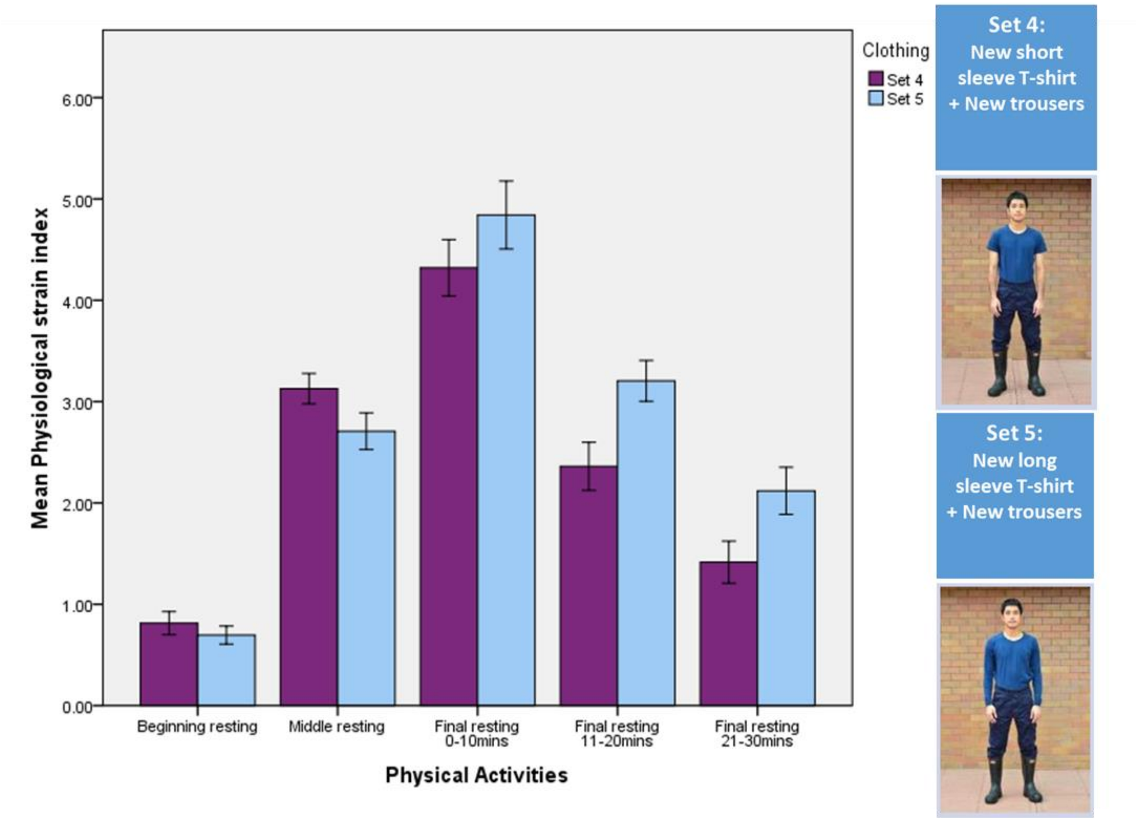



Fig. 4.16 Comparison of Mean PSI between Set 4 and Set 5 in resting sessions

4.3.6. $TEE_{cmc}$

Fig. 4.17 showed the mean $TEE_{cmc.}$ between Set 1 and Set 3 in different activities. Based on the result, Set 3 uniform was lower mean PSI than Set 1 shirt in every activity sessions. The result was the same as Fig. 4.13 that mentioned the mean PSI between Set 1 & 3.

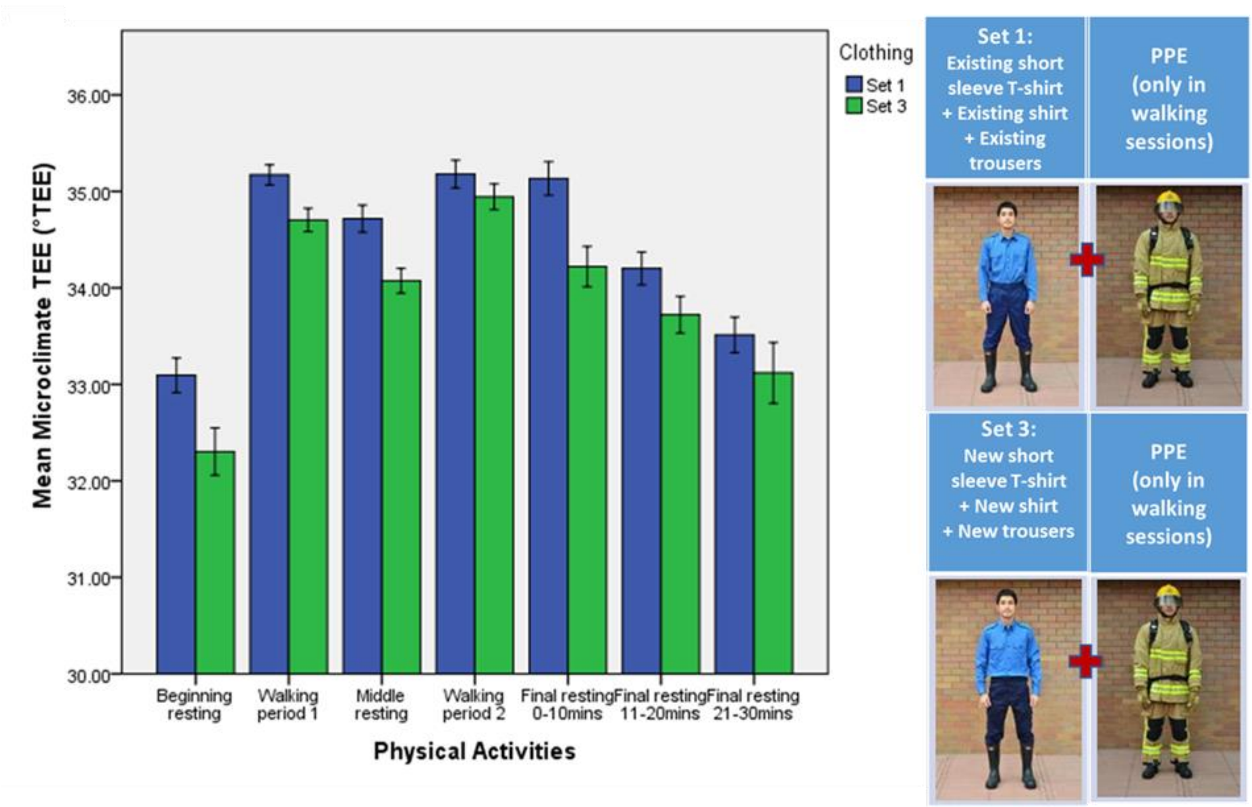



Fig. 4.17 Comparison of Mean $TEE_{cmc.}$ between Set 1 and Set 3 in every session

Fig. 4.18 showed the mean $TEE_{cmc.}$ between Set 2 and Set 4 in the walking period. During walking period, moisture managed uniform Set 4 was similar and lower value than Set 2 uniform.

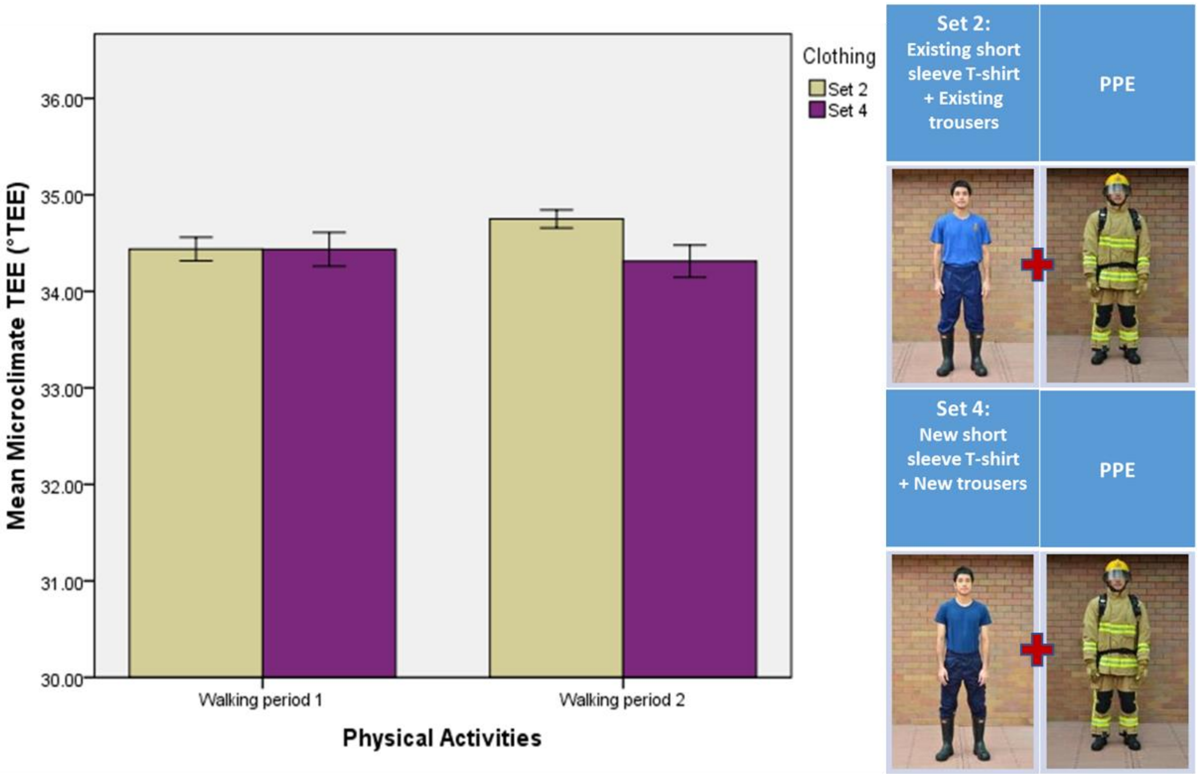



Fig. 4.18 Comparison of Mean $TEE_{cmc.}$ between Set 2 and Set 4 in walking period

Fig. 4.19 showed the mean $TEE_{cmc}$ between Set 2 and Set 4 in resting period. Based on the result, Set 4 was lower $TEE_{cmc}$ than Set 2 in middle and the final resting. It showed moisture managed uniform Set 2 benefit to heat release after walking sessions. In the 3 parts of final resting, it was obvious that the decreasing rate of $TEE_{cmc}$ in Set 4 was much faster than uniform Set 2. Moisture managed fabric is a benefit in the heat release for a firefighter.

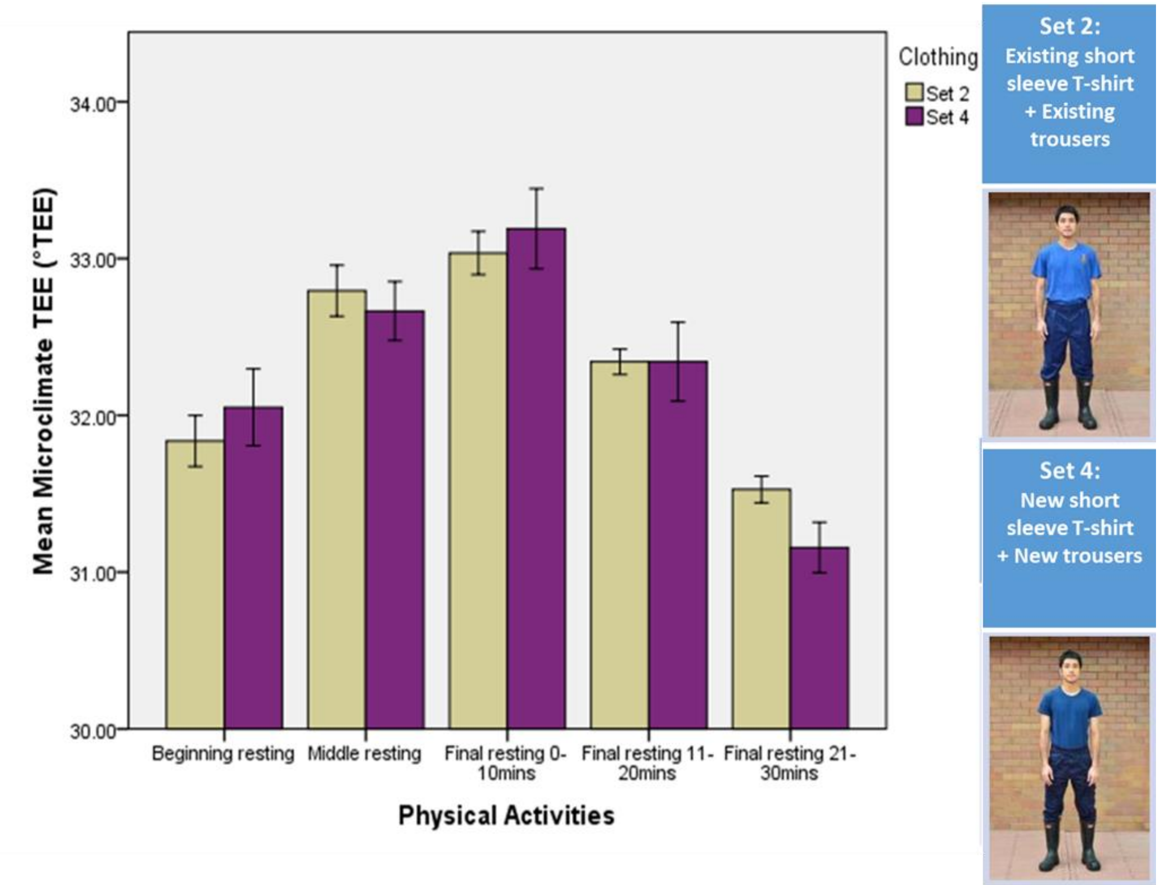



Fig. 4.19 Comparison of Mean $TEE_{cmc}$ between Set 2 and Set 4 in resting period

Fig. 4.20 and Fig. 4.21 showed the mean $TEE_{cmc}$ between short sleeve Set 4 and long sleeve uniform Set 5 in walking and resting period. Set 4 was lower $TEE_{cmc}$ than Set 5 in sessions. Thermal stress of a firefighter was lower when wearing Set 4 since lower temperature felt by firefighter body inside the portable environment created by uniform and PEE.

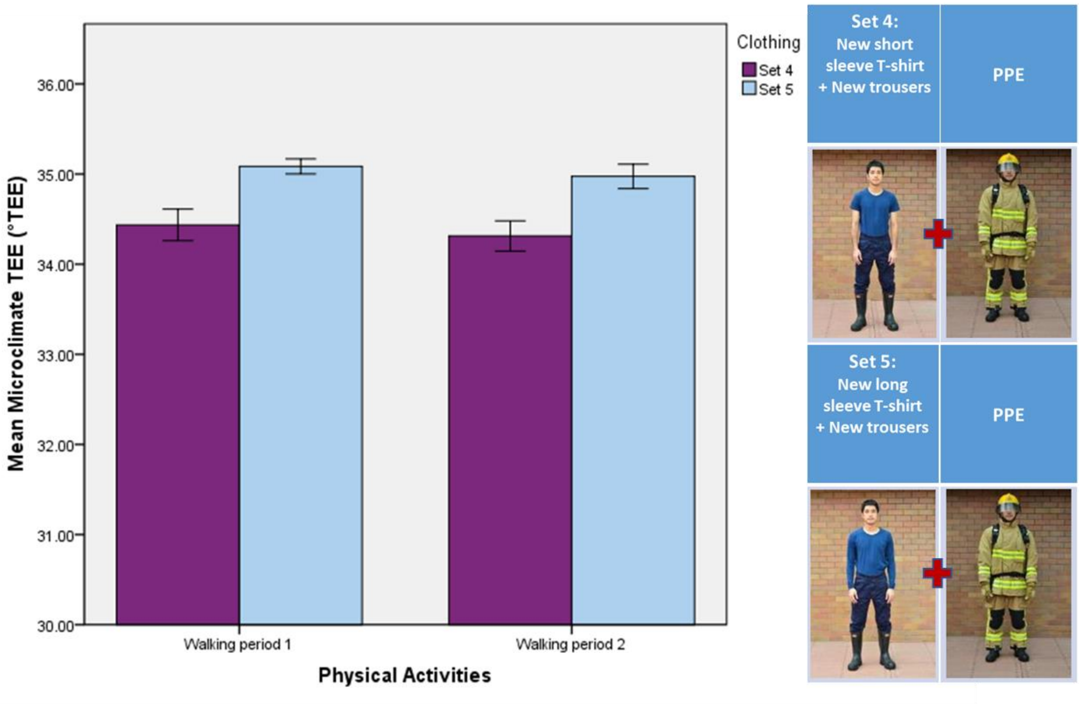



Fig. 4.20 Comparison of Mean $TEE_{cmc}$ between Set 4 and Set 5 in waking period

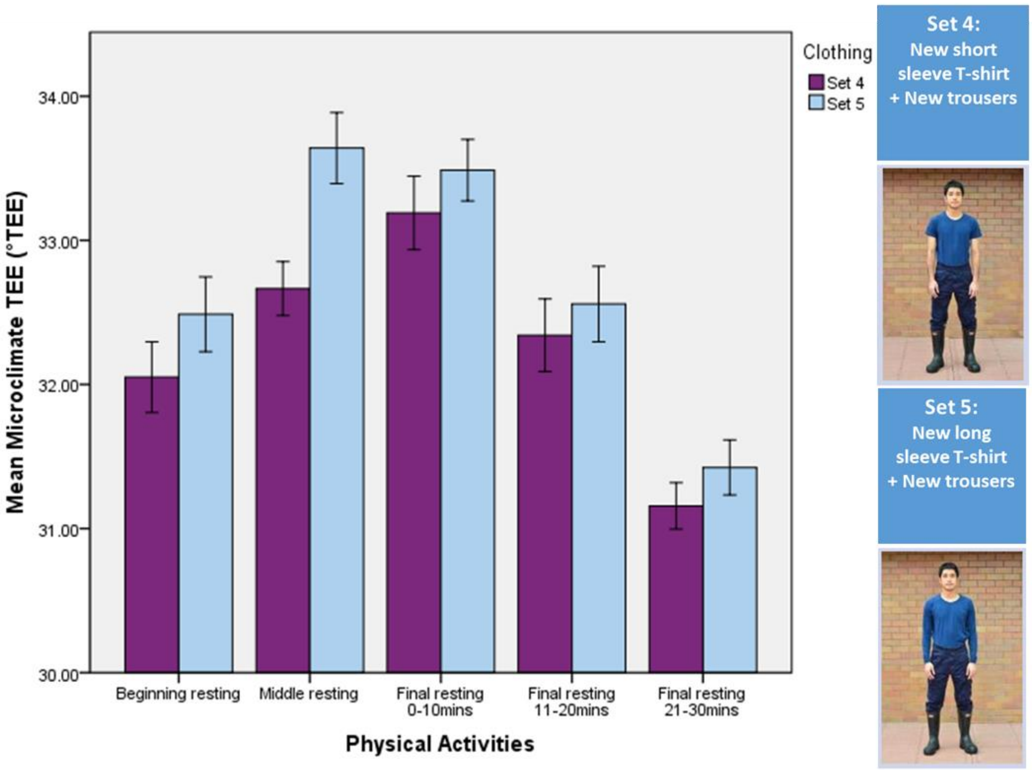



Fig. 4.21 Comparison of Mean $TEE_{cmc}$ between Set 4 and Set 5 in resting period

4.3.7 the relationship between PSI and $TEE_{cmc}$

Based on Fig. 4.22, The tread line shows the positive linear relationship ($r^2 = 0.3521$, $p < 0.05$) between the mean values of PSI and TEE are in 5 different uniforms and 6 different activities (excl. briefing) among 12 subjects in climate chamber experiment.

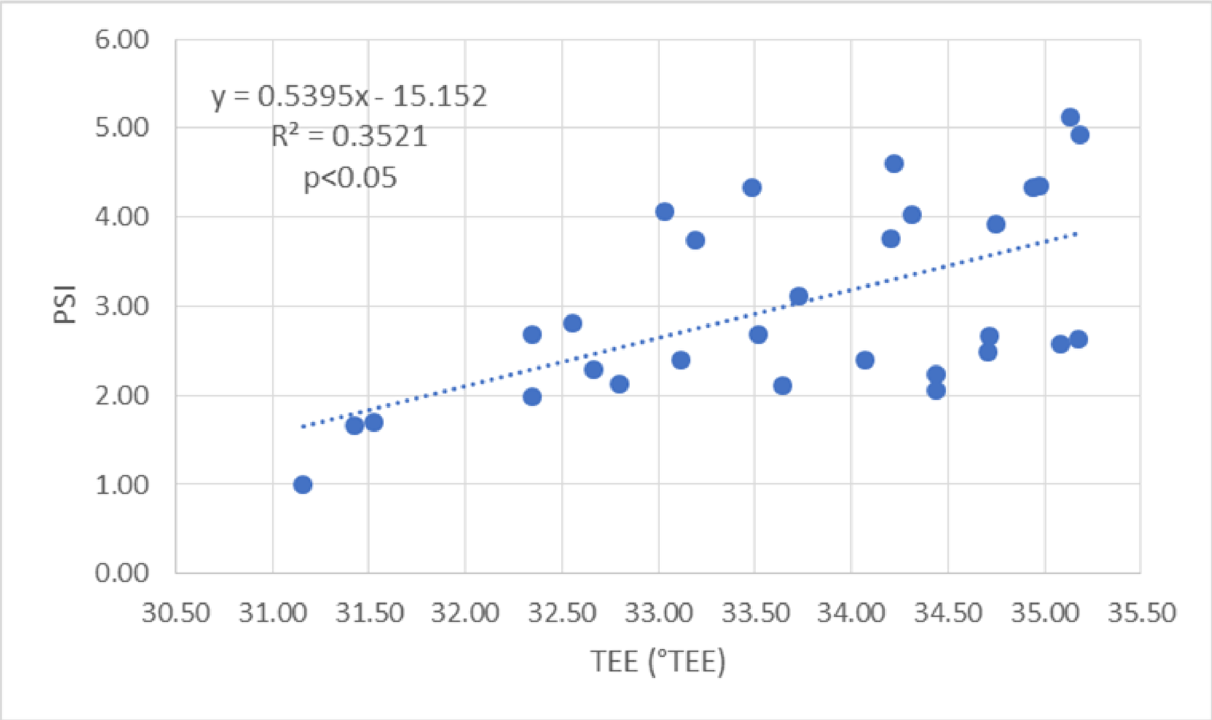



Fig. 4.22 PSI vs $TEE_{cmc}$ in climate chamber experiment

Moreover, the values of PSI corresponding to different $TEE_{cmc}$ were calculated based on the two regression equations:

In training center, $y = 0.5162x - 14.022$ and

In the controlled chamber, $y = 0.5395x – 15.152$

Where y = PSI, x = $TEE_{cmc}$.

Table 4.9 showed the PSI with different TEE in two experiments. And Fig. 4.23 showed the linear relationship between PSI and TEE based on the result in Table 4.3.

| $TEE_{cmc}$ | PSI in training center | PSI in climate chamber |
|---|---|---|
| 32 | 2.50 | 2.112 |
| 33 | 3.01 | 2.6515 |
| 34 | 3.53 | 3.191 |
| 35 | 4.05 | 3.7305 |
| 36 | 4.56 | 4.27 |
| 37 | 5.08 | 4.8095 |

Table 4.9 PSI with different TEE in two experiments

Fig. 4.23 showed that the PSI and $TEE_{cmc}$ have a linear relationship whether in training center with multiple conditions and controlled chamber with the same condition during the experiment.

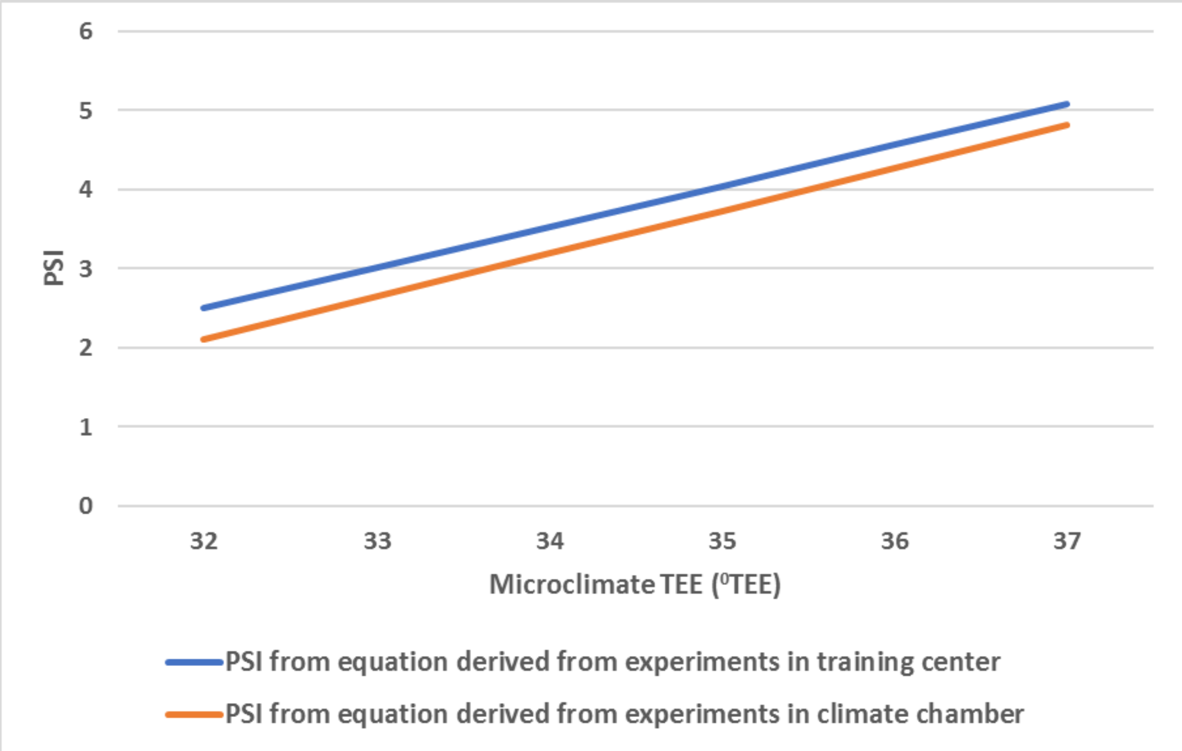



Fig. 4.23 Linear relationship between PSI and TEE in the two experiments

## 4.4 Discussion

### 4.4.1 Advantages of microclimate TEE index over PSI

The experimental results in both the firefighting training center (Chapter 3) and the climate climber showed that $TEE_{cmc}$ and PSI have a significant positive linear relationship, which implies the feasibility of applying $TEE_{cmc}$ index to supplement the PSI in the measurement of the thermal stress of firefighters.

The advantages of $TEE_{cmc}$ over the PSI are that it is simpler and easier to record $T_{cmc}$ and $RH_{cmc}$ by microclimate sensors stably attached to the skin, inside the portable environment created by highly insulated PPE.

In contrast, the PSI refers to the change of $T_{core}$ and HR. These physiological responses have other uncontrollable factors, such as psychological sensations and the fitness of the human subjects. Therefore, $TEE_{cmc}$ is considered a simpler and more direct index to quantify the thermal stress than the conventional PSI.

### 4.4.2 Key findings of TEE & PSI

The two key elements of PSI are core temperature ($T_{core}$) and heart rate (HR). $T_{core}$ continuously increased during the experiment, regardless of the types of activities. On the other hand, HR responded sensitively to different activities. It is because $T_{core}$ increased when the metabolic rate of activities increases, but even when the subjects took off the PPE and sat down for resting after every walking sessions, time was not enough for body thermoregulatory system to adjust

$T_{core}$ to the normal state. The increase of $T_{core}$ was faster than the reduction inside the body. Therefore, $T_{core}$ increased and kept rising during the entire period of the experiment.

In contrast, $TEE_{cmc}$ decreased due to the heat and moisture released immediately from the microclimate inside PPE. The change of $TEE_{cmc}$ in different sessions was more obvious than $T_{core}$. Therefore, $TEE_{cmc}$ is considered as a more sensible index to identify the thermal stress rather than relying on too complicated physiological responses.

Moreover, the measurement of $T_{core}$ used portable capsule methods that are complicated and sometimes inaccurate. Possible errors may be due to the fluctuation of the readings of $T_{core}$ even though the water intake was controlled in the experiment. Another error may be the locations of the receiver that may move slightly with the body even though it is placed close to the subject. To prevent the connection error, it is recommended to use rectal or tympanic sensors upon the subjects' consents in the future study.

For the measurement of HR, each subject needed to wear the belt and recording watch tightly on his chest and wrist. They may feel uncomfortable. The belt may also be loosened slightly during activities in the experiments. Therefore, $TEE_{cmc}$ as a new and simpler measurement method is suitable to identify the thermal stress of firefighters and valuable in development and application of protective garments.

### 4.4.3 Effects of fabrics

All the core temperature, heart rate and PSI of firefighters wearing moisture managed fabric was the lowest at the end of experiment because the overall moisture management capacity of the new fabric increases the rate of liquid sweat transformed from the skin side to the opposite side of fabric (Guo, 2008). However, when the subjects wore the PPE during the walking sessions, the extremely high heat insulation of PPE impedes the heat transmission and moisture evaporation from the uniform are inside surface to the environment (Al-ajmi, 2008) and keep the sweat and body heat accumulated inside the PPE. The influence of moisture managed fabric was limited in the walking session, so the uniform Sets 4 and 5 had similar mean PSI in all walking sessions.

The mean PSI of uniform Set 4 was higher than Set 2 in both walking sessions. The sweat was absorbed and accumulated in the relatively thicker uniform Set 4 during the walking session. When a large amount of sweat was absorbed by the fabrics, it became saturated and stopped absorbing the sweat.

When the fully wet fabric stuck to the body, the discomfort made the firefighter feel stressful and increased their HR and PSI (Taelman, 2008) (Huang, 2013). PSI was affected by psychological sensations such as stress and personal feelings.

On the other hand, the $TEE_{cmc}$ of Set 4 was lower than Set 2 during walking. The heat release from the skin through the microclimate effectively because moisture managed fabric provides relatively higher wicking rate of sweat. The result of $TEE_{cmc}$ was different from that of PSI probably because $TEE_{cmc}$ is not affected by the psychological sensations of the subjects.

Fig. 4. 24 shows the mean PSI of Set 2 and Set 4 with photos of the liquid transport from the skin to the face of moisture managed and non-moisture managed fabric. For Set 4, the back of fabric was hydrophobic, so the wet molecules readily transmit to the face of the fabric. Fig. 4. 25 shows the process of how the fabric, with and without moisture management treatment, enable the sweat to be transmitted from the body to the environment (Guo, 2008) (Onofrei, 2014).

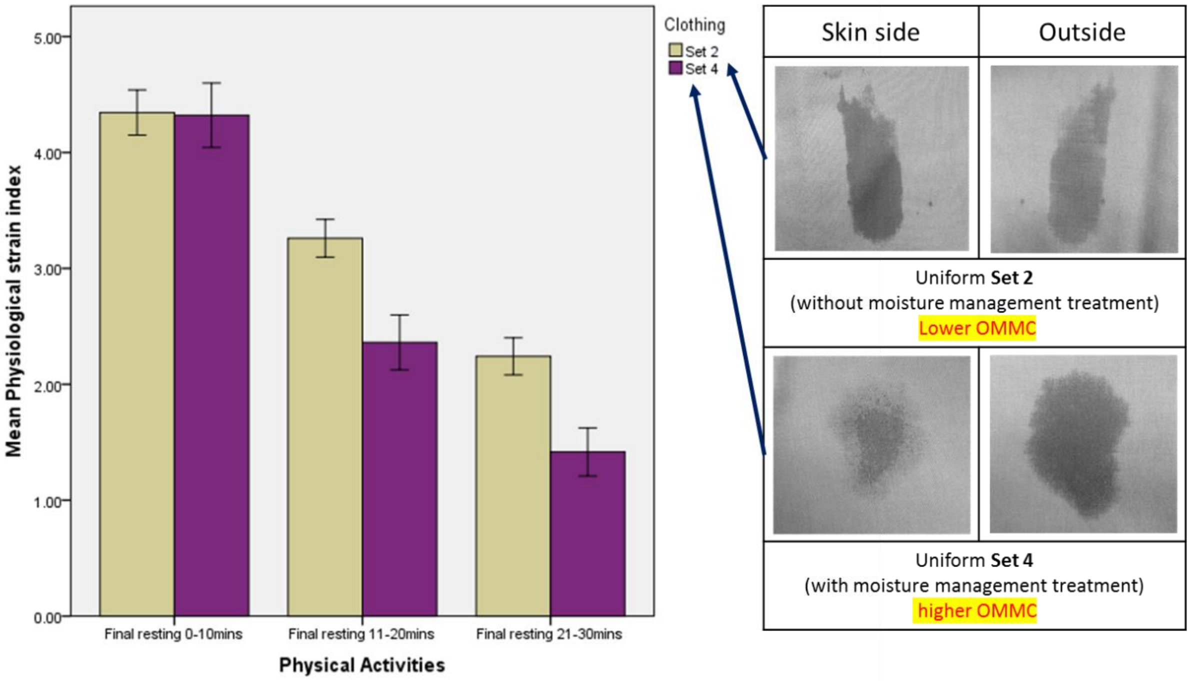



Fig. 4.24 PSI comparison between uniform set 2 and set 4 with different OMMC fabric

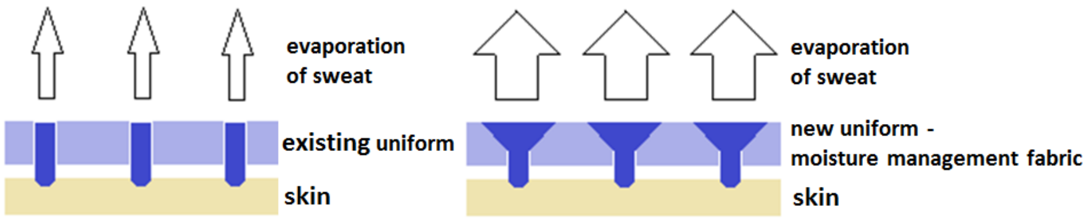



Fig. 4. 25 The process of how the fabric with and without moisture management treatment enables the sweat to be transmitted from the body

4.4.4 Effects of uniform design

The $T_{core}$ of Set 2 and Set 4 with short sleeve T-shirts have unchanged during walking session 2 after middle resting. The results are different from the Sets 1, 3 and 5 with long sleeve shirt or T-shirt. According to the literature (Parsons, 1993) (Al-ajmi, 2008), thermal insulation and water vapour permeability were the important factors related to thermal stress. Short-sleeve T-shirt provides a more uncovered area (forearm) with no heat insulation and better water vapour permeability to the subjects. Therefore, relatively lower core temperature resulted after better heat release from the subjects.

The PSI of the subjects wearing uniform Set 5 decreased during middle resting in Fig 4.4 because of the sweat absorption of long sleeves after walking session 1. More sweat was absorbed by the moisture-managed fabric of long sleeves compared to the short sleeves. Drier microclimate condition made the subjects feel better and therefore have lower PSI and more thermal stress. After walking session 2, the PSI increase in set 5 was high and eventually higher than that in Set 2 & Set 4. It is because the moisture managed fabric of Set 5 was fully wet after two walking sessions. The fabric has accumulated a large amount of liquid sweat that could not be evaporated fast enough. Therefore, a higher cover area of Set 5 provided higher water vapour resistance. The thermal stress was increased by Set 5 that induced a high skin wetness and therefore higher PSI. The same happened in the result as shown in Fig. 4.15 that the uniform Set 4 had higher mean PSI than Set 5 in all walking sessions.

## 4.5 Conclusion

After investigating five sets of firefighter uniforms during walking and resting in a controlled chamber, it is interesting to find that

a) Moisture managed fabrics reduced the thermal stress of the subjects because they allow better moisture evaporation and heat release through the clothing microclimate.

b) Two-layer clothing (Set 1 and Set 3) increased the thermal stress. Short- sleeve uniforms (Set 2 and Set 4) caused lower thermal stress than the long sleeve uniform (Set 5) in all activities.

c) The effects of fabric and design were more significant during the resting period since the effects of uniform have been overridden by the high-insulated PPE being worn during walking sessions. Therefore, future studies into the effects of garment designs on the thermal stress reduction inside high insulated clothing must include the resting sessions in the experiment.

d) PSI and $TEE_{cmc}$ had a positive linear relationship no matter in the training center (mentioned in Chapter 3) or the controlled chamber. However, the experiment of simulated firefighting in the training center was more demanding therefore the slope of the increase in $TEE_{cmc}$ was steeper.

e) It is feasible to apply $TEE_{cmc}$ index to supplement the PSI in the measurement of the thermal stress of the firefighters since the measurement of parameters and data in $TEE_{cmc}$ ($T_{cmc}$ and $RH_{cmc}$) are relatively simpler and $TEE_{cmc}$ was not affected by psychological sensations of subjects.

# Chapter 5 Prediction of thermal stress

## 5.1 Introduction

Heat illness can cause death in firefighters. The prediction of thermal stress is important and mentioned in previous chapters. To predict the thermal stress and thermoregulatory responses of firefighters wearing various designs of uniforms, a computational program called "S-Smart" based on theoretical equations was used. These theoretical models and data provide a scientific understanding of thermal stress experienced by a firefighter. Moreover, the application of $TEE_{cmc}$ is applied in the simulation of S-smart in order to verify this new heat stress index by the prediction of physiological parameters.

## 5.2 Computer simulation by S-smart

S-smart is a computer simulation program. The input data of the model include the human body properties, firefighter uniform properties, the metabolic rate of different activities and the environmental condition. These are used to simulate the heat and moisture transfer process in the human body since the S-smart will calculate the physiological responses based on the properties of the human body, clothing and environmental condition.

## 5.3 Theoretical models and Computational Simulations

In S-smart, the description of theoretical models in heat and moisture transfer processes within the clothing have been reported by many researchers (Farnworth, 1983) (Henry, 1939) (Li, 2003). The equation mentioned in session 5.2.1 to 5.2.3 give mathematical descriptions of the thermal behaviors in clothing, which consist of a series of partial differential equations and are established according to the conservation of mass and heat energy.  Moreover, many particular nomenclatures and symbols have been used in the description. All of the nomenclatures used in the equations are mentioned in table 5.1.

| | | | |
|---|---|---|---|
| $C^*$ | Saturated water vapor concentration kg $m^{-3}$ | $P_h$ | Proportion of dry heat loss at the clothing-covered area |
| $C_a$ | Water vapor concentration in the air filling the inter-fiber void space, kg $m^{-3}$ | $p_m$ | Proportion of moisture vapor from the skin at the clothing-covered area |
| $C_f$ | Water vapor concentration in the fibers of the fabric kg $m^{-3}$ | $R_{skU}$ | Radioactive heat loss from the skin in the area uncovered by clothing, $Wm^{-2}$ |
| $C_{res}$ | Dry respiration heat loss W $m^{-2}$ | $r$ | Fiber radius |
| $C_{skA}$ | Convective heat loss from the skin in the area covered by clothing, $Wm^{-2}$ | $S_c$ | The heat storage of the core, $Wm^{-2}$ |
| $C_{skU}$ | Convective heat loss from the skin in the area uncovered by clothing, $Wm^{-2}$ | $S_s$ | The heat storage of the skin, $Wm^{-2}$ |
| $c_v$ | Volumetric heat capacity of the fabric, kJ $m^{-2}$ $K^{-1}$ | $T$ | Temperature of the fabric, K |
| $D_a$ | Diffusion coefficient of water vapor in the air of the fabric $m^2s^{-1}$ | $T_{cr}$ | Temperature of core, K |
| $D_f$ | Diffusion coefficient of water vapor in the fibers of the fabric $m^2s^{-1}$ | $T_{sk}$ | Temperature of skin surface, K |
| $DRY$ | Dry heat loss from human body, $Wm^{-2}$ | $T(T_{fi}$ | Temperature of the fabric K |
| $E_{rsw}$ | Evaporative heat loss by regulatory sweating from skin, $Wm^{-2}$ | $\lambda_v$ | Heat of sorption or desorption of vapor by fibers kJ $kg^{-1}$ |
| $E_{res}$ | Latent respiration heat loss, $Wm^{-2}$ | $\lambda_l$ | Heat of sorption or desorption of liquid by fibers kJ $kg^{-1}$ |
| $E_{dif}$ | Diffusive heat loss from skin surface, $Wm^{-2}$ | $V_{bl}$ | Skin blood flow rate, 1 $h^{-1}$ $m^{-1}$ |
| $E_{skA}$ | Evaporative heat loss from the skin in the area covered by clothing, $Wm^{-2}$ | $W$ | Moisture transfer resistance, $sm^{-1}$ |
| $E_{skU}$ | Evaporative heat loss from the skin in the area uncovered by clothing, $Wm^{-2}$ | $\alpha$ | effective angle of capillaries in the fabric |
| $F_{L(R)}$ | Elementary total thermal radiation incident inside the clothing traveling to the left (right), $Wm^{-2}$ | $\beta$ | Radiation absorption constant of the fiber, $m^{-1}$ |
| $\Gamma_f$ | Effective sorption rate of the moisture | $\varepsilon$ | Porosity of the fabric |
| $\Gamma_{lg}$ | Evaporation/condensation rate of the liquid/vapor | $\varepsilon_a$ | Volume fraction of water vapor |
| $h_{lg}$ | Mass transfer coefficient for evaporation and condensation, m $s^{-1}$ | $\varepsilon_l$ | Volume fraction of liquid phase |
| $K_{min}$ | Minimum thermal conductance of body tissue, $Wm^{=2}$ - $K^{-1}$ | $\varepsilon_f$ | Volume fraction of fibers |
| $K_{mix}$ | Effective thermal conductivity of the fabric, $Wm^{-1}$ $K^{-1}$ | $\sigma$ | Stefan–Boltzmann constant, $Wm^{-2}$ $K^{-1}$ |
| $K_l$ | Thermal conductivity of the liquid water, $Wm^{-1}$ $K^{-1}$ | $\rho_l$ | Density of the liquid water, kg $m^{-3}$ |

| | | | |
|---|---|---|---|
| $l$ | Distance between skin surface and inner surface of clothing or the neighboring clothing layers, m | $\xi_1$ | Proportions of moisture sorption at fiber surface covered by air |
| $M$ | Metabolic rate of human body, Wm$^{-2}$ | $\gamma$ | Surface tension of fiber, J m$^{-1}$ |
| $P_A$ | Proportion of clothing-covered area | $\tau_a$ | Effective tortuosity of the fabric for water vapor diffusion |

Table 5.1 Nomenclature of equation

5.3.1 Thermoregulatory Model of the Human Body

Studies mentioned a two-node model for theoretical models of the thermoregulatory system of the human body (Gagge, 1972). The system was further developed as a standard to predict the thermal comfort (Li., 2006) (Mao, 2008) the following balance equations are listed:

| Energy balance of the clothing | | | Reference source |
|---|---|---|---|
| Body core node | $S_{cr} = M - E_{res} - C_{res} - W -(K_{min} + c_{bl}v_{bl})(T_{cr} - T_{sk})$ | (Equation 5.1) | (Gaage, 1971) (Gagge., 1986) |
| Body skin node | $S_{sk} = (K_{min} + c_{bl}v_{bl})(T_{cr} - T_{sk}) -(E_{skA} + E_{skU}) - DRY$ | (Equation 5.2) | |
| No sweat on skin | $E_{skA} = P_A(E_{rsw} + E_{dif}); -E_{skU} = (1 - P_A) \times (E_{rsw} + E_{dif})$ | (Equation 5.3) | |
| Sweat on skin | $E_{skA} = K_l \times \frac{T_{sk} + T_{fi}}{l} \quad E_{skU} = E_{rsw}$ | (Equation 5.4) | |
| | $DRY = (R_{skA} - R_{skU} + (C_{skA} + C_{skU})DRY = R_{skU} - C_{skU}$ | (Equation 5.5) | |

Table 5.2 Equations of the energy balance of human body (see Table 5.1 for the nomenclature of equation)

The simulation results of this model generate the vital thermal physiological parameters of the human body, such as core temperature and mean skin temperature.

### 5.3.2 Heat and Moisture Models of the Clothing

In order to describe the complicated heat and mass transfer mechanisms in the porous clothing materials, the mathematical models are developed (Mao, 2008). Bouddour et al. have investigated the evaporation-condensation of wet porous materials (Bouddour, 1998). Fan and Wen were reported a model about evaporation and mobile condensation. (Fan, 2002) The assumptions used and numerical solutions that generated with the computer calculation have been identified by Nordon and Dave in 1950s. (Nordon, 1967) Finally, Li et al. have investigated and derived the models to apply the fiber moisture absorption/desorption mechanisms into the computations (Henry, 1948) (Li, 1992). The new mathematical model involved many physical mechanisms such as the liquid water diffusion by capillary action, the function of fiber surface energy, contact angle and the fabric pore size distributions. After the consideration and analysis, the mathematical equations describing the heat and moisture transfer processes in clothing materials can be expressed as follows:

| Energy balance of the clothing | | Reference source |
|---|---|---|
| Water vapor | $\frac{\partial(C_a\varepsilon_a)}{\partial t}=\frac{1}{\tau_a}\frac{\partial}{\partial x}\left(D_a\frac{\partial(C_a\varepsilon_a)}{\partial x}\right) -\varepsilon_f\xi_1\overline{\Gamma}_f+\overline{\Gamma}_{lg}$ (Equation 5.6) | (Li, 2003)<br>(Li, 2004)<br>(Li., 2006)<br>(Li, 1992)<br>(Chatonnet, 1965)<br>(Henry, 1948)<br>(Wang, 2003) |
| Mean moisture sorption of all the fibers | $\overline{\Gamma}_f=\sum_{ti=1}^{tn}\left(f_{ti}\left[\frac{1}{r_{ti}}\frac{\partial}{\partial r_{ti}}(r_{ti}(D_f)_{ti}\frac{\partial C_f}{\partial_f}\right]_{ti}\right)$ (Equation 5.7) | |
| mean evaporation /condensation rate of the fabric | $\overline{\Gamma}_{lg}=\sum_{ti=1}^{tn}\left(f_{ti}(\frac{2\varepsilon_a}{r\varepsilon}\varepsilon_f h_{lg}(C^*(T)-C_a)_{ti}\right)$ (Equation 5.8) | |
| Liquid water | $\frac{\partial(\rho_l\varepsilon_l)}{\partial t}=\frac{1}{\tau_1}\frac{\partial}{\partial x}(\sum_{ti=1}^{tn}\left(D_l(\varepsilon_l)\frac{\partial(\rho_l\varepsilon_l)}{\partial x}\right)_{ti} -\varepsilon_f\xi_2\overline{\Gamma}_f-\overline{\Gamma}_{lg}$ (Equation 5.9) | |
| liquid diffusivity of the fiber | $D_l(\varepsilon_l)=\frac{\gamma\cos\theta\sin^2\alpha d_c\varepsilon_l^{\frac{1}{3}}}{20_\eta}$ (Equation 5.10) | |
| Energy balance equation | $\overline{c}_v\frac{\partial T}{\partial t}=\frac{\partial}{\partial x}\left(\overline{K}_{mix}(x)\frac{\partial T}{\partial x}\right)+\frac{\partial F_R}{\partial x} -\frac{\partial F_L}{\partial x}+\varepsilon_f\overline{\Gamma}_f(\xi_1\overline{\lambda_v}+\xi_2\overline{\lambda_l}) -\lambda_{lg}\overline{\Gamma}_{lg}-q(x,t)$ (Equation 5.11) | |
| Thermal radiation in the left and right way | $\frac{\partial F_R}{\partial x}=-\overline{\beta}F_R+\overline{\beta}\sigma T^4$ (Equation 5.12) | |

Table 5.3 Equation of the Clothing heat and moisture models (see Table 5.2 for the nomenclature of equation)

5.3.3 Interactions between Models of Clothing and the Body

In S-smart, appropriate boundary condition has to be identified for the generation of a smooth data flow of the clothing heat and moisture models and the body thermoregulatory model. Fig. 5.1 shows the human-clothing environment thermal system. A human body gains and/or loses heat generated by metabolic heat due to the internal biological and physical activities of muscles and organs through heat conduction, convection, radiation and the evaporation of sweat and perspiration. Moreover, HCE is a thermal system affected by the external thermal environment through clothing with different reflection (Li, 2006).

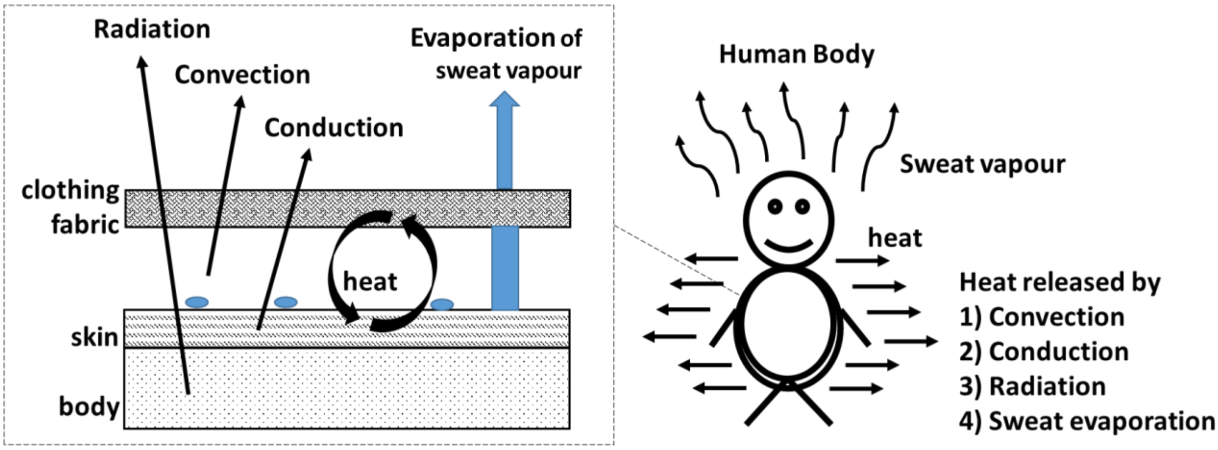



Fig. 5.1 Human-clothing environment thermal system

The development of the boundary condition equations in the clothing heat and moisture models had involved the thermal status of the external environment and the body. The boundary condition equations of the clothing heat and moisture model for the inner side of the clothing close to the skin surface including the clothed area and unclothed area are expressed as in Table 5.4.

| Contact between the skin and the inner side of the clothing | | Reference source |
|---|---|---|
| Indirect contact | $K_{mix} \frac{dT}{dx}\Big\|_{x=0} + P_h \begin{pmatrix} H_{c0}(T_{sk} - T_{fi}) \\ +h_r(T_{sk} - T_{fi}) \end{pmatrix} + P_h E_{skA} = 0$ (Equation 5.13) | (Li, 2003) |
| | $F_R(0,t) = (1 - \varepsilon_0)F_L(0,t) + \varepsilon_0 \sigma T^4(0,t)$ (Equation 5.14) | |
| | $D_a \frac{\partial(C_a \varepsilon_a)}{\partial x}\Big\|_{x=0} + h_{m0}(C_{sk} - C_{fi}) + p_m E_{skA}/\lambda = 0$ (Equation 5.15) | |
| Direct contact | $K_{mix} \frac{dT}{dx}\Big\|_{x=0} + E_{skA} = 0$ (Equation 5.16) | |
| | $F_R(0,t) = (1 - \varepsilon_0)F_L(0,t) + \varepsilon_0 \sigma T^4(0,t)$ (Equation 5.17) | |
| | $C_a(0,t) = C^*(T)$ (Equation 5.18) | |
| | $\varepsilon_f(0,t) = 1 - \varepsilon_f$ (Equation 5.19) | |

Table 5.4 Equation between the skin and the inner side of the clothing (see Table 5.3 for the nomenclature of equation)

Thus, the data flow between the models of clothing and the body is developed to integrate the models and enable the body, clothing, and environment to work as a highly interactive system in a virtual space.

5.4 Simulation of Thermal Performance of Clothing

The S-smart system is a window-based program of the computational simulation on the performance of a garment being worn by a user (Li., 2006) (Cao, 2009). There are three steps in the simulation including 1) pre-processing, 2) simulation and 3) post-processing.

In the pre-processing stage, a user needs to define the activities, the metabolic rates, environmental conditions, human body information, and clothing information. Moreover, the boundary conditions related to human body state, heat/mass transfer coefficient, environment and microclimate between fabric layers are determined according to the fabric's material properties and practical situation of the different garment and different wearing style. Furthermore, the simulation time step and the skin ratio covered by clothing are controlled. All data is input according to the experiment. The program interface is shown in Fig. 5.2 to Fig. 5.6.

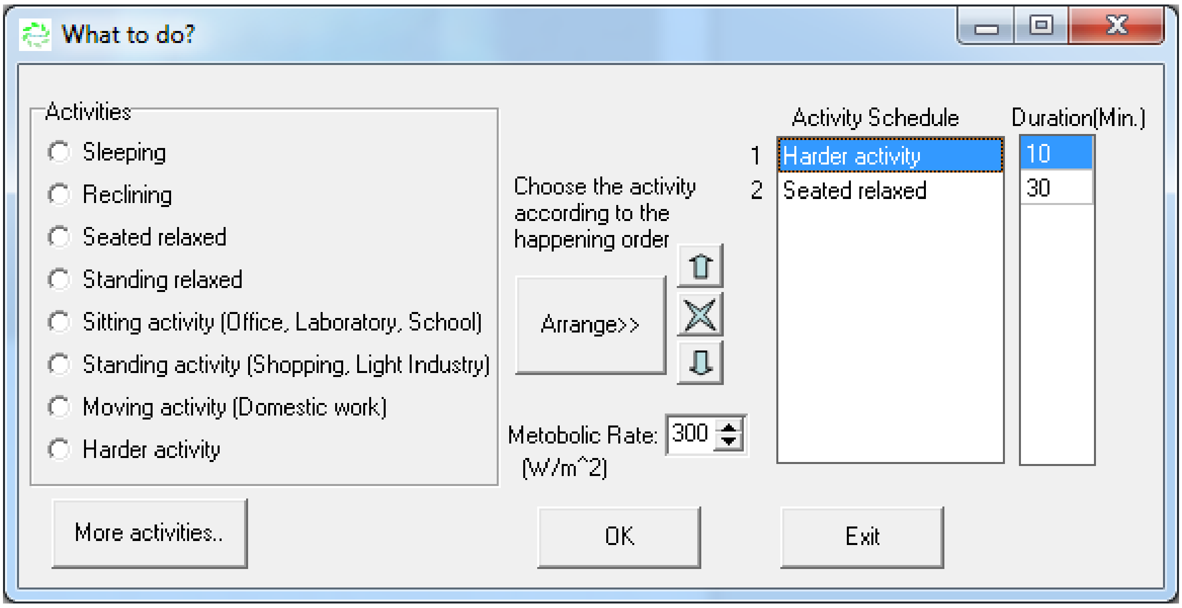


Fig. 5.2 Activities in simulation

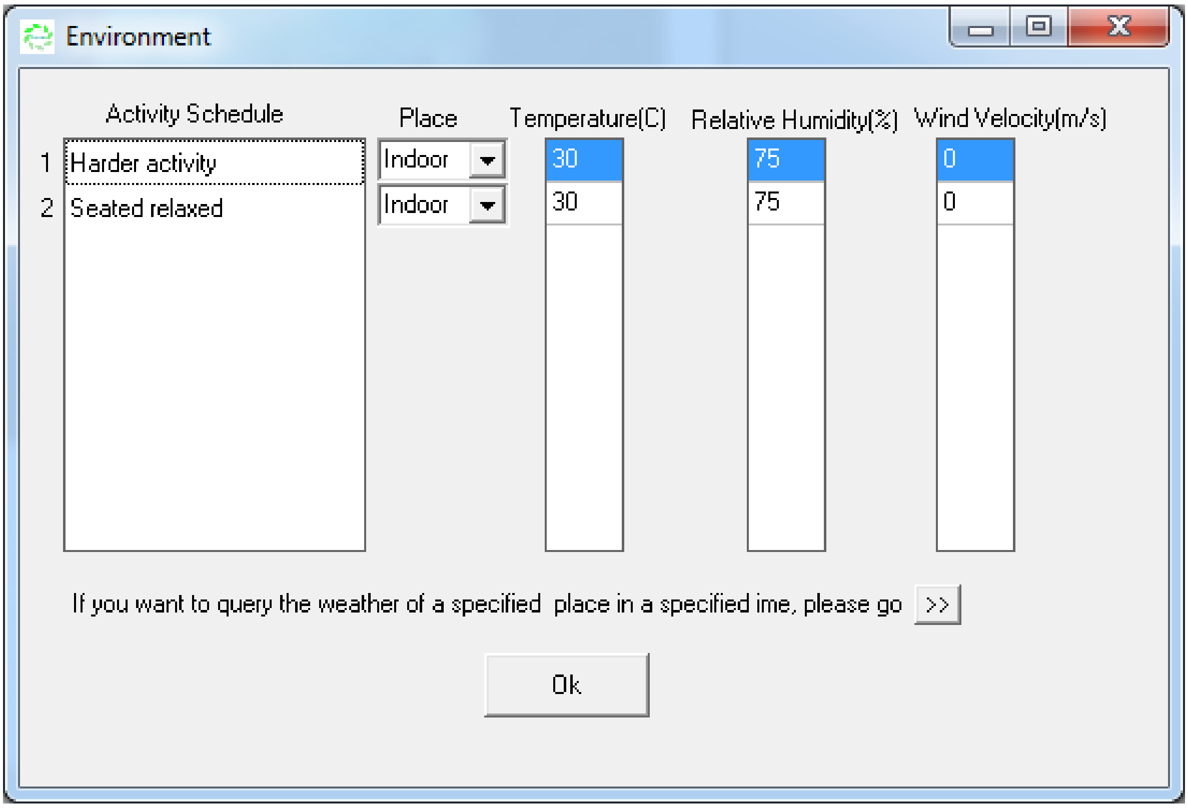


Fig. 5.3 Environmental condition in simulation

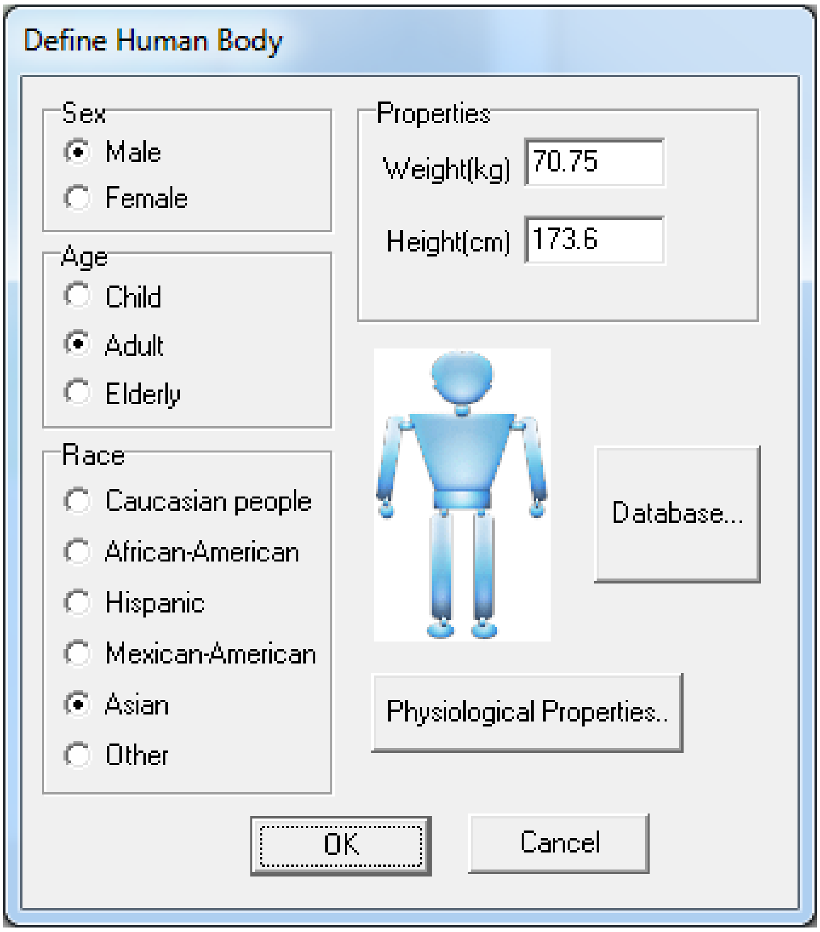


Fig. 5.4 Human body in simulation

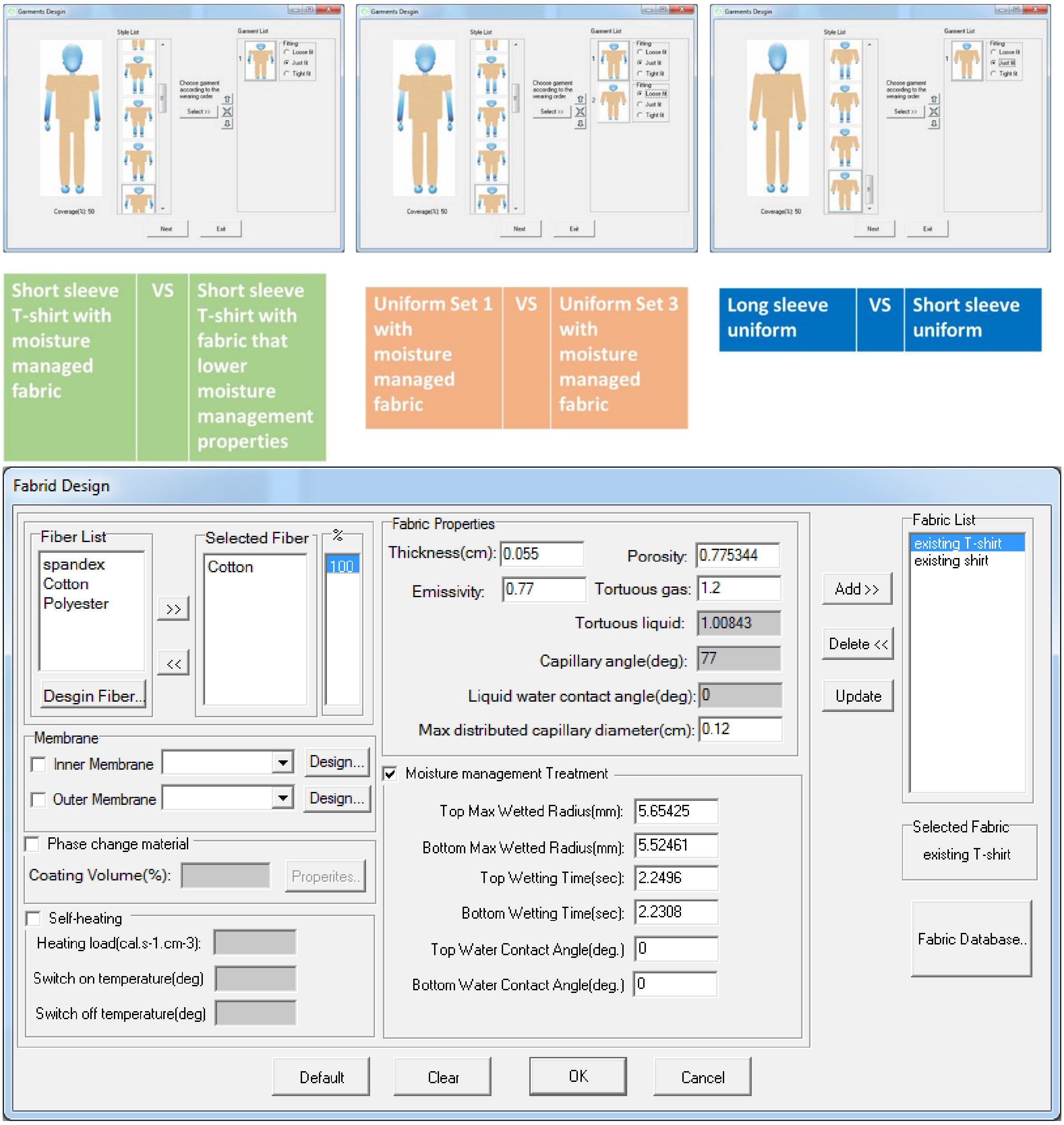


Fig. 5.5 Garment and fabric design in simulation

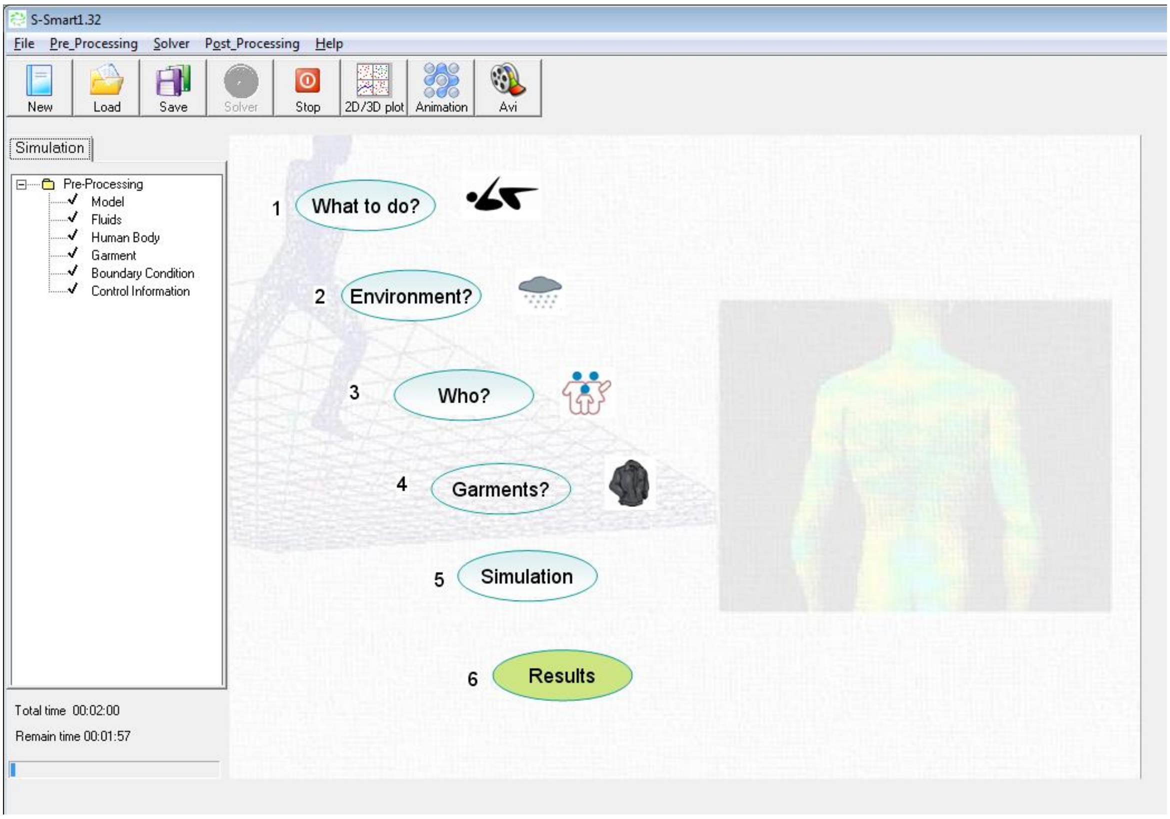



Fig. 5.6 The interface of computational simulation

The simulation is achieved by numerically solving the coupled models of heat transfer, moisture transfer, and thermoregulation. After simulation, the post-processing stage shows the 2D charts as shown in Fig. 5.7, to visualize the simulation results of the fabric, fiber, human body properties and body comfort. Therefore, the S-smart can be used to predict the thermal functional performance of different garment sets and compare the predictions of the experiment results.

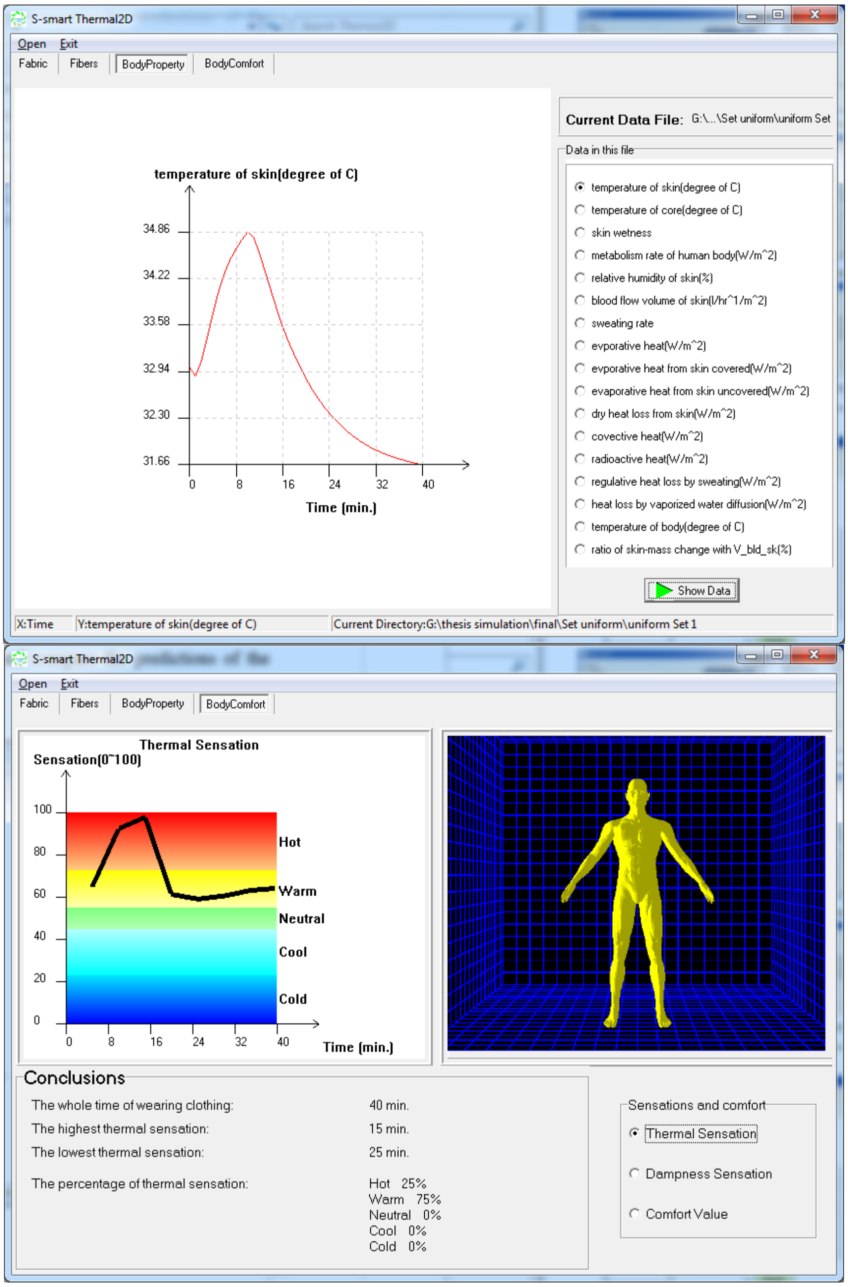



Fig. 5.7 The interface of 2D chart result in computational simulation

5.5 Data used in the simulation

The tested fabric properties of existing and new firefighter uniform were input into the S-smart system. There were 3 sets of uniform combination in the simulation as shown in Fig. 5.8 – 5.10.

Existing T-shirt and shirt

New T-shirt and shirt

Fig. 5.8 First combination of uniform simulation


Existing T-shirt


New T-shirt

Fig. 5.9 Second combination of uniform simulation


Long short sleeve T-shirt


New long sleeve T-shirt

Fig. 5.10 Third combination of uniform simulation

The fabric properties used in the S-smart simulation were summarized in Table 5.5. Since the laboratory did not have the particular testing instrument, the default values of 1.2 tortuous gas and 0.12cm maximum distributed capillary diameter were assumed in different fabrics.

| Sample | Fiber | Thickness (mm) | Porosity | Top Water Contact (deg.) | Bottom Water Contact (deg.) | Emissivity |
|---|---|---|---|---|---|---|
| Existing T-shirt | 100% Cotton | 0.55 | 0.775 | 0 | 0 | 0.77 |
| Existing shirt | 35% Cotton 65% Polyester | 0.68 | 0.626 | 0 | 0 | 0.9 |
| New T-shirt | 5% Spandex 95% Cotton | 0.66 | 0.811 | 0 | 0 | 0.77 |
| New shirt | 35% Cotton 65% Polyester | 0.32 | 0.770 | 0 | 0 | 0.9 |

Table 5.5 Fabric properties of the existing and new uniform

The details of the activities are listed in Table 5.6. Two activities were chosen to determine the performance of the different uniforms. Two sets of activities with different metabolic rate illustrated the different influence performed by the garment.

| Activity | Metabolic Rate($W/m^2$) | Clothing | Interval (min) |
|---|---|---|---|
| Work | 300 | Uniform (different combination) | 10 |
| Rest | 58 | | 30 |

Table 5.6 The activities in simulation

The temperature is 30°C, humidity is 75% and wind velocity is 0m/s, simulated as in the conditions of the controlled chamber mentioned in Chapter 4. However, the protocol of Chapter 4 included two styles of wearing setting (uniform with PPE during walking sessions and uniform without PPE during resting sessions) cannot be simulated in one case. Wearing uniform without PPE in controlled chamber condition (chapter 4) have been designed as the complex wearing condition.

## 5.6 Results of S-smart simulation

### 5.6.1 Core temperature

Fig. 5.11 shows the results of simulation of $T_{core}$ of five sets of uniforms. The $T_{core}$ increased in first 10 minutes due to the 300 W/m$^2$ metabolic rate, then decreased immediately upon the start of the 30-min rest period (60 W/m$^2$ metabolic rate).

In the first 23 minutes, Set 1 (existing fabric and two layers design) gave the highest $T_{core}$, followed by Set 2 (existing fabric short sleeve T-shirt), Set 3 (moisture managed fabric with two layers design) and Set 5 (moisture managed fabric with long sleeve) that had similar $T_{core}$. Set 4 (moisture managed fabric short sleeve T-shirt) gave the lowest $T_{core}$.

After the subjects have cooled down to a steady state, the $T_{core}$ keeps 37.1°C in all sets of uniforms until the end of rest phase. Table 5.7 shows that the results of three pairs of comparisons between different designs of uniforms in this S-smart simulation are the same as that in the wear trial experiments mentioned in Chapter 4. Based on the result of $T_{core}$, the clothing fabric and design are critical to the thermal stress performance of firefighter uniform.

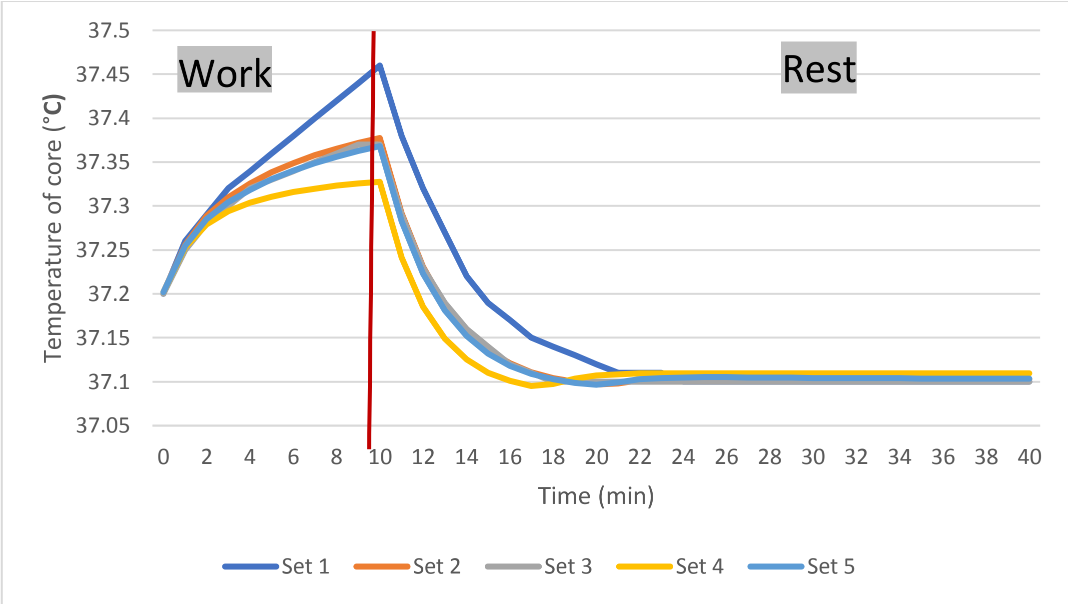



Fig. 5.11 Simulated core temperature in five sets of uniforms

| | | Core temperature ($T_{core}$) | | | | | |
|---|---|---|---|---|---|---|---|
| | Comparison | #1 | | #2 | | #3 | |
| | | Set 1 | Set 2 | Set 2 | Set 4 | Set 4 | Set 5 |
| | Clothing design | Two layers | One layer | Non-moisture managed | Moisture managed | Short sleeve | Long sleeve |
| Simulation | Work in first 10 mins | Higher | Lower | Higher | Lower | Lower | Higher |
| | Rest in final 30 mins | Higher | Lower | Higher | Lower | Lower | Higher |
| Experimen | Walking | Higher | Lower | Higher | Lower | Lower | Higher |
| | Final resting | Higher | Lower | Higher | Lower | Lower | Higher |

Table 5.7 Comparison of core temperature in different designs of clothing

5.6.2 Skin temperature

Fig. 5.12 shows that the $T_{skin}$ of all uniforms decreased in the first three minutes of work because it takes time for the body heat to release through the skin even at a high temperature (30°C) because the skin temperature (33°C) at initial state is higher than surroundings and the metabolism of first two minutes work is not high enough for stimulating of the skin temperature.After two minutes, $T_{skin}$ increased when a large amount of heat started to transfer from the blood vessels by convection, conduction, and radiation (Fourt, 1970) (Havenith, 1999).

Once the rest period started at the 10$^{th}$ minute, $T_{skin}$ of all uniforms decreased gently since the body heat release slowed down until it reached a steady state. The $T_{skin}$ between different uniforms was obviously different due to different levels of heat insulation. According to Fig. 5.12, Set 1 (existing fabric and two-layer design) has the highest heat insulation and Set 4 (moisture managed fabric short sleeve T-shirt) has the lowest heat insulation.

Table 5.8 shows that the results of three pairs of comparisons between different designs of uniforms in this S-smart simulation are the same as that in the wear trial experiments mentioned in Chapter 4.

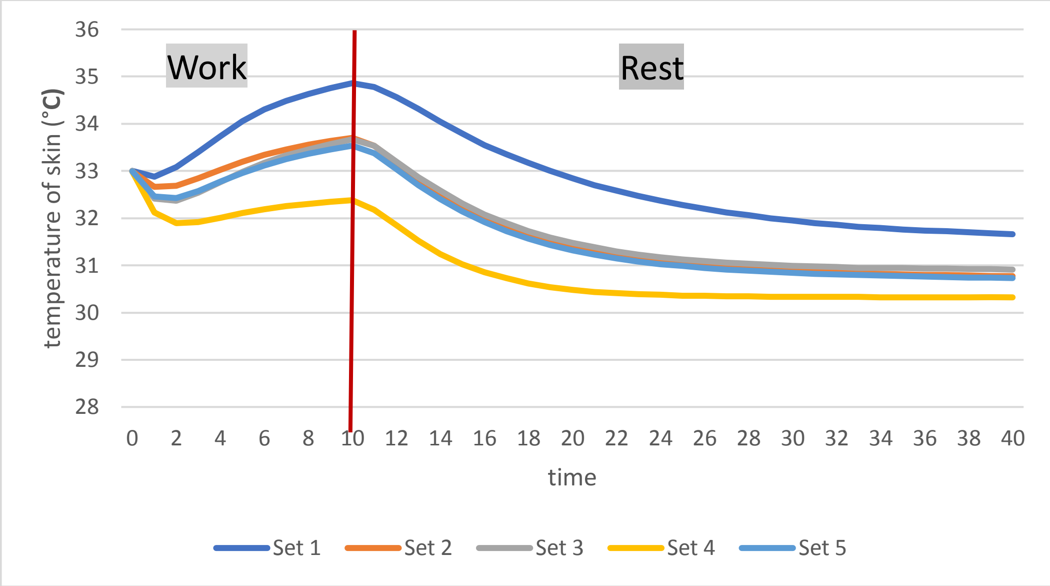



Fig. 5.12 Simulated skin temperature in five sets of uniform

| | | Skin temperature ($T_{skin}$) | | | | | |
|---|---|---|---|---|---|---|---|
| | Comparison | #1 | | #2 | | #3 | |
| | | Set 1 | Set 2 | Set 2 | Set 4 | Set 4 | Set 5 |
| | Clothing design | Two layers | One layer | Non-moisture managed | Moisture managed | Short sleeve | Long sleeve |
| Simulation | Work in first 10 mins | Higher | Lower | Higher | Lower | Lower | Higher |
| | Rest in final 30 mins | Higher | Lower | Higher | Lower | Lower | Higher |
| Experimen | Walking | Higher | Lower | Higher | Lower | Lower | Higher |
| | Final resting | Higher | Lower | Higher | Lower | Lower | Higher |

Table 5.8 Comparison of skin temperature in different designs of clothing

5.6.3 Relative humidity

Fig. 5.13 shows the $RH_{skin}$ of five sets of uniform in the simulation. The results are summarized in Table 5.9. At the beginning, $RH_{skin}$ of all uniforms was about 50%. In the first 2 minutes, the $RH_{skin}$ increased by 15 to 20% sharply. After 3 minutes to 40 minutes, the $RH_{skin}$ of all uniforms kept increasing gently no matter in the work or resting sessions. At the end of resting, Set 3 (moisture managed fabric with two layers design) had the highest $RH_{skin}$ of 90.5%. Set 2 (existing fabric short sleeve T-shirt) was the lowest $RH_{skin}$ of 83.2%. The difference between the highest and lowest was only 7.3%. Unexpectedly, Set 2 was not moisture managed fabric but the $RH_{skin}$ was lower than moisture managed fabric Set 4 probably because Set 2 (0.55mm thick) was thinner than Set 4 (0.66mm thick).

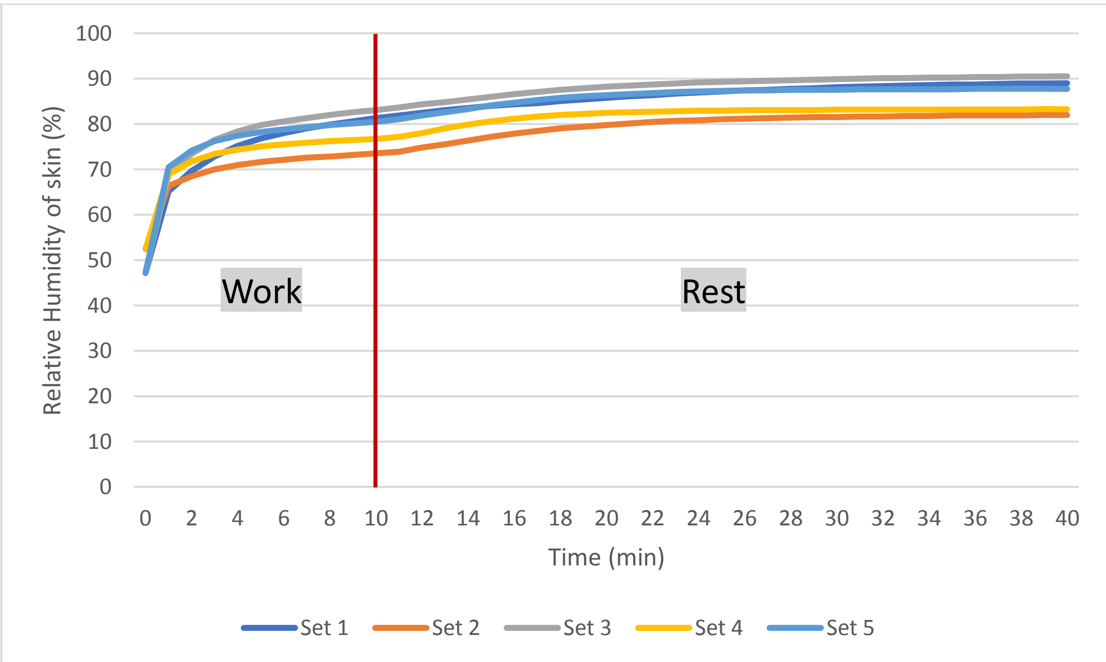



Fig. 5.13 Simulated relative humidity of skin in five sets of uniform

Table 5.9 shows that all uniforms gave an extremely high $RH_{skin}$ closed to 100% in the experiment whereas the PPE was worn. As the core temperature of a firefighter increase and the body tends to release heat, a large amount of sweat stays on the skin. Therefore, $RH_{skin}$ was high in all uniforms. However, in the setting of simulation, no PEE was worn and the amount of sweat released was smaller than that in the experiment. The difference of $RH_{skin}$ between different uniforms was discernible since $RH_{skin}$ was reaching 99% in the simulation.

| | | Relative Humidity ($RH_{skin}$) | | | | | |
|---|---|---|---|---|---|---|---|
| | Comparison | #1 | | #2 | | #3 | |
| | | Set 1 | Set 2 | Set 2 | Set 4 | Set 4 | Set 5 |
| | Clothing design | Two layers | One layer | Non-moisture managed | Moisture managed | Short sleeve | Long sleeve |
| Simulation | Work after first 10 mins | 80% | 73% | 73% | 77% | 77% | 88% |
| | Rest after final 30 mins | 88% | 82% | 82% | 83% | 83% | 88% |
| Experimen | Walking | 99% | 99% | 99% | 99% | 99% | 99% |
| | Final resting | 99% | 99% | 99% | 99% | 99% | 99% |

Table 5.9 Comparison of relative humidity in different designs of clothing

5.6.4 Microclimate TEE

Fig. 5.14 shows the simulated $TEE_{cmc}$ in five sets of uniforms. Since $RH_{skin}$ of all uniforms were similar, $TEE_{cmc}$ was mainly affected by $T_{skin}$. Once the rest period started, $TEE_{cmc}$ of all uniforms increased sharply in first 2 minutes from about 29°TEE to 31°TEE. And the $TEE_{cmc}$ kept increasing gently from the 3rd minute to the end of work session (10 minutes), then decreased immediately upon the 30$^{th}$ minute of rest period since the body heat release slowed down, lesser heat and sweat released from the body, so the skin was drier and cooler ($TEE_{cmc}$ decreased). The $TEE_{cmc}$ between different uniforms was obviously different. According to Fig. 5.14, Set 1 (existing fabric and two-layer design) has the highest heat insulation, followed by Set 3 (moisture managed fabric with two layers design), Set 5 (moisture managed fabric with long sleeve), set 2 (existing fabric short sleeve T-shirt) and Set 4 (moisture managed fabric short sleeve T-shirt) had the lowest $TEE_{cmc}$.

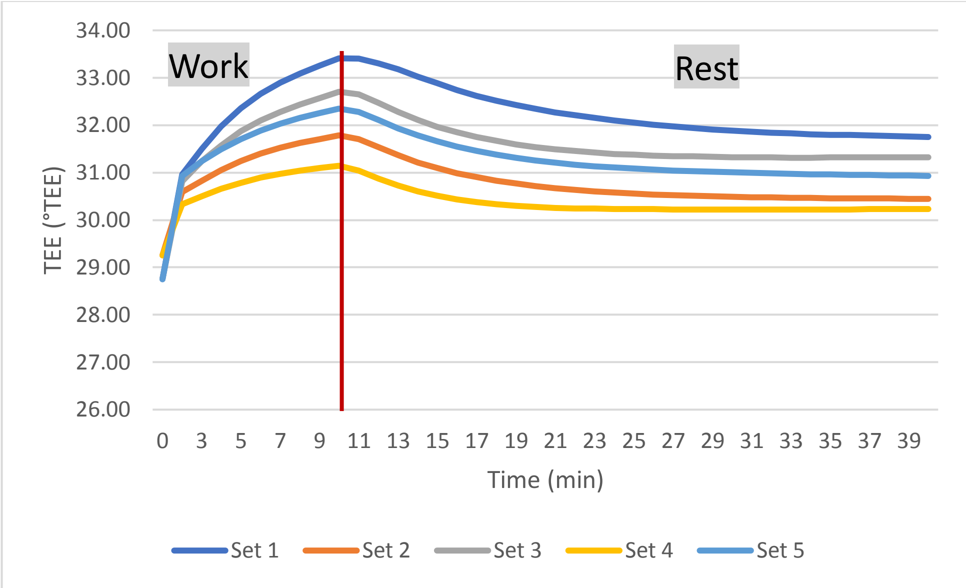



Fig. 5.14 Simulated $TEE_{cmc}$ in five sets of uniform

Based on the table 5.10, the first category shows the $TEE_{cmc}$ difference between two layers and single layer in clothing design. The values of simulation and experiment in two layers uniform were higher than single uniform. The second category shows the $TEE_{cmc}$ difference between different moisture management properties. Surprisingly, the result different in experiment between Set 2 and Set 4 after the first walking session was not significant in $TEE_{cmc}$. The third category shows the $TEE_{cmc}$ difference between the uniform with short and with long sleeves. The values of simulation and experiment were also higher in long sleeve than short sleeve. Higher thermal stress was provided to firefighters in Set 2 to Set 1 and Set 5 to Set 4.

| | | Microclimate Equivalent Effective Temperature (TEEcmc) * = p < 0.05 | | | | | |
|---|---|---|---|---|---|---|---|
| | | | | | | | |
| | Comparison | #1 | | #2 | | #3 | |
| | | Set 1 | Set 2 | Set 2 | Set 4 | Set 4 | Set 5 |
| | Clothing design | Two layers | One layer | Non-moisture managed | Moisture managed | Short sleeve | Long sleeve |
| Simulation | Work after first 10 mins | Higher 33.41 | Lower 31.79 | Higher 31.79 | Lower 31.14 | Lower 31.14 | Higher 32.35 |
| | Rest after final 30 mins | Higher 31.75 | Lower 30.45 | Higher 30.45 | Lower 30.23 | Lower 30.23 | Higher 30.93 |
| Experiment | After Walking 1 | Higher* 35.98 | Lower* 35.50 | Lower 35.50 | Higher 35.56 | Lower* 35.56 | Higher* 35.86 |
| | After middle resting | Higher* 36.25 | Lower* 34.61 | Higher* 34.61 | Lower* 34.45 | Lower* 34.45 | Higher* 34.87 |

Table 5.10 Comparison of $TEE_{cmc}$ in different designs of clothing

Fig. 5.15 shows the scatter diagram between $TEE_{cmc}$ and $T_{core}$ in the walking session. The trendline of 5 sets uniforms indicates a positive linear relationship. The slope of trendline of the short sleeve T-shirts (Set 2 & Set 4) was obviously steeper than the long-sleeves (Set 5). The increase of $T_{core}$ per unit increase of $TEE_{cmc}$ in short-sleeve T-shirts is larger than that in long sleeve T-shirt.

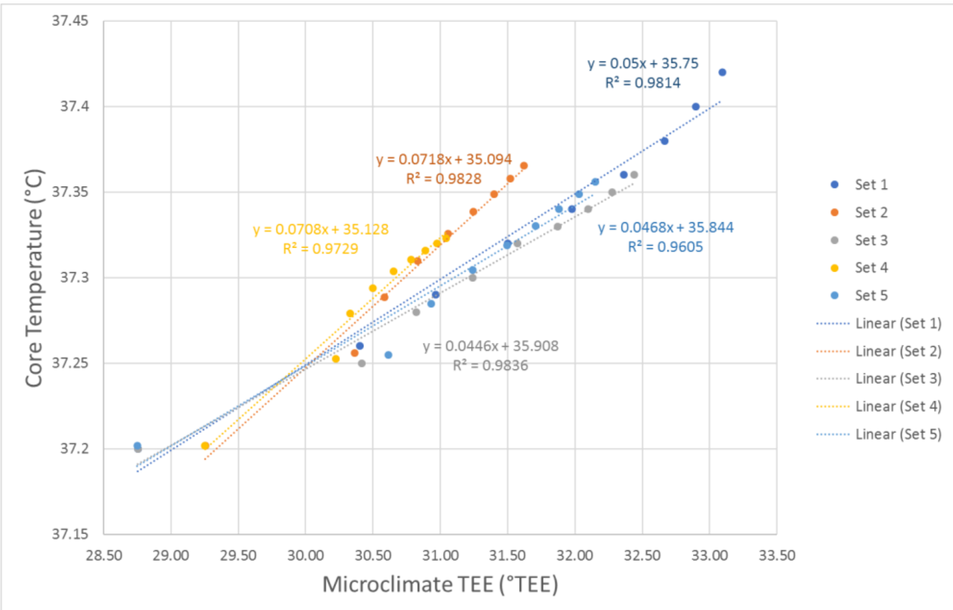



Fig. 5.15 Relationship between $TEE_{cmc}$ and $T_{core}$ during walking

Fig. 5.16 shows that $TEE_{cmc}$ and $T_{core}$ in all sets of uniforms had a nonlinear positive relationship. The difference of equations is due to the different starting point of a rest period in terms of $TEE_{cmc}$ (range from 37.3°C to 37.5°C). $T_{core}$ decreased quickly at the beginning, then slowly until a steady state of approximately 37.1°C. There is a 2nd order polynomial equation representing the relationship between $T_{core}$ and $TEE_{cmc.}$ For example in Set 1,

$y = 0.1673x^2 - 10.718x + 208.78$ ($r^2 = 0.9437$) where y is $T_{core}$ and x is $TEE_{cmc.}$

It is probably because the metabolic rate during rest (56W/m$^2$) was significantly lower than that at work (300W/m$^2$), so $T_{core}$ quickly decreased from work to rest. After $T_{core}$ = 37.2°C, the decrease of $T_{core}$ was slower even when the $TEE_{cmc}$ ($T_{skin}$ and $RH_{skin}$) keep decreasing because $T_{core}$ takes time to reach a steady temperature to make the firefighter feel comfortable.

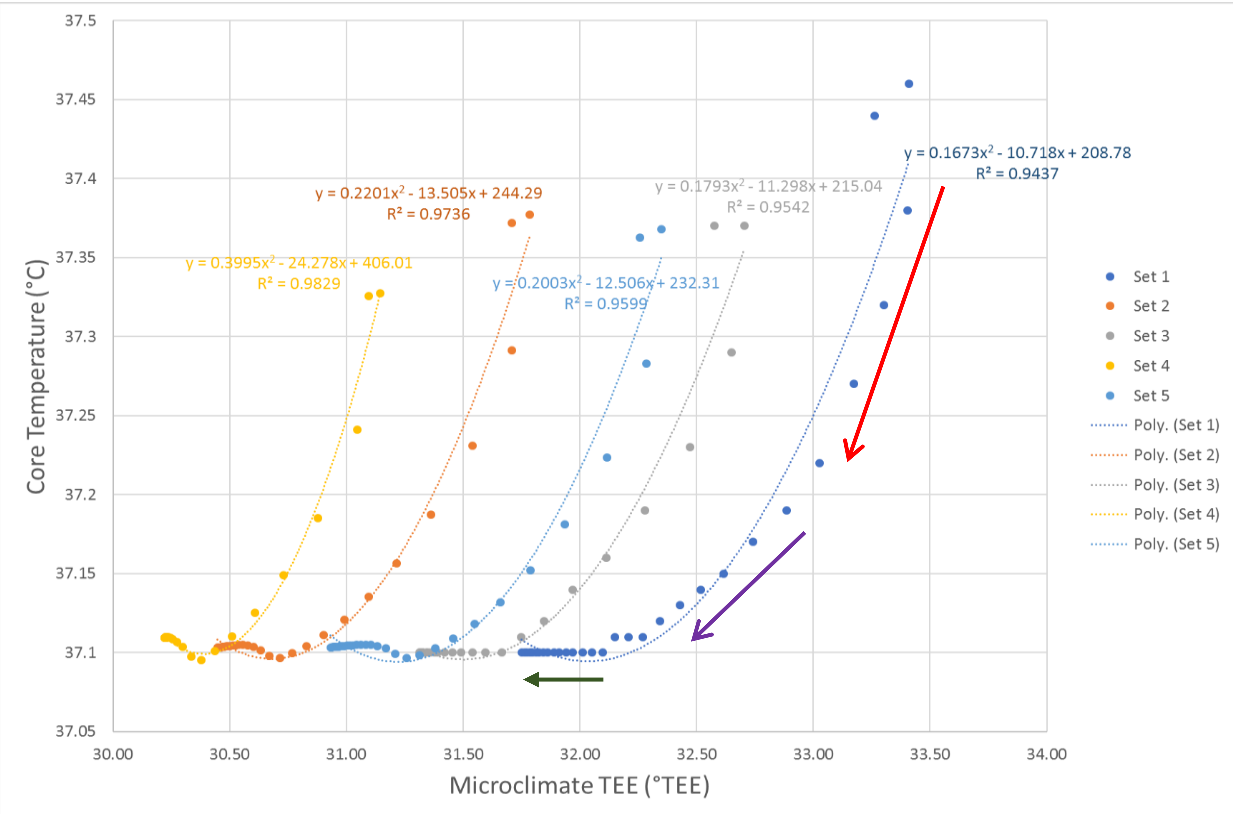



Fig. 5.16 Relationship between $TEE_{cmc}$ and $T_{core}$ during resting

## 5.7 Discussion

S-smart efficiently simulated $T_{skin}$ and $RH_{skin}$ but not the heart rate. Therefore, only the core temperature is used in the analysis of thermal stress, but not PSI. Assuming that $T_{skin}$ and $RH_{skin}$ are the temperatures and relative humidity between skin and clothing (i.e. $T_{cmc}$ and $RH_{cmc}$). The thermal stress can be identified by $TEE_{cmc}$ which is calculated by $T_{cmc}$ and $RH_{cmc}$.

The results show that the simulated $T_{core}$ increase when $T_{skin}$ increase in the body regulatory system, due to an increase in the blood flow and the vasodilatation of a blood vessel near skin respectively (Laing, 2002). The body heat was released from the skin by convection, conduction, and radiation (Bejan, 1993) (Dorkin, 1997). The simulated results show that $T_{core}$ in uniform Set 1 was the hardest to reduce and the $T_{skin}$ of Set 1 was the highest in both walk and rest phases. The efficiency of heat release was the lowest in two-layer and non-moisture-managed fabric. In contrast, uniform Set 4 has the lowest $T_{core}$ and $T_{skin}$ benefited from the better heat release through the short-sleeve T-shirt and moisture managed fabric. These two results explained the importance of the fabric properties and clothing designs of firefighter uniform in terms of thermal stress.

The long sleeves of uniform (Set 1, 3 and 5) reduced the heat and moisture transfer between skin and surroundings. The RH setting of surroundings was 70%. The direct skin exposure to surroundings was higher in short-sleeve uniform (Set 2 and 4) than a long sleeve of the uniform. Therefore, the initial value of simulation (47% $RH_{skin}$ in uniform Set 1,3 & 5, 70% $RH_{skin}$ in Set 2 & 4 was affected by the clothing design.

The results of the three pairs of comparison between fabric layer, sleeve type, and fabric properties confirm that the simulated and experimental results of $T_{core}$ and $TEE_{cmc}$ are the same. However, it is difficult to validate the actual data in the simulation due to the assumptions including no impact of subject's personal sensation and limitations including the unmeasurable physiological data of the subject and other excluded fabric properties. Even so, the simulated and experimental results in the comparison between different clothing designs were well matched with each other.

In S-smart, the protocols of simulation cannot be the same as the protocol in Chapter 4 since firefighter need to wear PPE during walking and put off PPE during resting. Since S-smart can only choose one set of clothing combination in a protocol, wearing PEE in the whole experiments is suggested for a comparison of the computed $TEE_{cmc}$ changes with experimental measurements.

## 5.8 Conclusion

This chapter demonstrates the application of S-smart simulation of $T_{core}$ and $T_{cmc}$ in the comparisons between 1) two-layer and one-layer clothing, 2) non-moisture-managed fabric and moisture managed fabric and 3) short-sleeve and long-sleeve clothing. It found that the two layers, moisture managed and short sleeve clothing gave a lower thermal stress. The results of the simulation were the same as the experiment result reported in Chapter 4. Moreover, the $T_{core}$ and $TEE_{cmc}$ showed a positive linear relationship in the walking session and a nonlinear positive relationship in resting session.

# Chapter 6 Conclusion and future work

## 6.1 Conclusion

This study aims to develop and verify a heat stress index called "equivalent effective temperature of clothing microclimate" ($TEE_{cmc}$) that was used to identify the thermal stress in high-risk occupations such as firefighters when they wore firefighter uniforms under highly insulated personal protective equipment (PPE) during simulated firefighting rescue in two experiments and computer simulation. All the objectives have been achieved in the studies.

According to the physiological responses of firefighters when they undertook the simulated-firefighting training in the training center, the vigorous physical activity induced dangerously high values of physiological responses of $T_{core}$, and HR. The clothing microclimate temperature and humidity also indicated that the firefighters had been exposed to the danger category of heat illness during the training sessions. It implies that 30-min rest should be provided after 60-min to 80-min duties for the firefighters to dissipate heat loads and prevent heat illness. To ensure health and safety, a newly proposed heat stress index of microclimate, $TEE_{cmc}$ has been developed which is better than the existing TEE of the ambient environment because the microclimate under the high insulated PPE is the most important to the firefighters.

To verify the new index of $TEE_{cmc}$, another experiment of five sets of firefighter uniforms during walking and resting in a controlled climate chamber was conducted. PSI and $TEE_{cmc}$ had a positive linear relationship in both the training center and the controlled chamber. Therefore, it is feasible to apply $TEE_{cmc}$ index to supplement the PSI in the measurement of the thermal stress of the firefighters since the measurement of parameters and data in $TEE_{cmc}$

($T_{cmc}$ and $RH_{cmc}$) is relatively simpler and $TEE_{cmc}$ was not affected by psychological sensations of subjects.

Regarding the effects of different designs and fabric properties of firefighter uniforms on thermal stress, Moisture managed fabrics reduced the thermal stress of the subjects because they allow better moisture evaporation and heat release through the clothing microclimate. Single layer clothing (Set 1 and Set 3) short sleeve uniform caused lower thermal stress in all activities. The effects of fabric and design were more significant during the resting period since the effects of uniform have been overridden by the high-insulated PPE being worn during walking sessions. Therefore, future studies into the effects of garment designs on the thermal stress reduction inside high insulated clothing should include the resting sessions in the experiment.

In the S-smart computer simulation of the thermal stress of the firefighters wearing different uniforms, the $TEE_{cmc}$ results have been verified and compared with experimental results. It found that the two layers, moisture managed and short sleeve clothing gave a lower thermal stress. The results of the simulation were the same as the experiment result. Moreover, the $T_{core}$ and $TEE_{cmc}$ showed a positive linear relationship in the walking session and a nonlinear positive relationship in resting session.

## 6.2 Future work

The major objectives of this study have been achieved. This established an important foundation for further studies on relative topics of different protective equipment for different high-risk occupations in different environments.

Application of $TEE_{cmc}$ for the construction worker or astronaut to maintain a comfortable portable environment under protective clothing.

Apart from the physiological responses, related subjective sensations may also affect the thermal comfort and the performances of uniform. It will be valuable to investigate the relationship between subjective sensations and $TEE_{cmc}$ to further enhance the application of this index.

Although the effects of moisture managed, short-sleeve and single layer uniform is a benefit to thermal stress reduction, the high insulated PPE still increase the thermal stress of firefighter significantly. Further research can be focused on the design of PPE for the firefighters.

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