Thermal strain and its alleviation in workers wearing firefighting protective clothing

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Thermal strain and its alleviation in workers wearing firefighting protective clothing

消防用防火服着用時の暑熱ストレスとその軽減法に関する研究

2009 年 1 月

周　金枚

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Abstract

The objectives of this study were to investigate the relationship between clothing property factors and physiological effects, and techniques for alleviating physiological strain and enhancing the performance of firefighters on physiological and subjective responses while wearing protective clothing (PC). The studies measured rectal temperature (*Tre*), mean skin temperature ($\bar{T}sk$), heart rate, body weight loss and subjective responses.

The first study examined the relationships between clothing properties and the physiological effects on physiological/subjective responses for four types of PC and a light work garment. Eight male firefighters performed a bicycle ergometer exercise at 30%, 45% and 60% of $\dot{V}_{O2peak}$ for 10 minutes each at 30ºC. Clothing surfaces coated with aluminized sliver (PC2) compared to other PCs were almost the same or lower in regard to clothing weight and thermal insulation (clo-value). The latent heat resistance of PC2 was the greatest. Physiological and subjective heat strain experienced while using PC2 was greater than other PCs. The physiological strain of firefighting protective clothing, shown in the difference between *Tre* and $\bar{T}sk$, depends more upon resistance to latent heat than clothing weight and clo-value, suggesting that latent heat

resistance is more closely related than clothing weight or clo-value to the physiological effects.

The second study examined the effectiveness of ice-packs (ICE) and phase change material (PCM) cooling devices in reducing physiological load based on subjects' physiological/subjective responses while exercising on an ergometer and wearing protective clothing at 30ºC. Eight non-firefighter subjects participated in four exposures: control (CON), ICE, PCM at 5 ºC (PCM[5]) and 20 ºC (PCM[20]), rested for 10 minutes, performed 30 minutes, exercise at 55% $\dot{V}_{O2peak}$, and had a 10 minute-recovery period. An increase in *Tre* for PCM(5) and PCM(20) which was less than that for CON and ICE was observed. The increases in $\bar{T}sk$ were lower while using cooling devices, and the cooling effects of PCMs were greater than that of ICE. The larger surface cooling area, higher melting temperature and softer material of PCMs, which reduce absorption capacity, caused a decrease in *Tre* and $\bar{T}sk$ for PCM(5) and PCM(20) which was more than that for CON and ICE. Furthermore, PCM(20) does not require refrigeration. PCM(20) is more effective than other cooling devices in reducing physiological load at 30°C.

The final study examined the effects of wearing trousers/shorts under firefighting protective clothing with PCMs on physiological/subjective responses with exercise on a treadmill at 4.8 km·h^{-1} with a 3% gradient at 30ºC for 30 minutes (the average Japanese actual firefighting task time) and the mobility of firefighters. Performance was improved while wearing shorts under protective clothing with PCMs, although no significant difference in reducing thermal stress while wearing shorts instead of trousers was revealed.

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• Chapter 1

General Introduction

1.1 Hazards of firefighting activities

Firefighters have special duties that place them at high risk in regard to personal safety during the course of duty. This risk is associated with emergent danger, uncertainty and unpredictability. General emergency scene hazards for firefighters involve physical, environmental, chemical, biological, thermal, electrical, radiation-related, and equipment hazards (International Association of Fire Fighters, 2003).

In Japan, there were 18 deaths of firefighters during firefighting activities, firefighting training, and occupational tasks in 2002. 2,545 firefighters were reported injured according to the Fire and Disaster Management Agency (2003). Furthermore, in the United States 52 percent of firefighters have reported injuries, and of those, 10 percent involved burns while 22 percent were caused by excess fatigue (Karter and Leblance 1995; Ross, 2003). Moreover, in incidents resulting in death, over 50 percent (23 out of 43) were caused by heart attacks and 48 percent by heat stress. (Washburn et al., 1996; Ross, 2003).

1.2 The structure and efficiency of protective clothing

Firefighting protective clothing is what firefighters wear when they perform firefighting or rescue activities at fire scenes. Therefore, high heat-resistance and flame-resistance are required for clothing to protect firefighters from heat and flames experienced during firefighting activities (Pandolf and Goldman, 1978; Speckman, 1988; Nunneley, 1989; Faff and Tutak, 1989; White and Hodous,1989; White et al., 1991b; ISO11613, 1999; Graveling and Hanson, 2000). Firefighting protective clothing consists of capsulated type clothes with high thermal resistance. Firefighting protective clothing generally consists of outer and inner layers to block flame, and decrease shock from falling objects (Faff and Tutak, 1989). Firefighting protective clothing in such multilayer construction is mainly of the fully encapsulated types which have an extremely high thermal resistance, resulting in high heat insulation capacity (Raheel, 1994). The total weight of a firefighter's equipment, which includes heavy self-contained breathing apparatus and firefighting clothing (the clothing itself is heavy and bulky) in actual firefighting activities, reaches as much as 25 to 35 kg and the burden caused by the weight is remarkable (Gavhed and Holmér, 1989; Simth et al., 1997; von Heimburg et al., 2006; Eglin, 2007).

However, heat-resistance, flame-resistance and water-resistance lead to clothing with poor moisture permeability which does not allow the release of sweat or evaporation, that is, the clothing restricts the release of latent heat produced by sweating (Ftaiti et al., 2001), because it is made with materials which do not allow liquids or gases to pass. With heat storage due to physical metabolism and the thermal burden from the external environment, firefighters experience an excessive thermal load. Therefore, it is critical to design high-quality firefighting protective clothing to raise the concentration levels on the job of battling the blaze and rescuing trapped persons, and also to reduce the risk.

Physiological and subjective responses while wearing firefighting protective clothing should be considered. Consequently, firefighting protective clothing has been developed to protect the human body from the external environment and to reduce the risk of thermal load at the same time (Faff and Tutak, 1989; Simth et al., 1997; Holmér, 2006; Eglin, 2007).

1.3 Physiological strain of protective clothing

During the past decades, interest in protective clothing research for worker safety and health in hazardous environments has grown. The Occupational Safety and Health Administration and the Environmental Protection Agency have issued guidelines, recommendations, and rules for worker safety in various occupational hazard situations. Moreover, industry and independent organizations have developed standards for personal protective equipment such as the International Organization for Standardization and the European Standardization Organization (Raheel, 1994; Holmér , 2006).

Figure 1.1 shows a representation of the multidimensional problem of physiological strain factors on physiological and subjective responses during firefighting activities with protective clothing. Many studies have been carried out to investigate the effects of firefighting activities in high temperature and humid environments on physiological responses (Duncan et al., 1979; O'Connell et al., 1986; Romet and Frim, 1987; Davis and Dotson, 1987; Gavhed and Holmér, 1989; White et al., 1991b; Shults et al., 1992; Holmér, 1995; Nakayama, 1998; Baker et al., 2000; Machida et al., 2000; Ikuno et al., 2002; Mclellan and Sellirk, 2004; Eglin et al., 2004;

Eglin, 2007; Reinertsen et al., 2008), and thermal sensation (Aoyagi et al., 1998; Holmér, 1995). In order to develop materials leading to less thermal stress, many studies have been carried out and reported by Kunimoto et al. (1987), Mäkinen et al. (1988), Veghte (1988), and Richardson and Capra (2001). Moreover, there have been many studies which reported that the clothing weight and insulating properties of protective clothing impose additional heat stress on humans (Whitle and Hodous, 1989; Nunneley 1989; Graveling and Hanson, 2000). Several studies have been carried out to investigate the effects of self-contained breathing apparatus during maximal exercise on humans (Raven et al., 1977; Manning and Griggs, 1983; Tsdua et al., 1986).

The above studies have been conducted to investigate physiological load and clothing properties; there are, however, few that have taken up psychological effects such as comfort when working in firefighting protective clothing. Moreover, Davis and Santa Maria (1975) mentioned that while wearing firefighting protective clothing under a moderate workload, a firefighter's working efficiency decreased by 33% before working at strenuous firefighting activity. It is necessary to consider the design of firefighting protective clothing in the future from a viewpoint that includes both physiological and psychological effects such as the alleviation of physiological load and the easing of discomfort caused by the clothing, to allow firefighters to concentrate on their firefighting activities and to perform efficiently. Protective clothing needs to be designed to be more efficient.

Other studies have been carried out to investigate actual firefighting activity or protective clothing ensembles via questionnaires and/or simulated firefighting tasks (Lemon and Hermiston, 1977; Kunimoto et al., 1993; Bilzon et al. 2001; Nakahashi et al., 2003; Havenith and Heus, 2004) as well as investigating the fitness levels and physical ability of experienced and novice firefighters (Borghols et al., 1978; Ito et al., 1999; Fukasaku et al., 2005; Lalić et al., 2007; Richmond et al., 2008), but little is known about the requirements for protective clothing and experience of heat illness during actual firefighting in firefighters. In the next section, a questionnaire survey regarding firefighters' protective clothing is shown.

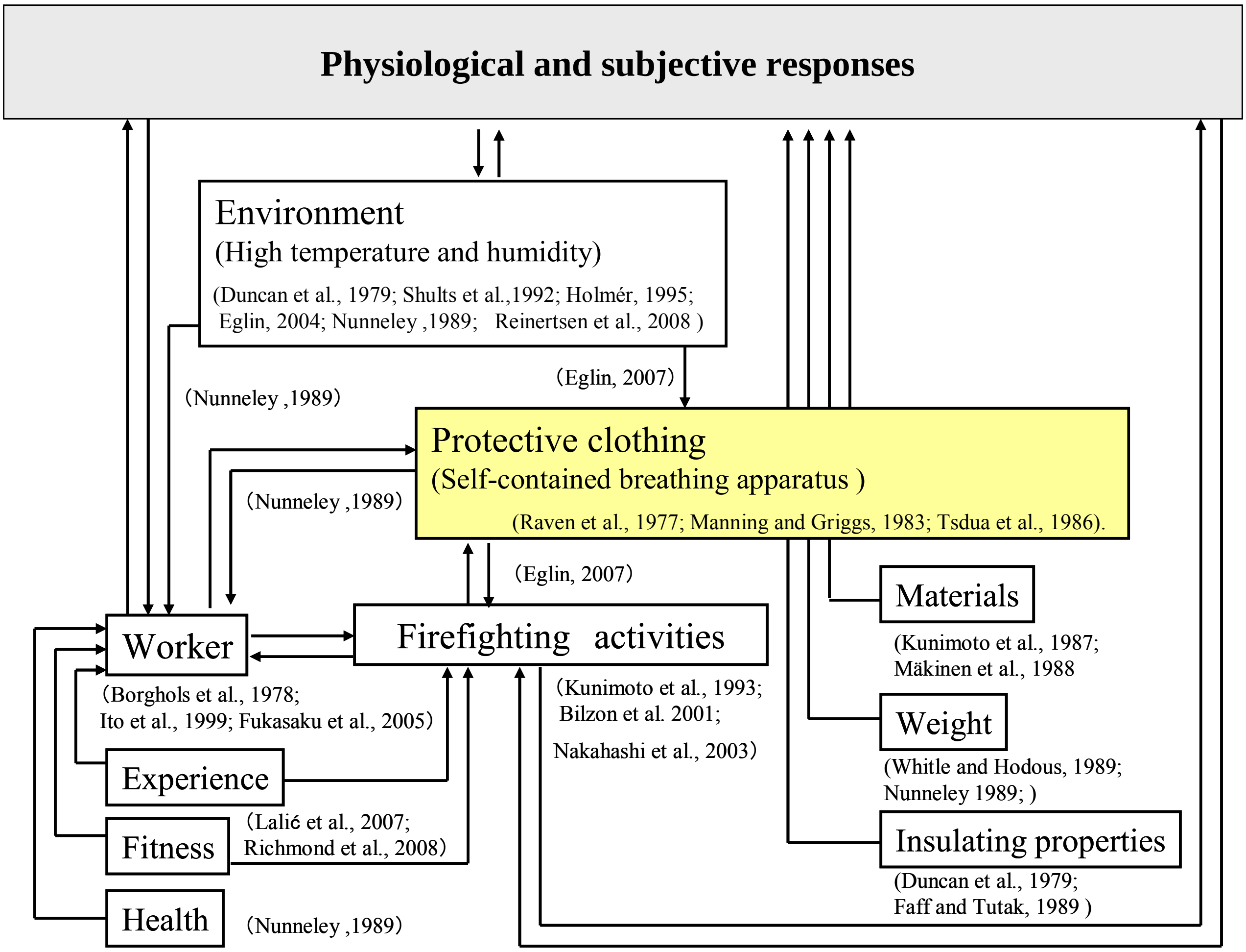

Figure 1.1. Diagram of physiological strain factors on physiological and subjective responses during firefighting activities with protective clothing

1.4 The questionnaire survey on firefighters' protective clothing

1.4.1 Introduction

Firefighters conduct dangerous missions. Firefighters' protective clothing should be designed with great heat, flame, and water-resistant properties to protect wearers (ISO11613, 1999). On the other hand, it must also be designed to alleviate physiological strain and discomfort. Strain and discomfort occur when wearing protective clothing in conditions of great thermal storage by the body's metabolism and heat stress from fire (Smith et al., 1997; Baker et al., 2000; Havenith and Henus, 2004). Although a large number of studies have been made using questionnaires for firefighters (Lemon and Hermiston, 1977; Kunimoto et al., 1993; Bilzon et al. 2001; Nakahashi et al., 2003; Havenith and Henus, 2004), little is known about the requirements for protective clothing and experience of heat illness during actual firefighting.

This study conducted a questionnaire survey with 796 Japanese firefighters to investigate their experience of heat illness during practice and firefighting work and their evaluation of their protective clothing.

1.4.2 Methods

Subjects and period

The participants for this study were 796 firefighters, 792 male and 4 female, from 16 fire departments in Japan. The average physical characteristics of the subjects were age 39.8 years (from 18 to 60 years); height 171.2cm (from 157 to188 cm); weight 69.1kg (from 45 to 104 kg). This study was conducted in October and November 2004.

A questionnaire included the following items:

1) Basic Information on each subject

2) Priorities for protective clothing selection

   Protection and safety, ease of movement, and comfort

3) Trouble experienced with protective clothing during the previous year

- Due to heat
- Due to cold
- Due to difficulty of movement
- Due to burn injury
- Due to it being torn

4) Evaluation of PC worn the previous year

- Ease of putting on and taking off protective clothing
- Ease of movement
- Light weight
- Not excessively stiff
- Not excessively hot while wearing protective clothing
- Flame resistance
- Degree of waterproofing
- Not excessively cold while wearing protective clothing

1.4.3 Results

1) Priorities for protective clothing selection

Firefighters ranked degrees of importance for protective clothing selection on 3 factors: protection and safety, ease of movement, and comfort (**Figure 1.2**). Ease of movement ranked higher than protection and safety, and comfort.

2) Difficulties experienced while firefighting

Firefighters were asked to describe difficulties they experienced while working (**Figure 1.3**). 48.6% had experienced feeling very ill because of heat during the previous year.

The second highest (41.0%) response rate was the experience of restricted movement while firefighting. 16.3% of the firefighters had experienced tearing whilst wearing their protective clothing.

Follow-up questions were asked to the 387 firefighters who had experienced heat illness. The number of times they had experienced heat illness was an average of 3, while about 30 firefighters had experienced it over 10 times. The questions regarding handling heat illness resulted in multiple answers (**Figure 1.4**). 79.1% had gone on firefighting at some time in spite of feeling ill. 40.1% had stopped firefighting for some time during the year. Symptoms of heat illness were dehydration for over 40% of firefighters and dizziness or nausea for 40%. **Figure 1.5** shows the periods and times for firefighters who had experienced heat illness. Heat illness was experienced most often in July (27%) and August (49.4%), between 1-2 pm (41.4%).

3) Evaluation of protective clothing in current use

Firefighters were asked to rank their current protective clothing according to five grades. The questions involved the following aspects of protective clothing: ease of putting on and taking off, ease of movement, thermal sensations, and protective properties, etc. (**Figure 1.6**). Firefighters' evaluation indicated that they felt discomfort arising from heat and dampness while wearing protective clothing. A five-grade evaluation of protective clothing produced a response of “poor” or “somewhat poor” from over 70% of firefighters for heat and dampness. The next highest levels of complaints were for ease of movement, weight, and stiffness of protective clothing, producing a response of “poor” or “somewhat poor” from about 40% of firefighters. Regarding ease of putting on and taking off protective clothing, flame resistance and thermal properties against cold, they evaluated their protective clothing ‘poor” or “somewhat poor” at a rate of less than 30%.

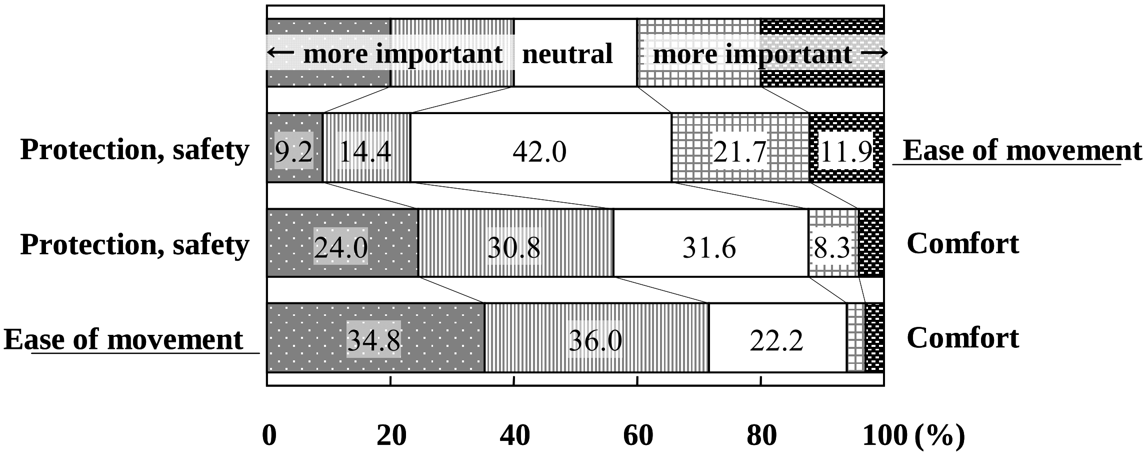

Figure 1.2. Degrees of importance for protective clothing selection

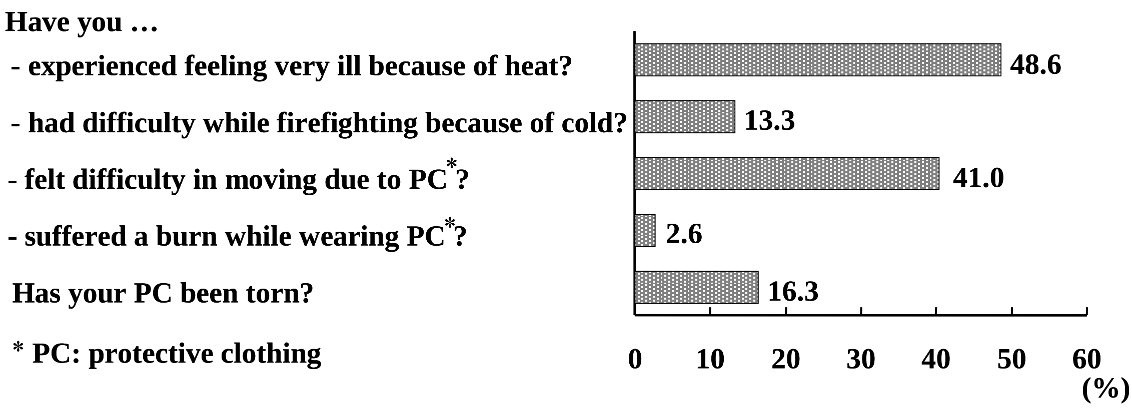

Figure 1.3. Difficulties experience while firefighting

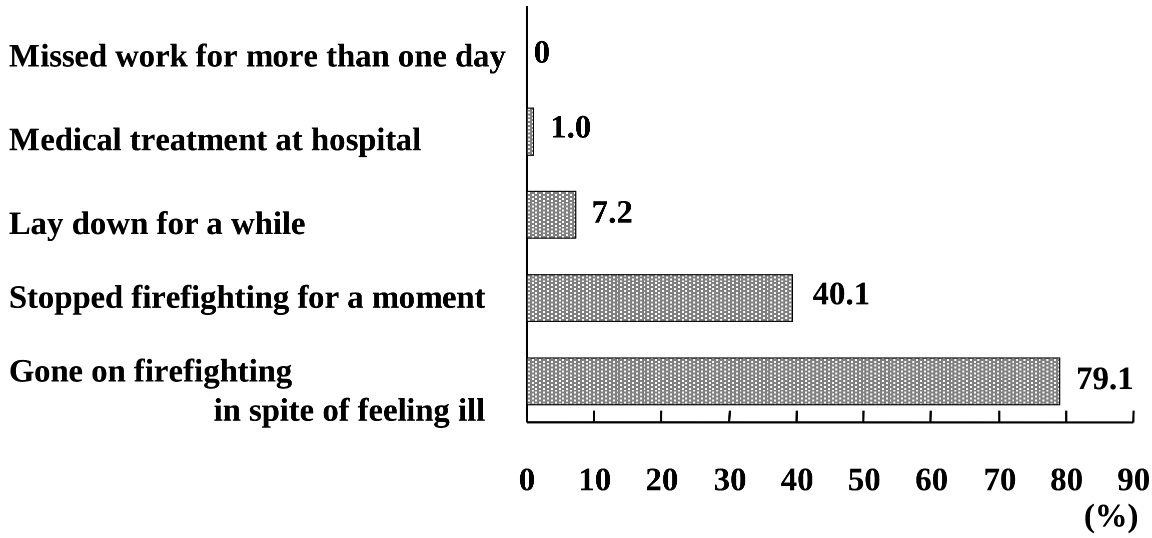

Figure 1.4. Handling heat illness

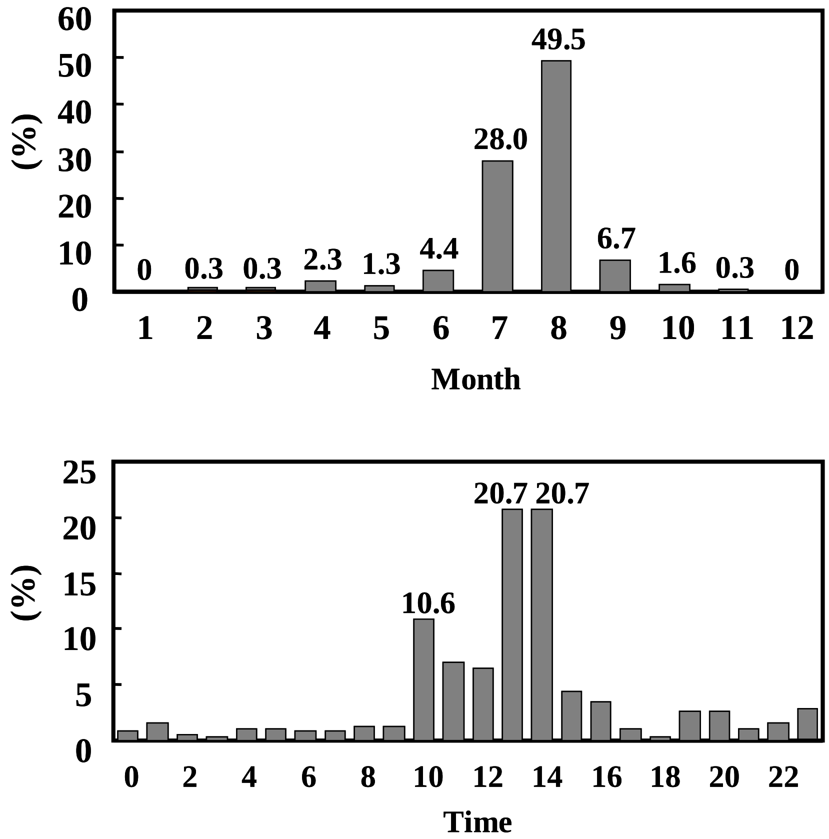

Figure 1.5. The periods and times for firefighters who experienced heat illness

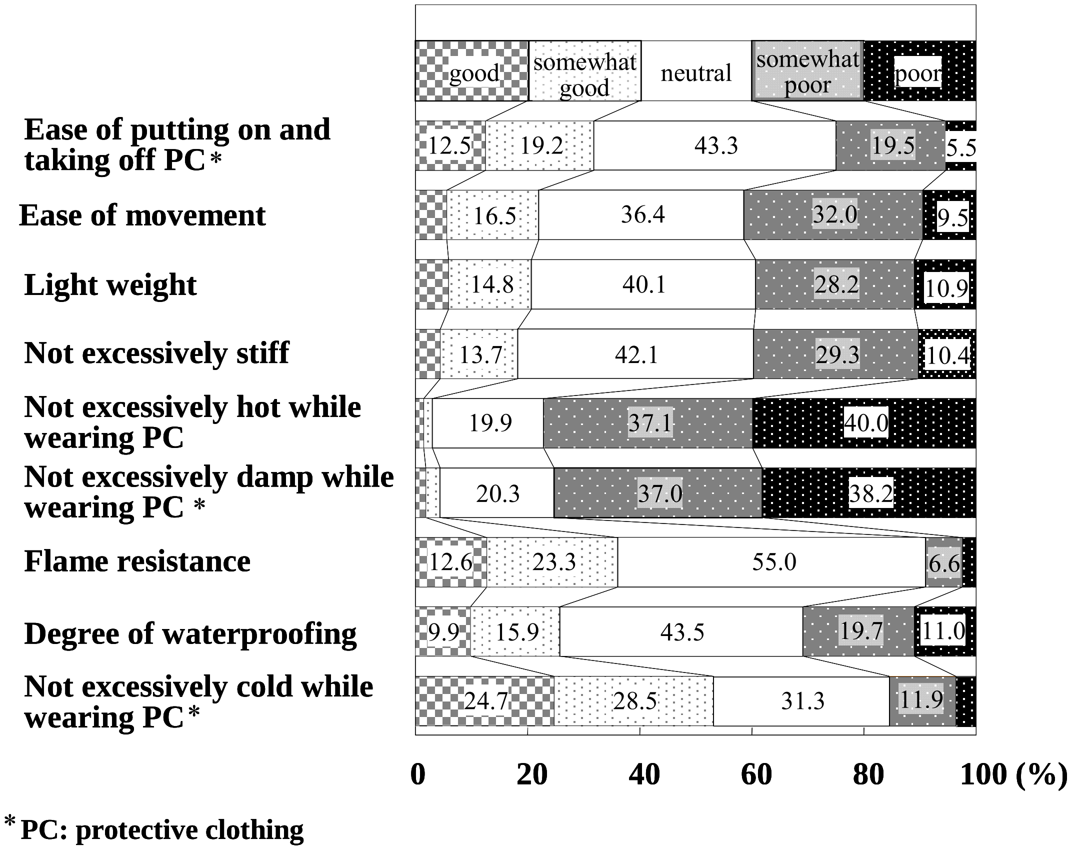

Figure 1.6. Evaluation of protective clothing

1.4.4 Discussion

Priority for protective clothing selected by firefighters ranked ease of movement during firefighting work higher than protection and safety, and comfort as shown in **Figure 1.2**. However, the most common difficulty (48.6%) experienced while working was heat illness (**Figure 1.2**). Next, they also felt restricted movement while firefighting (41%). It was found that heat illness was induced during the hottest hours of the day in summer. About 80% of firefighters had gone on firefighting in spite of heat illness, while 40% of firefighters who had suffered more severe heat illness had taken countermeasures like short breaks (**Figure 1.4**).

These results suggested that firefighters tended to select protective clothing for work performance over their own comfort and safety during firefighting. This might cause a higher risk of heat illness, leading to wearers experiencing feelings of extreme discomfort. Firefighters also felt discomfort arising from heat and dampness while wearing protective clothing (**Figure 1.6**). Moreover, the frequency of heat illness rose as evaluation of protective clothing scored worse in terms of heat, dampness, and weight. Therefore, protective clothing design must consider comfort and usability to avert the risk of heat illness and concentrate firefighters on efficient firefighting, in addition to protective properties to reduce heat stress.

1.5 Alleviating physiological strain and discomfort

An exterior thermal load is added to the heat stock from the body metabolism that causes an excessive heat load upon firefighters. While the functions of firefighting protective clothing have improved, there is still the possibility that the physiological load on firefighters may increase. The questionnaire survey on 792 firefighters, reported that 48.6% had experienced feeling very ill because of heat during the previous summer. Therefore it is important to examine the reduction methods of thermal stress on firefighters from protective clothing.

Several different techniques such as using cooling devices (including ice, dry ice, and air-cooled and water-cooled modes of cooling), misting, fans, forearm submersion, etc (Bennett et al., 1957; Konz et al., 1974; Smith et al., 1997; Bishop et al., 1991; White et al., 1991a; Nag et al., 1998; Carter et al., 1999; Muir et al., 1999; Monobe et al., 2002a, b; Duffield et al., 2003, 2007; Price and Mather 2004; Ross et al., 2004; Selkirk et al., 2004; Carter et al., 2007) are available to extend work capacity in the heat and to accelerate rehabilitation from hyperthermia. It has been found that using a cooling vest with ice-packs can reduce heart rate, skin temperature and perspiration rate (Muir et al., 1999; Webster et al., 2005). Bennett et al. (1995) and Carter et al. (1999)

have reported that torso cooling attenuates the rise in core temperature with reductions of 0.4 to 1.7 ºC in a variety of occupations, including firefighters. Recently, the use of phase change materials (PCM) has been applied in many fields, such as in garments, home furnishings and cooling products (see Appendix A). Pause et al. (2003) and McLellan and Frim (1998) reported that a protective suit with PCM can slow down the rate of temperature increase and prevent heat stress. PCM can reduce thermal stress and provide improved thermal comfort for wearers of protective clothing (Mondal, 2008; Reinertsen et al., 2008).

An additional technique of alleviating the impact of excessive heat strain is using hand and forearm cooling, as an effective technique to accelerate recovery from hyperthermia (House et al., 1997; Selkirk et al., 2004; Carter et al., 2007). Hand and forearm immersion in cool water at 10ºC and 20ºC reduced heat strain quickly and effectively dropped from 1.2 to 1.6ºC for 25-30 minutes to accelerate recovery from hyperthermia in heavy firefighters clothing (House et al., 1997). Moreover, Selkirk et al. (2004) found that using forearm submersion at 17ºC reduced heat strain effectively during the first rest period core temperature dropped 0.4ºC, mister reduced heat strain effectively during the first rest period core temperature dropped 0.08ºC (Selkirk et al., 2004; Cater et al., 1999). Fan cooling has been found to attenuate the rise in core temperature by 0.6-0.7 ºC during work and rest periods.

McLellan and Selkirk (2004) and Malley et al., (1999) reported reduced physiological responses when wearing short pants and T-shirts under a firefighting protective uniform, compared with wearing long pants and T-shirts.

Figure 1.7 shows a simplified representation of methods of alleviating physiological strain and discomfort.

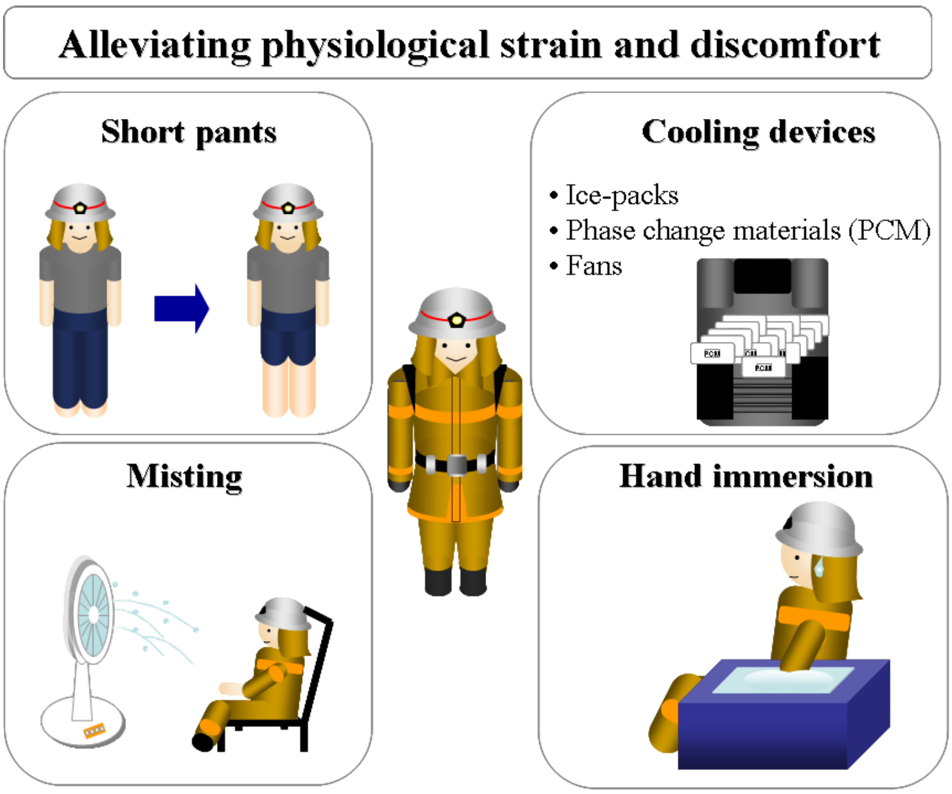

Figure 1.7. Diagram of methods of alleviating physiological strain and discomfort

1.6 Objectives of this thesis

A number of studies have documented the environmental, physiological, and physical stress of physically demanding firefighting duties, which physically demanding. Hence, it is important to design ways of alleviating physiological strain and discomfort in firefighters' protective clothing, in order to protect firefighters.

Therefore, the present study, investigated physiological and subjective responses to different garments during strenuous firefighting activities by examining clothing property factors related to the physiological effects on the firefighter. Techniques of alleviating physiological strain and enhancement of performance while wearing firefighters' protective clothing were also investigated.

1.7 Structure of this thesis

1.7.1

Chapter 2: Effect of clothing properties on physiological and subjective responses of working firefighters' protective clothing

The purpose of this study was to investigate the physiological and subjective responses of four kinds of firefighters' protective clothing and a light work garment during strenuous firefighting activities by examining clothing properties such as clothing weight, thermal insulation (clo-value) and resistance to latent heat, and factors related to physiological effects while wearing for firefighters' protective clothing.

Publication

Chapter 2 has been submitted to the Journal "Industrial Health", under the title "*Effect of clothing properties on physiological and subjective responses of working firefighters' protective clothing*" (Chinmei Chou, Yutaka Tochihara and Mohamed Saat Ismail).

1.7.2

Chapter 3: Physiological and subjective responses to cooling devices on firefighting protective clothing

The purpose of the this study was to examine ice-packs and phase change materials cooling devices for reducing physiological load based on subjects' physiological and subjective responses under the condition of exercising on a bicycle ergometer while wearing firefighting protective clothing in a relatively high temperature environment.

Publication

Chapter 3 has been published in the "European Journal of Applied Physiology", Vol 104 (2), p369-p374, 2008, under the title "*Physiological and subjective responses to cooling devices on firefighting protective clothing*" (Chinmei Chou, Yutaka Tochihara and Taegyou Kim).

1.7.3

Chapter 4*: *Effects of wearing trousers or shorts under firefighting protective clothing on physiological and subjective responses

The purpose of this study was to examine the effects of wearing trousers or shorts under firefighting protective clothing using Phase change materials on physiological and subjective responses with a 30-minute exercise period which is the average Japanese actual firefighting task time.

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• Chapter 2

Effect of clothing properties on physiological and subjective responses of working firefighters' protective clothing

2.1 Introduction

Firefighters work at a variety of strenuous tasks in varied environments while wearing firefighting protective clothing. Hence, firefighters' protective clothing should be designed with great heat, flame, and water-resistant properties to protect wearers. However, it has been reported that protective clothing causes physiological stress, which increases skin temperature, heart rate and core body temperature (Bishop et al., 1994; Duncan et al., 1979; Faff and Tutak, 1989; Smith et al., 1997). Duncan et al. (1979) reported that insulative clothing led to greater physiological strain when working in high temperatures. The strain and discomfort occurred when wearing protective clothing in conditions of great thermal storage from body metabolism and heat stress from fire.

Moreover, Tochihara et al. (2005) conducted a survey of 796 Japanese firefighters to investigate their experiences of heat illness during training, firefighting activities and firefighters evaluation of their protective clothing. It was reported that 48.6% had experienced feelings of illness because of high temperatures during the previous summer.

Davis and Santa Maria (1975) mentioned that while wearing firefighting protective clothing under a moderate workload, walking efficiency decreased by 33% before a firefighter worked at a strenuous firefighting activity. Alleviating physiological strain and discomfort could result in firefighters' increased ability to concentrate on efficient firefighting. It is important to consider that firefighters' protective clothing should be designed to alleviate physiological strain and discomfort.

Thus, although it seems that the development of the material and efficiency of firefighting clothing has advanced in recent years, research has not fully investigated the physiological burden whilst wearing firefighting clothing. Moreover, although much research has been carried out regarding the physiological responses to firefighter protective clothing (Faff and Tutak, 1989; Graveling and Hanson, 2000; Mclellan and Sellirk, 2004), little is known regarding specific clothing property factors pertaining to its physiological effects.

Therefore, the purpose of this study was to describe physiological and subjective responses of four kinds of firefighters' protective clothing and a light work garment during strenuous firefighting activities by examining clothing properties such as clothing weight, thermal insulation (clo-value) and resistance to latent heat, and factors related to physiological effects while wearing firefighters' protective clothing.

2.2 Methods

2.2.1 Subjects

The subjects were eight male Fukuoka City firefighters. The physical characteristics of the subjects were as follows (mean±SD): age 35.8±3.8 years; height 169.9±5.0 cm; weight 68.9±11.2 kg; body mass index 23.9±4.0 $kg \cdot m^{-2}$ and the maximal oxygen consumption 48.6±6.9 $ml \cdot min^{-1} \cdot kg^{-1}$. The subjects were informed of all details of experimental procedures and the associated risks and discomforts. Each subject gave informed consent before participation. This study was approved by the ethical committee of Kyushu University.

2.2.2 Determination of the maximal rate of oxygen consumption

The maximal oxygen consumption ($\dot{V}_{O2\ peak}$) was measured in a room at 30ºC (a relative humidity of 60%) using an expiration gas analyzer (AE300s, Minato Electronics Inc., Japan) conducted on a bicycle ergometer (Aerobike 75XL, Combi Co. Ltd., Japan). The subjects wore light clothing: a T-shirt, shorts, socks and running shoes. $\dot{V}_{O2\ peak}$ protocol was calculated using continuous incremental loading based on Fitchetts (1985). The protocol was divided into 4 phases of 4 minutes duration each, for a total of 16 minutes. Heart rate was monitored for one minute continuously using a Life Scope 6 (Nihon Kohden Co. Ltd., Japan).

2.2.3 Clothing conditions

This study provided five clothing conditions including four kinds of firefighters' protective clothing (PC1, PC2, PC3 and PC4) and a light work garment, which is currently used by several fire departments offices, as a control (CO).

Table 2.1 shows the specifications for the various types of protective clothing conditions. The PC1~PC4 conditions included protective clothing, basic clothing, gloves, boots, and a helmet. The firefighter's a light work garment condition (CO) consisted of a work-shirt, basic clothing, gloves, boots, and a helmet. The CO condition used a protective helmet was different to the PCs conditions helmet, and similar to those worn on building sites. The basic clothing consisted of a T-shirt, trousers, underwear and socks. However, no condition included respiratory protection (self contained breathing apparatus: SCBA).

The clothing weight of the four firefighter's protective garment and a light work garment were as follows- PC1: 2,480 g, PC2: 2,340 g, PC3: 2,160 g, PC4: 1,860 g and CO: 660 g. The thermal insulation (clo-value) of the PC1~PC4 and CO were as follows: - PC1: 1.60, PC2: 1.60, PC3: 1.65, PC4: 1.54 and CO: 1.25 (where 1 clo, or clothing unit $0.155 m^2 \cdot {}^{o}C \cdot W^{-1}$, Gagge et al. [1941]) (data from Tamura, 2007). The resistances to latent heat of the PC1~PC4 and CO were as follows: - PC1: 0.029 $kPa \cdot m^2 \cdot W^{-1}$, PC2: 0.045 $kPa \cdot m^2 \cdot W^{-1}$, PC3: 0.030 $kPa \cdot m^2 \cdot W^{-1}$, PC4: 0.029 and CO: 0.022 $kPa \cdot m^2 \cdot W^{-1}$ (data from Tamura, 2007). PC1 had heavier clothing weight than other conditions. The clo-value of PC3 was higher than other conditions, while PC1 and PC2 were the same values. PC2's latent heat resistance was higher than other conditions. PC1 and PC2 were manufactured with the same water-resistant and heat-insulating material, but there was a difference between PC2 and PC1 in that PC2 had a surface coated by silver aluminized. PC4 used the same heat-insulating layer as PC1; however, PC4 was without a water-resistant layer. All PCs materials were defined by the ISO 11613 (1999) standard except for PC4.

In the PC1~PC4 conditions, the total clothing weight measurement included protective clothing. In the CO condition, the total clothing weight measurement included the work-shirt and trousers. None of the clothing weights for PC1~PC4 and CO conditions included shorts, socks, gloves, boots or helmet.

Table 2.1. Specifications for the various types of protective clothing

	PC1	PC2	PC3	PC4	CO
Base material ($g{\cdot}m^{-2}$)	**Aromatic polyamide 280**	**Aromatic polyamide 280**	**Aromatic polyamide 240**	**Aromatic polyamide 240**	-
Heat insulation ($g{\cdot}m^{-2}$)	**Stripe geometry 200**	**Stripe geometry 200**	**Waffle geometry 150**	**Waffle geometry 150**	-
Water- resistance ($g{\cdot}m^{-2}$)	**Moisture -permeable waterproof film 100~140**	**Moisture -permeable waterproof film 100~140**	**Moisture -permeable waterproof film 100~140**	-	-
Surface layer	-	**Aluminum Coated**	-	-	-
Clothing Weight (g)	**2480**	**2340**	**2160**	**1860**	**660**
Clo-Value	**1.60**	**1.60**	**1.65**	**1.54**	**1.25**
Latent heat resistance ($kPa{\cdot}m^2{\cdot}W^{-1}$)	**0.029**	**0.045**	**0.030**	**0.029**	**0.022**
Photo					

2.2.4 Thermal environments and experiment procedures

The pre-test room acted as a control and was kept at a constant air temperature (T_a) of 25ºC and a relative humidity (*RH*) of 50~60%. The test-room was kept at a constant T_a of 30°C with an *RH* of 50%, and additional infrared heat radiation (1.1 $kw \cdot m^{-2}$) was used during exercise activities only. During exercise activities the black globe temperature started at 30°C rose to 70°C and then fell back to 30°C. The infrared heat radiation was produced using a bank of 375 W photoflood lamps (Toshiba Lighting and Technology Corporation, R100V375WRHE, Japan). Each subject rested in the pre-test room for 40 minutes before entering the test-room where they rested on a bicycle ergometer saddle for another 10 minutes, followed by exercise and recovery in turns of 10 minutes each for a total of 3 cycles.

The cycles are hereafter referred to as Exercise period I (E I), Recovery I (R I), and so on to Exercise III (E III), and Recovery III (R III). The exercise intensity was set at 30%, 45% and 60% of $\dot{V}_{O2\,peak}$ for E I, E II, and E III, respectively (**Figure 2.1, Figure 2.2-a,-b**).

Each subject drank 200 ml of water, and then urinated before testing began.

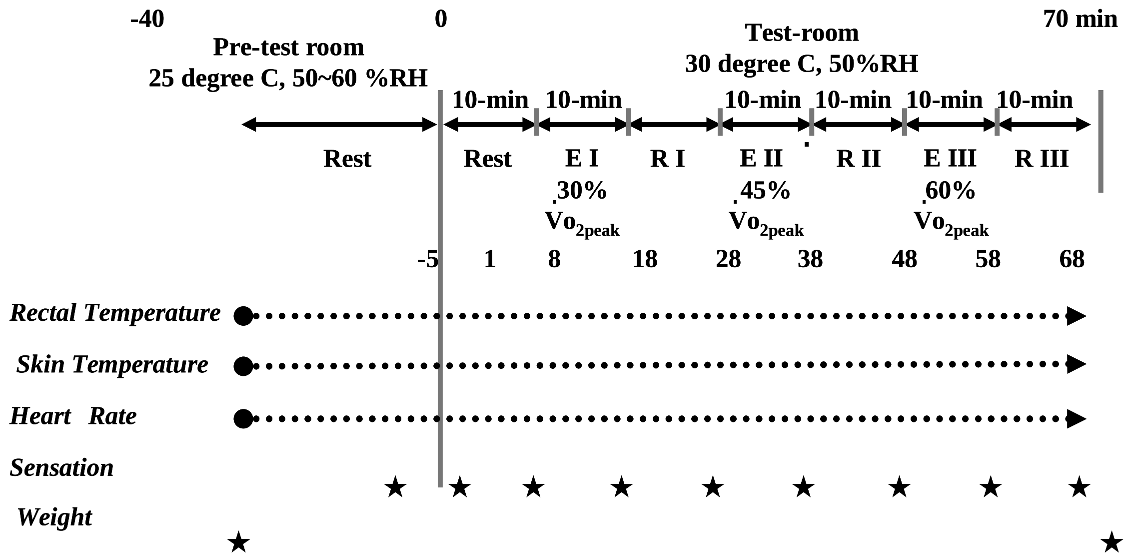


Figure 2.1. Experiment protocol and measurement items

(a) (b)

Figure 2.2. Subject remained on a bicycle ergometer saddle during the rest (a) and exercise periods (b)

2.2.5 Physiological responses

Rectal temperature (*Tre*) and skin temperatures were measured with thermistors. The subjects inserted a thermistor to a depth of 15 cm into the rectum. The skin thermistors were placed on the right side of the body (the head, abdomen, back, forearm, hand, thigh, calf and foot). The mean skin temperature ($\bar{T}sk$) was calculated using Hardy and DuBois' equation (1938). *Tre* and $\bar{T}sk$ were collected on a portable data logger (Gram, LT-8A, Japan). Heart rate was monitored using a Life Scope 6. Body weight loss (*BWL*) was determined using change in body weight (±1 g accuracy) (ID1, Mettler Toledo, Japan) weighing before and after the experiment. The absorbed sweat volume in clothing (*ASV*) was determined using the change in clothing weight (±1 g accuracy) (ID1, Mettler Toledo, Japan) weighing before and after the experiment. The physiological strain index (*PSI*) was calculated as suggested by Moran et al. (1998) as follows:

$$PSI=5(Tre_t-Tre_0)\cdot(39.5-Tre_0)^{-1}+5(HR_t-HR_0)\cdot(180-HR_0)^{-1}$$

Where Tre_0 and HR_0 are the initial Tre and HR, and Tre_t and HR_t are measurements taken in the last three minutes during the E III period. The *PSI* was scaled in a range of 0-10 to evaluate heat stress.

2.2.6 Subjective responses

Subjective responses included thermal sensation, thermal discomfort, humidity sensation and the rate of perceived exertion (*RPE*). The scale of thermal sensation was from slightly cold (-2) to very hot (9). The scale of thermal discomfort was from neutral (1) to very uncomfortable (8). The scale of humidity sensation was from slightly dry (-2) to very wet (7). The rate of perceived exertion was from extremely light (6) to extremely hard (20) (Borg, 1982).

2.2.7 Statistical analysis

The effect of the four kinds of firefighter's protective clothing and a light work garment on all measurements was examined by a two-way analysis of variances (ANOVA) with repeated measures for rest, followed by exercise and recovery in turns of 10 minutes each for a total of three separate cycles (experimental conditions: PC1, PC2, PC3, PC4 and CO; time). Scheffe's post hoc comparisons were used to assess significant main effects using ANOVA. In the E III period, the values were analyzed using Pearson's correlation coefficient of variance. Statistical significance was set at $p<0.05$. The values were presented as mean values with standard deviation (SD).

2.3 Results

2.3.1 Physiological responses

Rectal temperature and mean skin temperature

Rectal temperature for eight subjects for one hour fifty minutes duration in the five conditions is shown in **Figure 2.3**. The *Tre* showed almost the same transition from beginning to end under all conditions, with a gradual increase following the start of the exercise. The *Tre* was 38.2±0.3°C at its highest for PC2, 38.0±0.4°C, 37.9±0.4°C, 37.8±0.2°C for PC1, PC3, and PC4 at the E III period. The *Tre* at PC2 was significantly higher compared to CO conditions ($p<0.05$). The *Tre* was 38.8±0.4°C at its highest for PC2, 38.4±0.5°C, 38.5±0.6°C, 38.4±0.6°C for PC1, PC3, and PC4 in R III period at the end of the experiment. The *Tre* at PC2 was significantly higher compared to PC4 and CO conditions ($p<0.05$~0.001).

The mean skin temperature at PC2 showed a significantly higher difference than PC3, PC4 and CO conditions at the E III period ($p<0.01$~0.001). During the R III period, PC2 was significantly higher compared to all other conditions ($p<0.01$~0.001). However, no significant differences were found between PC1, PC3 and PC4.

Difference between *Tre* and $\bar{T}sk$ ($Tre - \bar{T}sk$) showed approximately 3°C at almost the same transition from beginning to the end under all conditions, with a gradual decrease following the start of the exercise. There was a significant decrease below 0 °C in $Tre–\bar{T}sk$ at PC2 at the end of E III period (p<0.001) and the difference for PC2 was significantly lower than for PC4 and CO (P<0.05). During the R III period, the PC2 were significantly lower compared to PC3, PC4 and CO conditions (p<0.05~0.001) (**Figure 2.4**).

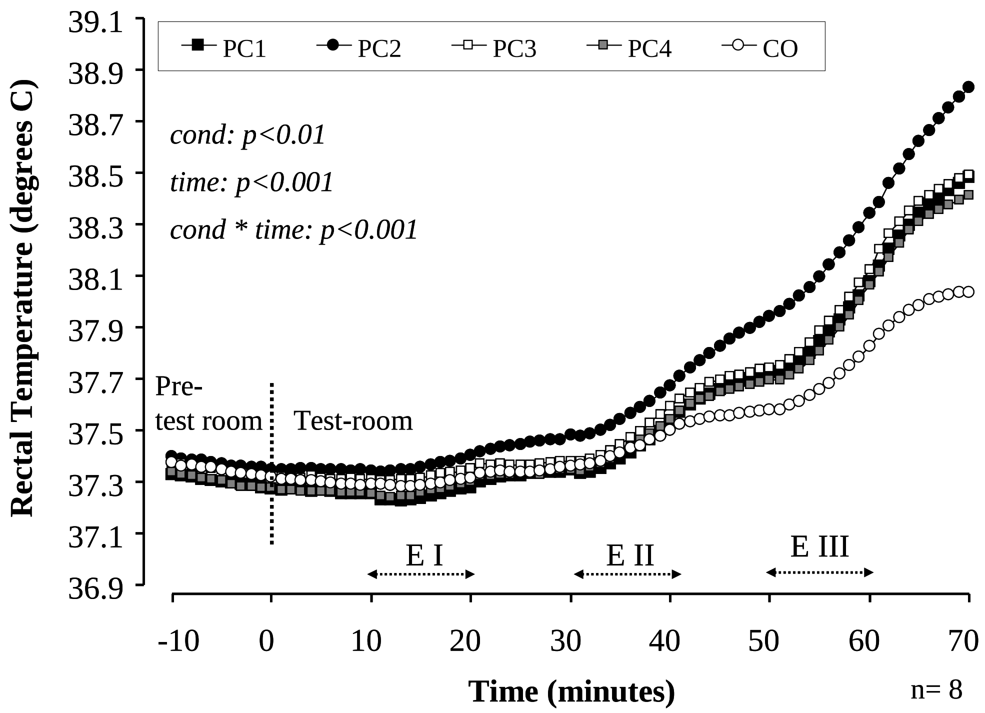


Figure 2.3. Time courses of the rectal temperature (Tre) of PC1~PC4, and CON. Values are means.

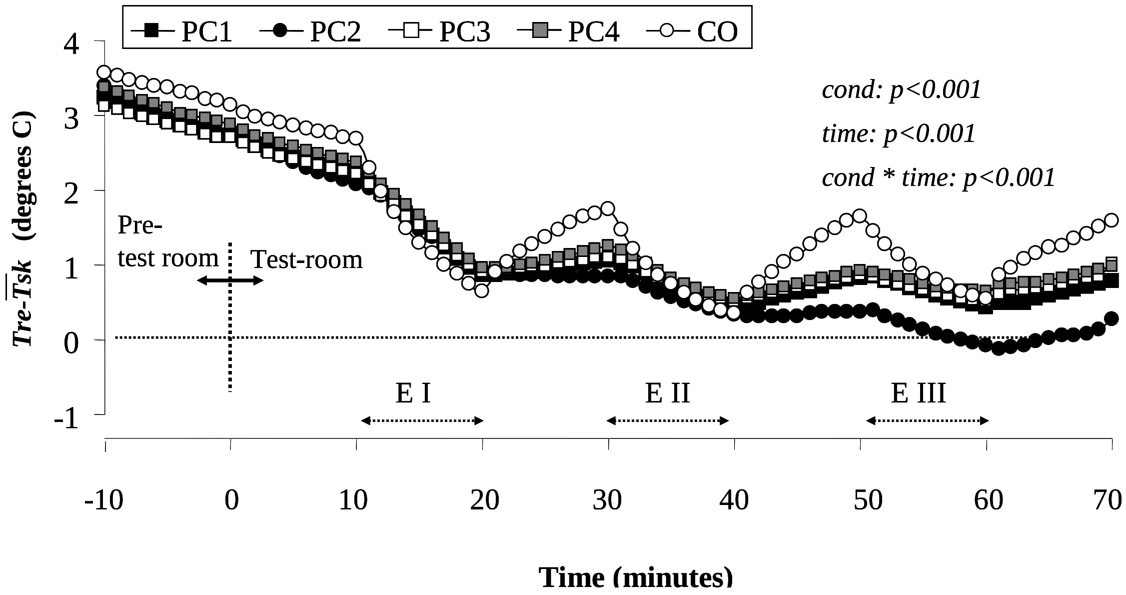


Figure 2.4. Time courses of the difference between rectal temperature and mean skin temperature of PC1~PC4, and CON. Values are means.

Heart rate

In **Figure 2.5**, *HR* increased during all exercises across time in the five conditions and decreased during all recovery periods. At the E III period, *HR* of PC2 (183.2±10.8 beats·min^{-1}) was significantly ($p<0.001$) higher compared to PC4 and CO, however, no significant difference was found between PC1, PC3 and PC4. At the R III period, the *HR* of PC2 was significantly higher compared to all other conditions ($p<0.01$~0.001).

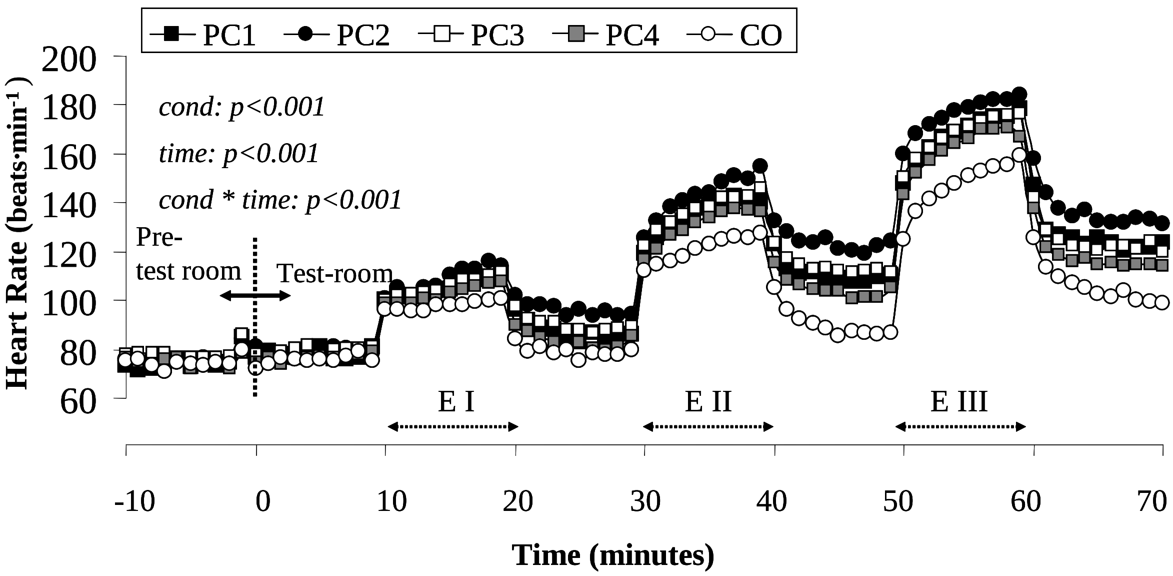


Figure 2.5. Time courses of the heart rate (HR) of PC1~PC4, and CON. Values are means.

Physiological strain index

The physiological strain index was greatest in PC2 at 9.2±2.1, followed by PC1 at 7.8±2.0, PC3 at 8.0±2.2, PC4 at 7.1±2.6 and CO at 5.3±1.6. Among PC conditions, the *PSI* of PC2 was significantly greater than in the PC4 condition (p<0.001). The PSI of the CO condition was significantly lower than all protective clothing conditions (*p*<0.001).

Body weight loss

There was a significant effect of the subjects' body weight on *BWL* ($p<0.001$). In four protective clothing conditions, the *BWL* at PC2 (1.3±0.3 kg) was significantly higher compared to PC1, PC3 and PC4 ($p<0.05$, $p<0.001$), however, no significant differences among PC1, PC3 and PC4 were ascertained. The *BWL* of the CO condition (0.8±0.3 kg) was significantly lower than all protective clothing conditions ($p<0.001$).

Absorbed sweat volume in clothing

There was a significant effect of clothing weight on the absorbed sweat volume in the clothing ($p<0.001$). In four protective clothing conditions, the *ASV* at PC2 (0.9±0.2 kg) was significantly higher compared to PC1, PC3 and PC4 ($p<0.001$). A significant difference existed between PC1 and PC4 ($p<0.05$), however, none was apparent between PC3 and PC4, or between PC3 and PC1. The *ASV* of the CO condition (0.3±0.1 kg) was significantly lower than all other protective clothing conditions ($p<0.001$).

2.3.2 Subjective responses

Figure 2.6 shows the time course of thermal sensation under five conditions. There were significant differences in whole body thermal sensation during E III and R III ($p<0.001$), which showed that the subjects with PC2 felt hotter than in the other conditions. However, there were no significant differences observed among PC1, PC3 and PC4 conditions.

Thermal discomfort during E III and R III periods at PC2 was significantly greater than CO condition ($p<0.01$). Similarly, there were significant differences ($p<0.01$) in humidity sensation during E III and R III periods between the PC2 and CO conditions, with PC2 being wetter. Significant differences were again shown in *RPE* during E III and R III periods with the PC2 and CO conditions, with PC2 being harder ($p<0.05$). However, no significant difference was observed among PC conditions in thermal discomfort, humidity sensation and *RPE*.

The physiological and subjective responses data for E III period for the five conditions are presented in **Table 2.2**.

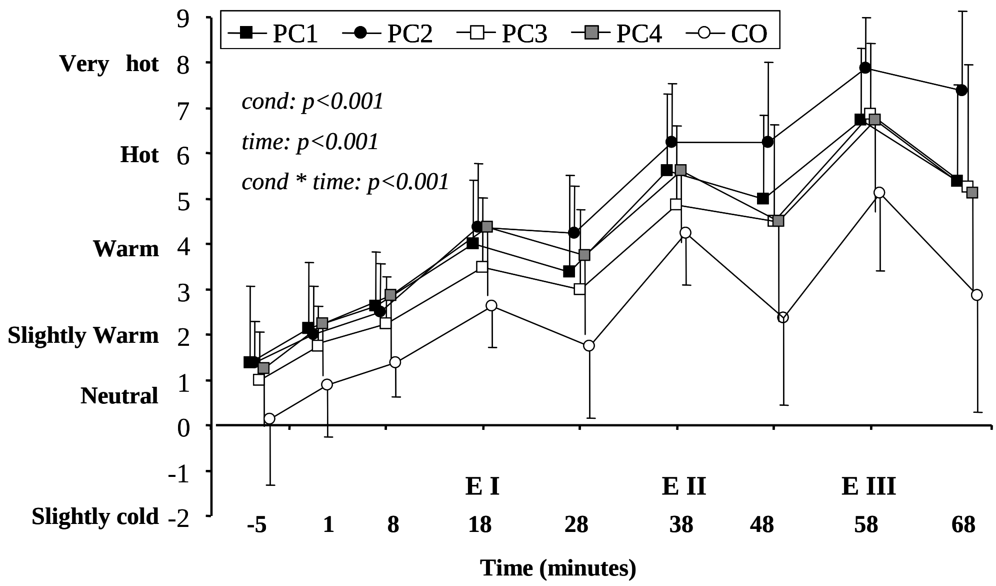


Figure 2.6. Time courses of thermal sensation of PC1~PC4, and CON. Values are means and SD.

Table 2.2. Physiological and subjective responses of firefighters in the five conditions. Rectal temperature (Tre), mean skin temperature ($\bar{T}sk$), heart rate (HR), difference between Tre and $\bar{T}sk$ (Tre–$\bar{T}sk$), the physiological strain index (PSI), body weight loss(BWL) and absorbed sweat volume in clothing (ASV)were the 3rd exercise period values. Also, subjective responses (thermal sensation, thermal discomfort, humidity sensation and the rate of perceived exertion [RPE]) were the 3rd exercise period values. Values are means and SD of eight subjects.

	Condition				
Variable	**PC1**	**PC2**	**PC3**	**PC4**	**CO**
Tre (°C)	**38.0±0.4**	**38.2±0.3 ***	**38.0±0.4**	**37.9±0.4**	**37.8±0.2**
$\bar{T}$sk (°C)	**37.5±0.3**	**38.2±0.8 *****	**37.5±0.3**	**37.3±0.5**	**37.1±0.3**
Tre–$\bar{T}$sk (°C)	**0.5±0.3**	**0.0±0.7 ***	**0.6±0.2**	**0.7±0.2**	**0.7±0.4**
HR (beats·min^{-1})	**176.1±9.8 *****	**183.2±10.8 *****	**175.9±13.5 *****	**169.4±11.0 *****	**156.5±12.2**
PSI	**7.8±1.8 *****	**9.2±2.0 *****	**8.0±2.1 *****	**7.1±2.4 ****	**5.3±1.5**
BWL (g)	**1087.6±288.3 *****	**1283.1±326.7 *****	**973.3±392.3 *****	**966.3±253.6 *****	**757.1±259.9**
ASV (g)	**626±190.1 *****	**888.1±216.3 *****	**552.3±209.8 *****	**493.1±179.6 *****	**267.4±132.8**
Thermal sensation	**6.8±1.6 ****	**7.9±1.1*****	**6.9±1.8 ****	**6.8±1.6 ****	**5.1±1.5**
Thermal discomfort	**6.0±1.5 ***	**6.9±1.2 *****	**5.75±1.6**	**6.25±1.5 ***	**4.75±1.7**
Humidity sensation	**5.8±0.7 ***	**5.9±0.8 ****	**5.9±1.0 ****	**5.6±0.7**	**4.9±0.6**
RPE	**17±2.8**	**16.3±2.1 ***	**16.5±2.2**	**16.7±2.3 ***	**14.5±2.1**

2.3.3 Color-coded Evaluation of Firefighting Protective Clothing

For the increased ability of a firefighter to perform firefighting activities with reasonable comfort, the National Research Institute of Fire and Disaster has proposed a grading scale system for comfort in firefighting protective clothing (***Table 2.3.***). The system employs a five-grade evaluation, each grade being represented by a different color. The color White denotes that the protective clothing is significantly lower in every measurement than other protective clothing (for instance it causes a lower rise in body temperature); Light Blue denotes the protective clothing has a low average in each measured item, although without significant differences; Blue means the protective clothing shows the most average performance in comparison with other protective clothing; Yellow denotes the protective clothing shows a significantly higher figure in each measurement item than other protective clothing (greater rise in body temperature, high discomfort index, etc.) and lastly Red denotes that the protective clothing showed prominently higher values or a significant rise in measurements than others.

In this study, data obtained was compared with the abovementioned grading scale (***Table 2.4.***). The average values of all the measurement items are shown for both firefighting protective clothing and a light work garment when worn, and are represented by colors based on the aforementioned standards. Using this evaluation method, comprehensively evaluated the physiological strain firefighting protective clothing causes. Almost all the indexes indicated that PC2 with silver aluminized surface showed the highest physiological strain and, the next highest were PC1 and PC3, and then PC4.

Table 2.3. Colored evaluation of firefighting protective clothing for firefighters

Color	Explanation
(white)	Work garment
(light blue)	Average loads are smaller, but not significantly
(blue)	Average loads
(yellow)	Loads are significantly bigger
(red)	Loads are significantly much bigger

Table 2.4. Color-coded evaluation of firefighting protective clothing for firefighters during the 3rd exercise period values.

Measured Item	PC1	PC2	PC3	PC4	CO
Tre (°C)	38.0	38.2	38.0	37.9	37.8
Tsk (°C)	37.5	38.2	37.5	37.3	37.1
Tre-Tsk (°C)	0.5	0.0	0.6	0.7	0.7
HR (beats/min)	176.1	183	176.0	169.4	156.5
Body weight loss (g)	1087.6	1283.1	973.3	966.3	757.1
Absorbed sweat volume (g)	626	888	552.3	493.1	267.4
Thermal sensation	6.8	7.9	6.9	6.8	5.1
Thermal discomfort	6	6.9	5.75	6.25	4.75
RPE	17	16.3	16.5	16.7	14.5
Humidity sensation	5.8	5.9	5.9	5.6	4.9

2.3.4 Relationships between clothing properties and physiological responses

The relationship between the resistance to latent heat and $Tre - \bar{T}sk$ of PC1~PC4 and CO conditions at the E III periods is shown in **Figure 2.7**. There was a significant negative correlation (r =-0.50, p<0.001) between the resistance to latent heat and $Tre - \bar{T}sk$. The $Tre - \bar{T}sk$ declined when resistance to latent heat was high during E III period. However, no significant relationship between clothing weight and $Tre - \bar{T}sk$ (r =-0.270), or between clo-value and $Tre - \bar{T}sk$ (r =-0.214) was seen.

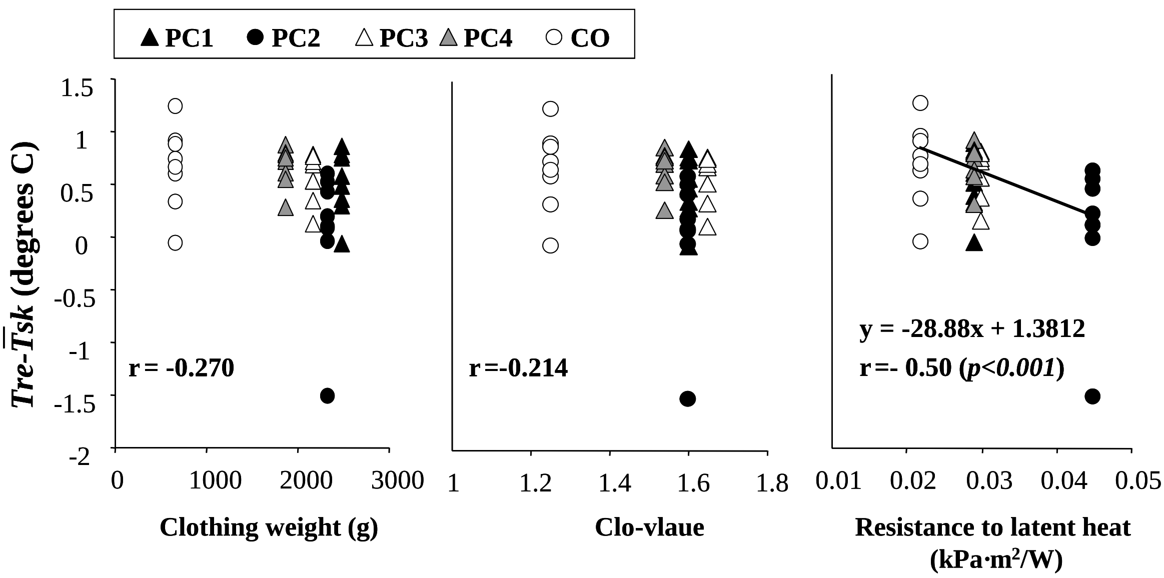


Figure 2.7. Relationships between clothing weight, thermal insulation (clo-value) and resistance to latent heat and difference between rectal temperature and mean skin temperature of PC1~PC4, and CO.

2.4 Discussion

This study examined physiological and subjective responses of four kinds of firefighter's protective clothing (PC1~PC4), as well as a light work garment (CO) under the condition of exercising on a bicycle ergometer, while wearing firefighter protective clothing.

Tre for PC2 continued to rise sharply even after the exercise, compared with a gradual rise for PC1, PC3, and PC4 (**Figure 2.3**). The difference between Tre and $\bar{T}sk$ (the gradient for heat exchange) was suggested as a good indicator of heat strain while wearing protective clothing in hot-humid environments (Ohnaka et al., 1993). When $\bar{T}sk$ rose more rapidly than *Tre* there was no possibility of heat transfer from the core body to its surface (Pandolf and Goldman., 1978). The gradient for heat exchange decreased to zero and heat stress was severe (Pandolf and Goldman., 1978). In this situation, heat loss from the body occurs readily. $\bar{T}sk$ rose above *Tre* at the end of the 3rd exercise period (E III) for PC2. (**Figure 2.4**). Hence it was suggested that wearing PC2 caused greater heat stress and storage in the body than other PCs.

The heart rate was the highest for PC2, attaining 183.2±10.8 beats·min^{-1} at the end of E III (**Figure 2.5**, **Table 2.2**), near the subjects' maximal value. This result was similar to that in the research done by Ftaiti et al. (2001) where *HR* (187 beats·min^{-1}) was recorded at the end of the exercise while wearing fireproof jackets. This condition might impair physical capability and threaten the safety of firefighters during firefighting.

Moran (1998) used a formula for calculating *PSI* based on *HR* and *Tre* to evaluate exercise heat stress in humans. In this study, *PSI* was the highest for PC2, attaining 9.21 at the E III period (**Table 2.2**). Additionally, PC2 showed higher *BWL* and *ASV* (**Table 2.2**). It was considered that the excessive sweat loss caused a decrease in body fluids, which suppressed heat dissipation from cutaneous blood flow and sweating, and induced body temperature rise (Hirata et al., 2002).

Furthermore, subjective responses such as thermal sensation, thermal discomfort, humidity sensation and *RPE* for PC2 (**Table 2.2**) were shown to be more uncomfortable than CO condition during the E III and R III periods. It has been reported that protective clothing with poor quality inside air and moisture impermeability has caused heat stress and could induce strain on cardiorespiratory and thermoregulatory functions, especially in a hot environment (Smith et al., 1997; Baker et al., 2000; Smith and Petruzzello, 1998).

In this study, although PC2 was made with the same water-resistant layer as PC1 and PC3, and the same heat-insulating layer as PC1, *HR*, *BWL* and *ASV* were greater in PC2 than in PC1. The clothing properties' difference between PC2 and PC1 was the surface layer-PC2 which used silver aluminized layer, making it inferior to the other protective clothing in terms of heat dissipation. This study confirmed that protective clothing using a silver aluminized surface caused greater heat stress than other clothing, due to the silver aluminized surface preventing heat from outside entering but not allowing sweat evaporation.

Numerous reports have shown that the clothing weight and insulating properties of protective clothing impose additional heat stress on humans (Duncan et al., 1979; Whitle and Hodous, 1989; Nunneley, 1989; Graveling and Hanson, 2000). Agui et al. (2005) also mentioned that the higher the heat resistance value, the higher the discomfort. In this study, the clothing weight of the PC1~PC4 and CO were ranged PC1>PC2>PC3>PC4>>CO. PC1 had greater clothing weight than other conditions. The clo-value range of the PC1~PC4 and CO were PC3>PC1=PC2>PC4>>CO. The clo-value of PC3 was higher than other conditions, while PC1 and PC2 were the same values. The resistances to latent heat range of the PC1~PC4 and CO were PC2>PC3>PC1=PC4>>CO. PC2's latent heat resistance was higher than other conditions. That means clothing weight for PC2 and PC1 were approximately equal and their clo-values were the same. However, the resistance of latent heat was greater in PC2 than in PC1. As mentioned above, PC1 and PC2 were manufactured with the same water-resistant and heat-insulating material, but an important difference between PC2 and PC1 was that PC2 had a surface coated with silver aluminized. This silver aluminized surface cause greater heat stress.

Moreover, as mentioned above, $Tre - \bar{T}sk$ was a good indicator of heat strain while wearing protective clothing. In this study, no significant relationships were found between $Tre - \bar{T}sk$ and clothing weight, or between $Tre - \bar{T}sk$ and clo-value. Only the relationship between PCs' resistance to latent heat and $Tre - \bar{T}sk$ showed a significant negative correlation as shown in **Figure 2.7**. This study suggests that, when wearing protective clothing, latent heat resistance is more closely related than clothing weight or clo-value to physiological effects.

2.5 Conclusions

Chapter 2 of this study examined physiological and subjective responses of four kinds of firefighter's protective clothing (PC1~PC4) and a light work garment (CO) under the condition of exercising on a bicycle ergometer, while wearing firefighter protective clothing. Although the clothing weight and clo-value of PC2 were almost the same or even lower than other PCs, the latent heat resistance of PC2 which had a surface coated with aluminized sliver was the greatest. Physiological and subjective heat strain in PC2 were greater than for other PCs. Moreover, it was shown that the physiological strain of firefighting protective clothing, as shown in $Tre - \bar{T}sk$, depends more upon resistance to latent heat than upon clothing weight and clo-value. This study suggests that, when wearing the protective clothing, latent heat resistance is more closely related than clothing weight or clo-value to the physiological effects.

• Chapter 3

Physiological and subjective responses to cooling devices on firefighting protective clothing

3.1 Introduction

An exterior thermal load is added to the heat stock from the metabolism of the body and that causes an excessive heat load upon firefighters. While the functions of firefighting protective clothing have been improved, there is the possibility that the physiological load on the firefighters may be increased. Furthermore, it has been reported that physiological stress is caused by impermeable garments, which increase skin temperature, heart rate and core temperature (Bishop et al., 1994; Duncan et al., 1979; Faff and Tutak, 1989). Tochihara et al. (2005) conducted a questionnaire study on 792 firefighters, and reported that 48.6% had experienced feeling very ill because of heat during the previous summer. Therefore, it is important to examine the methods for reduction of thermal stress on firefighters from firefighting protective clothing.

It is known that using a cooling vest with ice-packs (ICE) can reduce heart rate, skin temperature and sweat rate (Muir et al., 1999; Webster et al., 2005). Recently, the use of phase change material (PCM, a highly productive thermal storage medium) is being applied in many fields, such as in garments, home furnishing and cooling products. Pause (2003), and McLellan and Frim (1998) reported that a protective suit with PCM could slow down the rate of the increase in the user's temperature and prevent heat stress.

Although many studies have been conducted on the application of PCM in ordinary clothing fibers, few of them have investigated its application in preventing heat stress on firefighters. To the knowledge of the researchers, no published research is available that investigates the use of ICE and PCM cooling devices on firefighting protective clothing.

The aim of the this study was to examine ICE and PCM cooling devices for reducing physiological load based on subjects' physiological and subjective responses under the condition of exercising on a bicycle ergometer while wearing firefighting protective clothing in a relatively high temperature environment.

3.2 Methods

3.2.1 Subjects

The subjects were eight graduate students. They were informed of all details of experimental procedures and the associated risk and discomforts. Each subject gave informed consent before participation. The physical characteristics of the subjects were as follows (mean±SD): age 25.9±3.2 years; height 168.3±4.4cm; weight 62.5±9.2 kg; body mass index 23.0±2.6 $kg \cdot m^{-2}$ and the maximal oxygen consumption 45.8±2.2 $ml \cdot min^{-1} \cdot kg^{-1}$. This study was accredited by the ethical committee of Kyushu University.

3.2.2 Determination of the maximal rate of oxygen consumption

The maximal oxygen consumption ($\dot{V}_{O2\ peak}$) was measured in a room at 30ºC (a relative humidity of 50%) using an expiration gas analyzer (AE300s, Minato Electronics Inc., Japan) conducted on an ergometer (Aerobike 75XL, Combi Co. Ltd., Japan). $\dot{V}_{O2\ peak}$ protocol was calculated using continuous incremental loading based on Fitchetts et al. (1985). The protocol was divided into 4 phases of 4 minutes duration, each for a total of 16 minute. Heart rate was monitored continuously using a Dynascope DS-2151

(Fukuda Denshi Co. Ltd., Japan).

3.2.3 Clothing ensembles and cooling devices

The cooling devices contained two types of cooling materials. The cooling devices specifications are summarized in **Table 3.1**. All subjects participated in four conditions, namely: (1) no cooling devices; control (CON) (2) ice-packs (ICE), (3) PCM of 5ºC (PCM [5]) and (4) PCM of 20ºC (PCM [20]) administered in random order (**Figure 3.1**). During this experiment, subjects wore firefighting protective clothing (1.53 clo) and basic clothing: A T-shirt, trousers, underwear, socks, boots, gloves and helmet were worn.

The ICE condition included 5 ice-packs (refrigerant) inserted into a mesh vest. The total weight of ICE with vest was 1,203 g(2 on chest and 3 on back) frozen in a freezer. The dimension for a piece of ICE was 15.5×16.9×2.0 cm. The PCM condition included 16 packs of PCM (CoolVest™, Nippon Blower Co., Ltd.) inserted into a mesh vest with a total weight of 1,694 g. The dimension for each piece of PCM was 8×14×0.6 cm. The PCM(5) (6 packs on front torso and 10 on back) was cooled in a 5ºC refrigerator. The PCM(20) condition included 16 packs of PCM kept at 20ºC. The PCMs were very expensive.

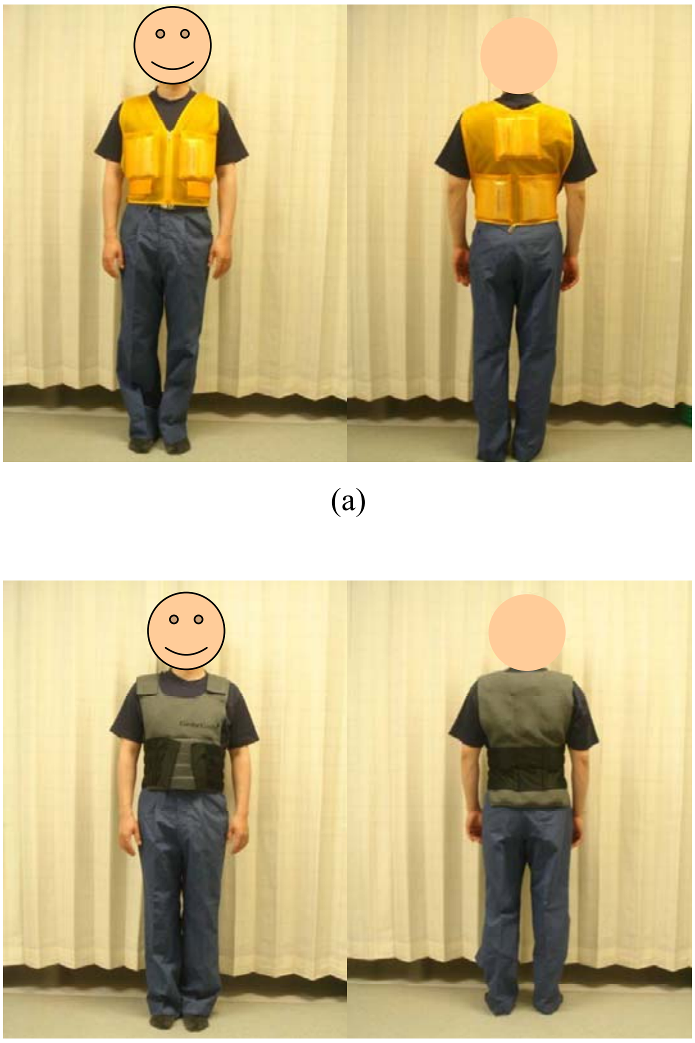
The melting temperature of the PCM was 28ºC. The melting heat and specific heat of the materials in the conditions were 35.1 cal·°C^{-1}·g^{-1}, and 0.69 cal·°C^{-1}·g^{-1}, respectively. The melting heat and specific heat of the materials in the ICE condition were 79.5 cal·°C^{-1}·g^{-1}, and 1.0 cal·°C^{-1}·g^{-1}, respectively.

Cooling devices ICE and PCM contain water and paraffin, respectively. When the temperature of ice or paraffin rises to 37°C (body temperature), theoretical heat absorption capacity of cooling materials is as follows: ICE at 302.2 kJ·m^{-2}, PCM (5) at 190.0 kJ·m^{-2} and PCM (20) at 155.6 kJ·m^{-2} (see Appendix B).

The total surface areas of the cooling materials for the ICE and PCMs were 1,310 and 1,792 cm^2, respectively.

Table 3.1. Specifications of the cooling devices

Condition	ICE	PCM(5)	PCM(20)
Cooling devices	  	  	
Quantity	5	16	
Weight (g)	210	84	
Dimension for a piece (cm)	15.5×16.9×2.0	8×14×0.6	
Total Weight with a vest (g)	1,203	1,694	
The melting heat (cal·°C^{-1}·g^{-1})	79.5	35.1	
Specific heat of the materials (cal·°C^{-1}·g^{-1})	1.0	0.69	
Total surface area of cooling materials (cm^2)	1,310	1,792	
Materials	Water	Paraffin	
Melting temperature (°C)	0	28	



(a)

(b)

Figure 3.1. Subject wearing (a) ice-packs (ICE); and (b) Phase Change Materials (PCM) at 5ºC (PCM [5]) and 20ºC (PCM [20]) .

3.2.4 Experiment procedures and physiological responses

The cooling effects were evaluated using rectal temperature (*Tre*), mean skin temperature ($\bar{T}sk$), heart rate (*HR*), body weight loss (*BWL*), body heat storage (S) and subjective responses. **Figure 3.2** shows the experiment protocol and measurement. The pre-test room as control was set with an air temperature (T_a) of 25ºC and relative humidity (RH) of 50% to 60%. The test-room was set with an T_a of 30°C and RH of 50%. The cooling devices were worn under the firefighting protective clothing. The duration of each condition was 50 minutes. The subjects initially rested in a pre-test room for 10 minutes before entering the test-room where they rested for another 10 minuets, followed by 30 minutes 55% $\dot{V}_{O2\ peak}$ exercise on a bicycle ergometer and 10 minutes recovery period. During the exercise activities, there was no additional infrared heat radiation for simulation purposes high risk conditions outside of actual firefighting where cooling conditions were more measureable.

Nakahashi et al. (2003) reported that in a typical Japanese wooden house, in the case of semi-destruction by fire, it takes about one hour to extinguish the fire, and the average actual fire-fighting time is about 30 minutes. Based on this reference, the exercises in our study were set for 30 minutes in the four conditions.

Subjects inserted a thermistor to a depth of 150 mm into the rectum. The skin thermistors were placed on the right side of the body (head, abdomen, chest, back, forearm, hand, thigh, calf and foot). $\bar{T}sk$ was calculated using Hardy and DuBois's equation (Hardy and DuBois 1938). The mean rectal temperature and the mean skin temperature were collected on a portable data logger (Gram, LT-8A). Heart rate was monitored using a Dynascope DS-2151 (Fukuda Denshi Co. Ltd., Japan). Body weight loss (*BWL*) was determined using change in body/clothing weight (±1 g accuracy) (ID2, Mettler Instruments) before and after the experiment. Body heat storage (S) was calculated using equation (1) (Burton 1935):

$$S= (3.48 \cdot Wt/A) \cdot (\Delta Tb), \qquad (1)$$

where 3.48 is the average specific heat of body tissues (in $kJ \cdot kg^{-1} \cdot °C^{-1}$) , A is the body surface area (m^2) . The body surface area (A)(in m^2) were estimated from measurements of heigh (H) and weight(W). ($A=100.315W^{0.383} \cdot H^{0.693}$) (Horikoshi et al., 1994). ΔTb is the rate of increase in mean body temperature (in °C). The mean body temperatures (ΔTb) (in °C) were estimated from measurements of *Tre* and $\bar{T}sk$. ($\Delta Tb=0.8 \cdot Tre+0.2 \cdot \bar{T}sk$) (Nakayama, 1998).

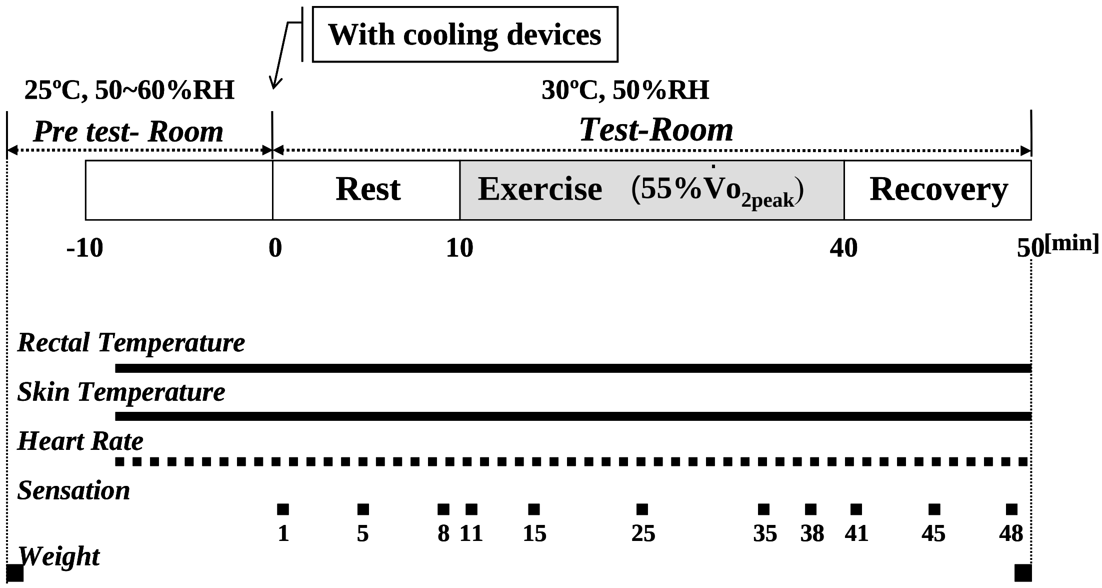


Figure 3.2. Experiment protocol and measurement items

3.2.5 Subjective responses

Subjective responses included thermal sensation, thermal discomfort, humidity sensation and the rate of perceived exertion (*RPE*). The scale of thermal sensation was from slightly cold (-2) to very hot (9). The scale of thermal discomfort was from neutral (1) to very uncomfortable (8). The scale of humidity sensation was from slightly dry (-2) to very wet (7). The rate of perceived exertion was from extremely light (6) to extremely hard (20) (Borg, 1982). Subjects were also asked how well they found the cooling devices fit their bodies.

3.2.6 Statistical analysis

The cooling device-related effects on all measurements were examined by a two-way analysis of variances (ANOVA) with repeated measures for rest, period of exercise and recovery, separately (experimental conditions: CON, ICE, PCM[5] and PCM[20]; time). Scheffé's post hoc comparisons were used to assess significant main effects using ANOVA. Statistical significance was set at $p<0.05$. The values were presented as mean values with standard deviation (SD).

3.3 Results

3.3.1 Physiological responses

Rectal temperature

The mean rectal temperature for 8 subjects across time in the four conditions is shown in **Figure 3.3**. *Tre* showed almost the same transition from beginning to end under all conditions, with a gradual increase following the start of the exercise. There was a significant difference in *Tre* between condition and time towards the end of the experiment. The experiment showed an increase in *Tre* for PCM(5) and PCM(20) which was less than that for CON and ICE.

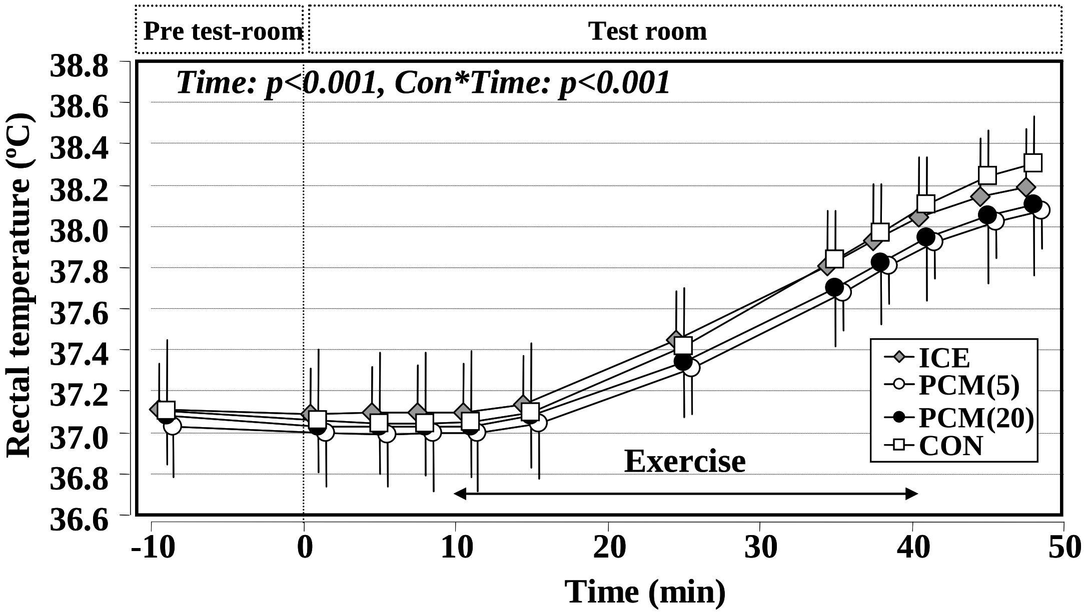


Figure 3.3. Time courses of the mean rectal temperature (Tre) of CON, ICE, PCM(5), and PCM(20). Values are means and SD. "Time: p<0.001" indicates a significant main effect of time. "Con*Time: p<0.001" indicates a significant interaction between conditions and time.

Mean skin temperature

Mean skin temperature over time in all conditions showed a significant difference between CON and PCM as shown in **Figure 3.4**. The experiment showed a lower increase in $\bar{T}sk$ in PCM(20) compared to CON from 5 min after starting the rest until the end of the experiment (p<0.05~0.01). During the latter half of the exercise, the significant differences observed in $\bar{T}sk$ in PCM(5) were lower than CON (p<0.05). The differences between CON and ICE were smaller than between CON and PCMs.

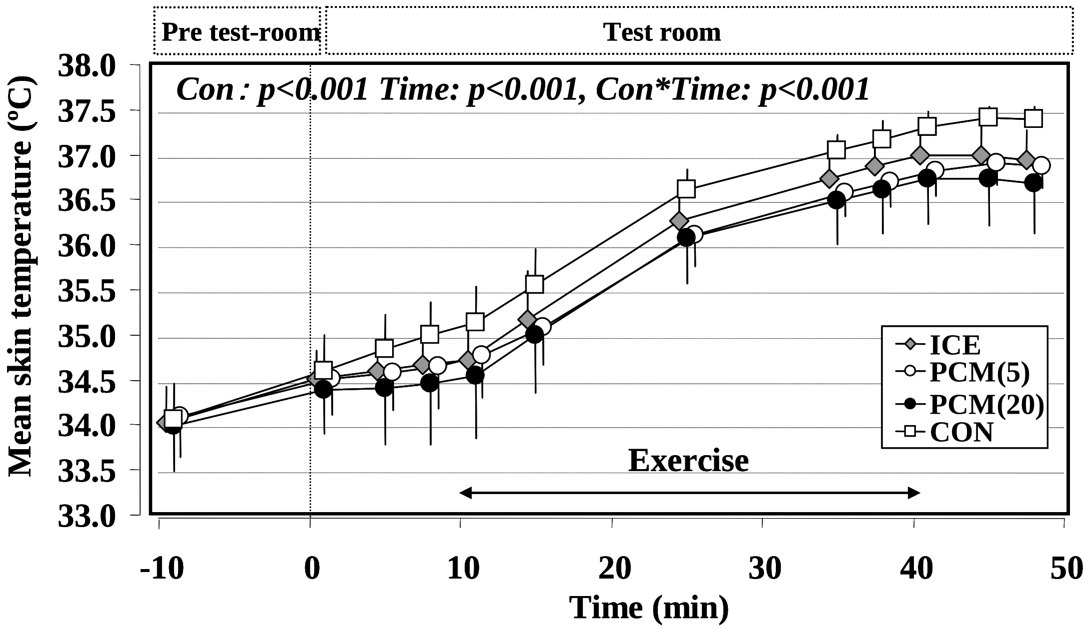


Figure 3.4. Time courses of the mean skin temperature ($\bar{T}sk$). Values are means and SD. "Con: p<0.001", indicates a significant main effect of conditions. "Time: p<0.001" indicates a significant main effect of time. "Con*Time: p<0.001" indicates a significant interaction between conditions and time.

Heart rate

Heart rate was almost the same from the beginning to the end of the exercise under all conditions as shown in **Figure 3.5**. However, after the exercise PCM(5) was significantly lower than CON in recovery.

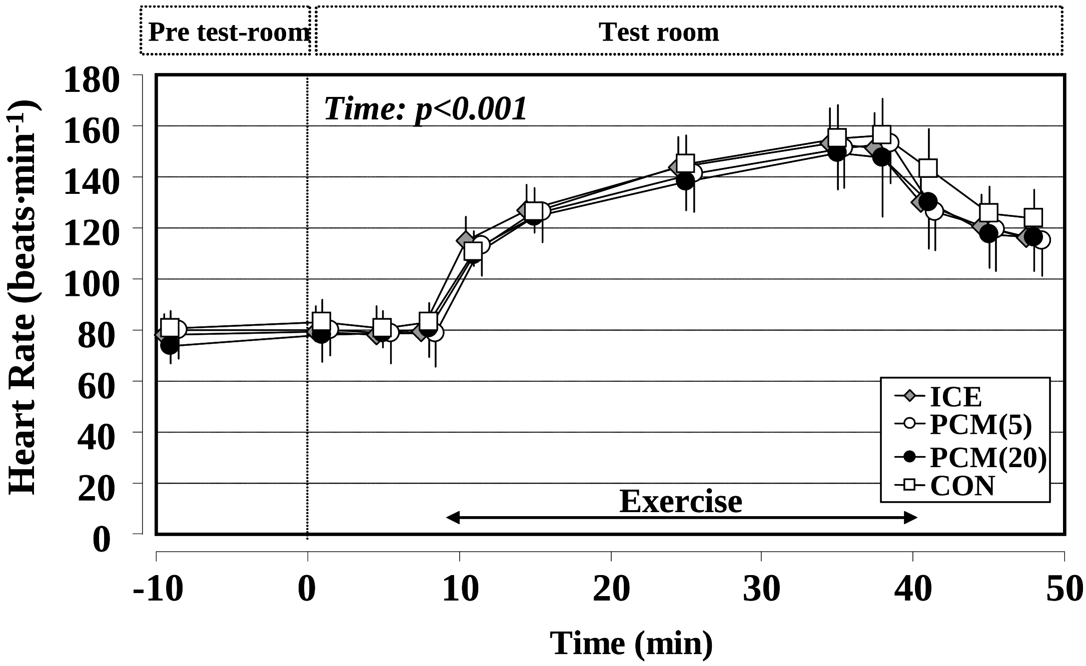


Figure 3.5. Time courses of the heart rate (HR) of CON, ICE, PCM(5), and PCM(20). Values are means and SD. "Time: $p<0.001$" indicates a significant main effect of time.

Body weight loss

The mean (SD) values of *BWL* were greatest in CON at 670±105 g, followed by ICE at 591±101 g, PCM(5) at 596±126 g and PCM(20) at 578±105 g as shown in **Figure 3.6**. The *BWL* of CON was significantly greater than the other three conditions. However, there were no significant differences noticeable among the cooling device conditions.

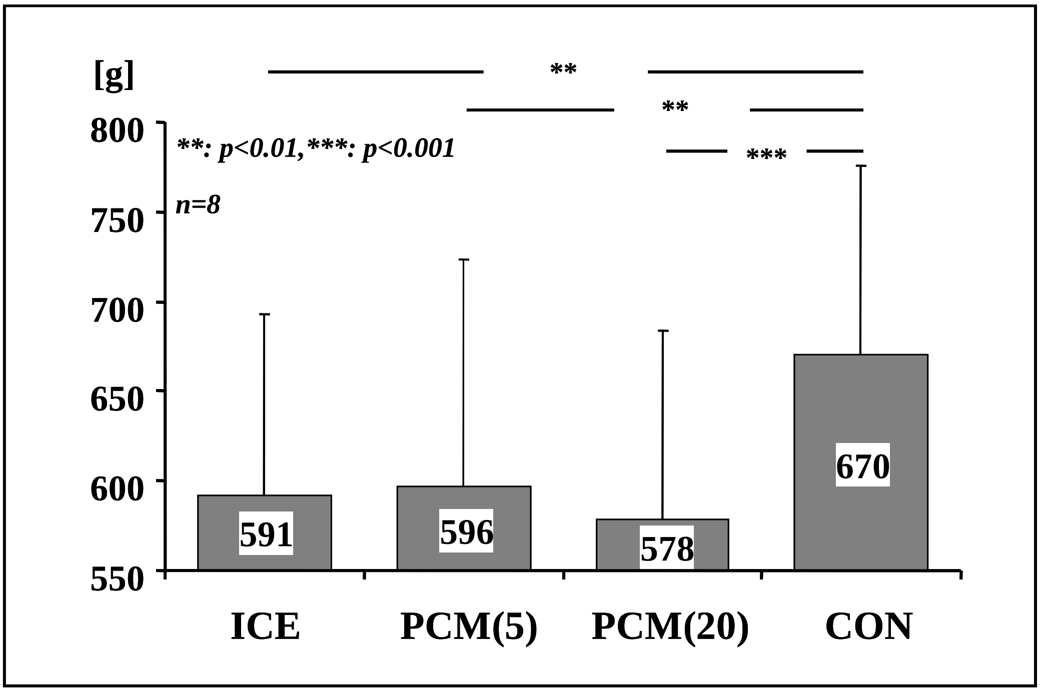


Figure 3.6. Body weight loss observed in each of the four test trial conditions. Values are means and SD. "**: $p<0.01$", indicates a significant difference between CON and ICE. "**: $p<0.01$", indicates a significant difference between CON and PCM(5). ": $p<0.001$", indicates a significant difference between CON and PCM(20).***

3.3.2 Subjective responses

Figure 3.7 shows the time course of the whole body thermal sensation under 4 conditions. There were significant ($p<0.001$) differences in whole body thermal sensation, which showed that the subjects with CON felt hotter than other conditions after entering the room. Similarly, also significant differences ($p<0.05$) in humidity sensation at the end of the exercise period, which indicates that CON was wetter than the other conditions (**Figure 3.8**). However, no significant differences in thermal discomfort were seen (**Figure 3.9**). All subjects reported that the PCM cooling devices fit their bodies better than the ICE.

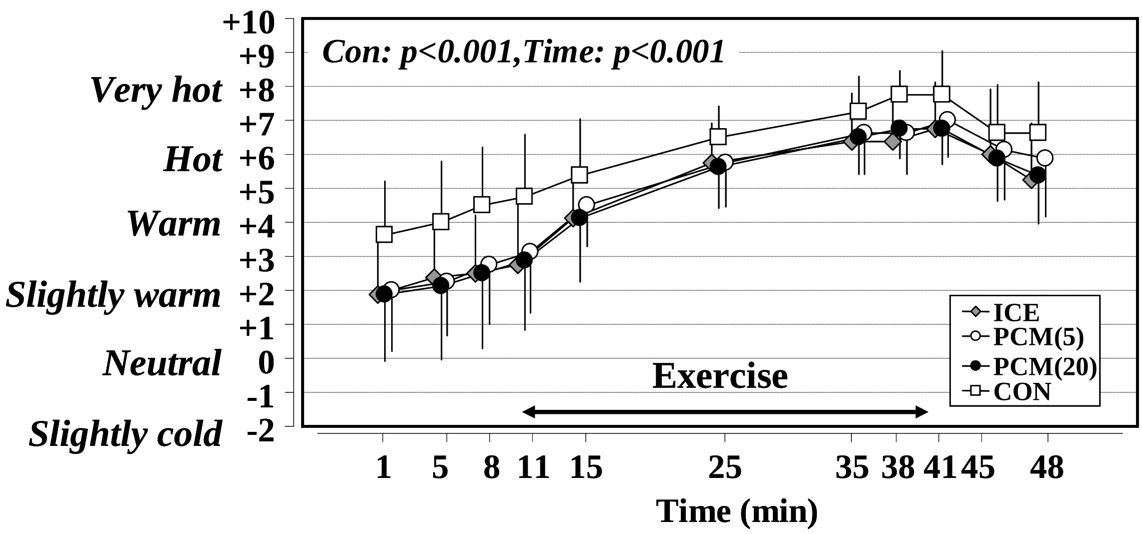


Figure 3.7. Time courses of the whole body thermal sensation. Values are means and SD. ''Con: p<0.001'', indicates a significant main effect of conditions. ''Time: p<0.001'' indicates a significant main effect of time.

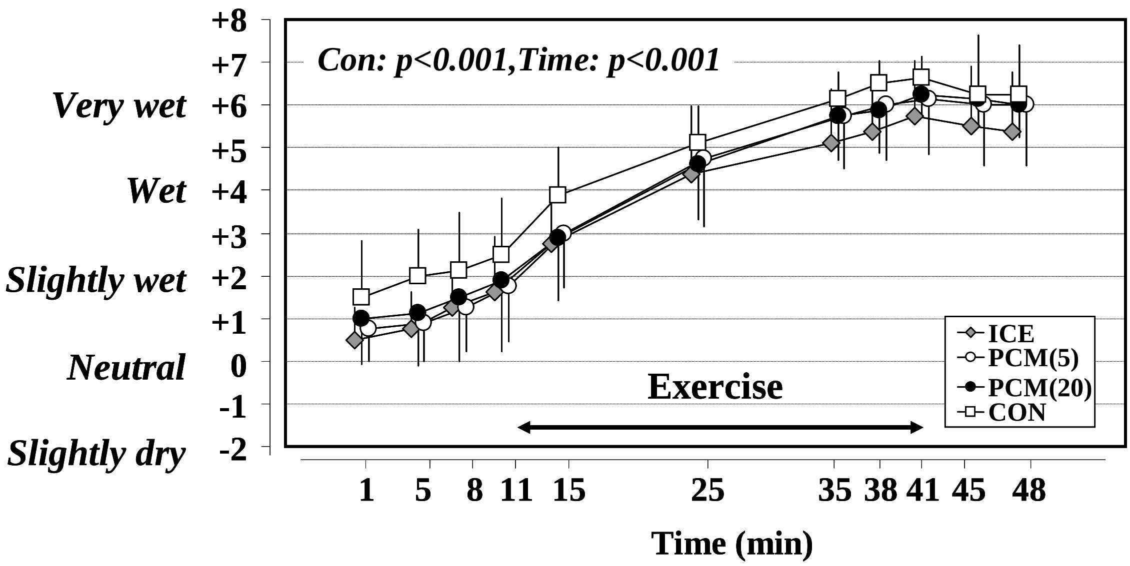


Figure 3.8. Time courses of the humidity thermal sensation. Values are means and SD. ''Con: p<0.001'', indicates a significant main effect of conditions. ''Time: p<0.001'' indicates a significant main effect of time.

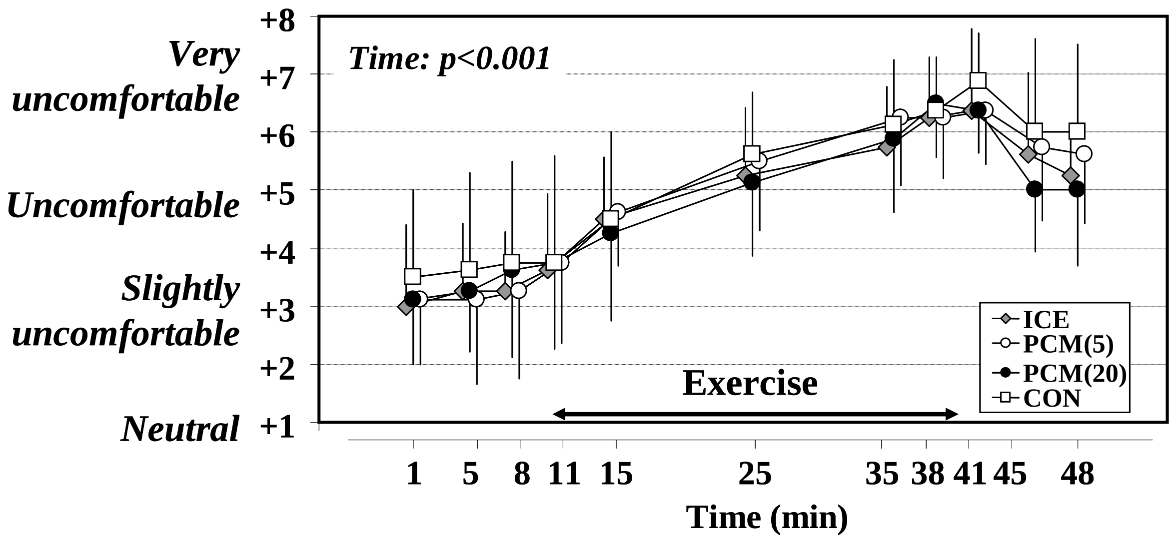


Figure 3.9. Time courses of the thermal discomfort. Values are means and SD. ''Time: p<0.001'' indicates a significant main effect of time.

3.3.3 Cooling devices for body heat storage

Figure 3.10 shows theoretical heat absorption capacity of cooling devices and calculated mean body heat storage for 50 minutes exposure at ICE, PCM(5) and PCM(20). Resulting mean reductions in body heat storage compared with CON are also shown. Body heat storage was greatest in the CON at 202.5 kJ·m^{-2}, followed by ICE at 177.6 kJ·m^{-2}, PCM(5) at 173.8 kJ·m^{-2} and PCM(20) at 171.0 kJ·m^{-2}. No significant differences in body heat storage among the four conditions were apparent.

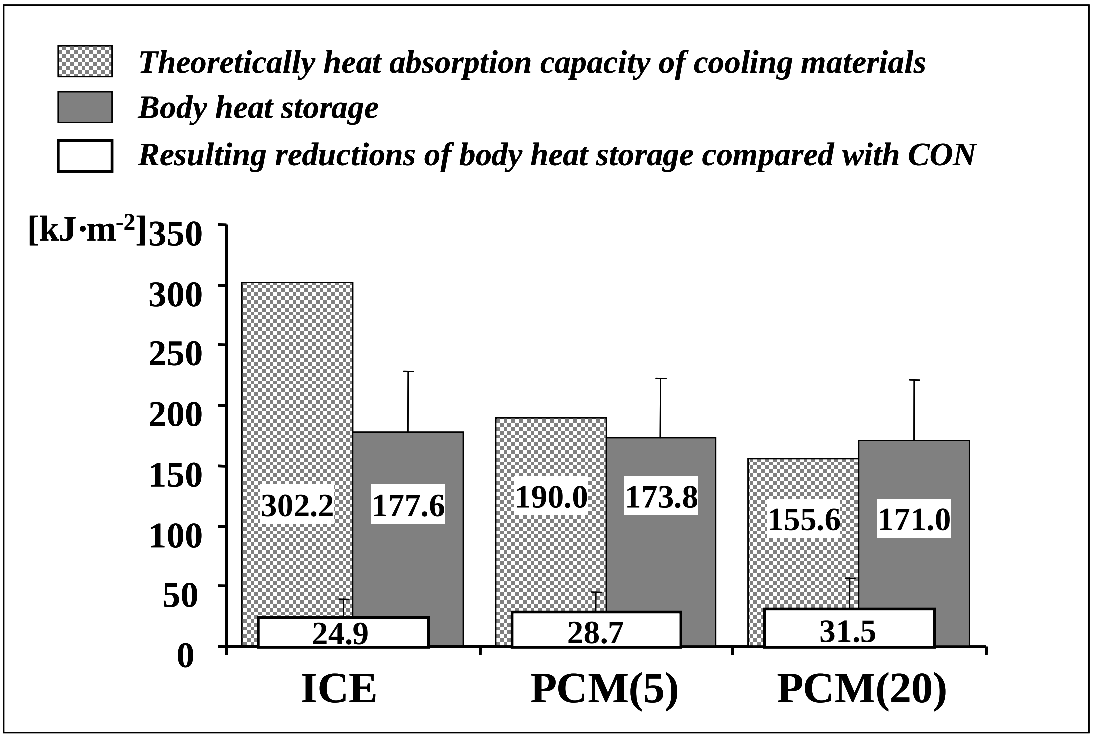


Figure 3.10. Theoretical heat absorption capacity of ICE, PCM(5), and PCM(20). Body heat storage and resulting reductions of body heat storage compared with CON. The values are means and SD.

3.4 Discussion

The aim of the Chapter 3 of this study was to examine ICE and PCM cooling devices for reducing physiological load based on subjects' physiological and subjective responses under the condition of exercising on an ergometer while wearing firefighting protective clothing in a relatively high temperature environment.

Muir et al. (1998) reported that using an ice-cooling devices compared with no ice cooling devices can reduce heart rate, skin temperature and rectal temperature during light exercise while wearing protective clothing. Also, Webster et al. (2005) reported that a light-weight cooling vest can enhance performance of athletes and lower heart rate, skin temperature and rectal temperature in the heat. In this study, compared with the condition without cooling devices (CON), ICE, PCM(5) and PCM(20) also reduce heat stress when wearing firefighting protective clothing as shown in **Figures 3.3**, **3.4**, **3.5 and 3.7**. Although the physiological differences are small among the cooling devices, $\bar{T}sk$ at CON is significantly higher than those at PCE(5) and PCM(20) as shown in **Figure 3.4**.

McLellan and Frim (1998) measured physiological and subjective responses during prolonged exercise of to 3 hours at 40°C (30%RH) while wearing NBC clothing. They evaluated cooling effects of liquid/air cooling system and PCM to reduce heat stress, and reported that cooling ability of PCMs was less than that of liquid/air cooling systems, but still useful when exercise time was not excessive. Since use of cooling systems is not practical during firefighting work, PCM may be a more practical alternative for firefighting over a relatively short time.

The theoretical heat absorption capacity of cooling materials is as follows: ICE at 302.2 kJ·m^{-2}, PCM(5) at 190.0 kJ·m^{-2}and PCM(20) at 155.6 kJ·m^{-2}. Theoretically ICE has a greater absorption capacity for cooling than PCMs. However, resulting reductions in body heat storage for ICE, PCM(5) and PCM(20) were 24.9 kJ·m^{-2}, 28.7 kJ·m^{-2} and 31.5 kJ·m^{-2}, respectively. Although the difference was not significant, resulting mean reductions in body heat storage of ICE were smaller than those of PCMs. The actual cooling efficiency of the heat absorption capacity of cooling devices was greatest in PCM(20) at 20.2%, followed by PCM(5) at 15.1%,and ICE at 8.2%. There are several reasons why the ICE has smaller heat stress reduction, although ICE has greater absorption capacity for cooling. First, PCM(5) and PCM(20) are cooling devices with six PCM inserted in the chest and back portion of a vest with a surface area of 1,792 cm^2. On the other hand, ICE is a cooling device with two ice bags placed in the chest and another three in the back portion of a mesh net vest, and with a surface area of 1,310 cm^2. Bennett et al. (1995) used four (425g each) and six (765g each) frozen gel thermostrips and proposed that the physiological burden decreased with an increase in the cooling area in contact with the body. Since the cooling area covered with PCM(5) and PCM(20) was greater than the area covered with ICE, it seemed that PCM(5) and PCM(20) limited more the increase of accumulation of heat in the body. Secondarily, due to the lower melting temperature of ICE and its thickness (2.0 cm), ICE is still hard even when it begins to melt. On the other hand, PCMs soon become soft after it begin to melt. Due to this softness, PCMs become more pliable and are able to touch the skin more easily and thus absorb the body heat effectively. The increase in heat storage in the body can be suppressed. Furthermore, all subjects reported protective clothing with PCM(5) and PCM(20) fit their bodies better than ICE. Finally, since the surface temperature of ICE reaches 0°C when it was frozen, wearing ordinary cooling materials on T-shirts may lead to not only body overcooling but possibly frostbite. Thus, ICE is a covered by a 1mm polyurethane foam laminated with aluminum sheets to protect the user. This insulation may influence the absorption effect of ICE.

No differences in heat stress reduction between PCM(5) and PCM(20), although PCM(5) has theoretical greater heat absorption capacity for cooling. Since PCM(5) requires refrigeration during storage, PCM(20) is much easier to use in real situations for firefighting work. These results suggest that PCM(20) is more effective than other cooling devices in reducing the physiological load while wearing firefighting protective clothing at 30°C.

In this results suggest that PCMs are effective in reducing heat stress for 30 min during high-intensity exercise in our experiment condition but new materials need to be developed for widespread use in actual firefighting with the following characteristics: (1) a high melting temperature (about 30°C) but with a greater latent heat capacity like ice, (2) nonflammability and (3) low production costs.

3.5 Conclusions

The larger surface cooling area of PCMs, the higher melting temperature and softer material of PCMs and lack of a cover which reduces absorption capacity cause a decrease in *Tre* and $\bar{T}sk$ for PCM(5) and PCM(20) which was more than that for CON and ICE. Furthermore, PCM(20) does not require refrigeration. These results suggest that PCM(20) is more effective than other cooling devices in reducing the physiological load while wearing firefighting protective clothing.

In this results suggest that PCMs are effective in reducing heat stress for 30 min during high-intensity exercise in our experiment condition but new materials need to be developed for widespread use in actual firefighting with the following characteristics: (1) a high melting temperature (about 30°C) but with a greater latent heat capacity like ice, (2) nonflammability and (3) low production costs.

• Chapter 4

Effects of wearing trousers or shorts under firefighting protective clothing on physiological and subjective responses

4.1 Introduction

Firefighters perform a variety of tasks in various environments and need to wear protective garments, in order to protect themselves. Unfortunately, wearing protective garments may increase thermal stress, which effects firefighting performance (Holmér, 1995; Baker et al., 2000; Machida et al., 2000; Ikuno et al., 2002; Mclellan and Sellirk, 2004; Eglin et al., 2004; Eglin, 2007; Reinertsen et al., 2008). It has been reported that thermal stress is caused by the weight and insulating properties of protective clothing, the environment and exercise performance (Duncan et al., 1979; Faff and Tutak, 1989; Bishop et al., 1994; Duffield et al., 2003; Mclellan and Sellirk, 2004, 2006; Eglin, 2007) Therefore, it is essential to examine the techniques of thermal stress alleviation and enhance the performance of firefighters while wearing firefighting protective clothing (Bennett et al., 1957; Smith et al., 1997; Bishop et al., 1991; Nag et al., 1998).

Several techniques (such as misting, immersion and hose streams and fans etc) are known that could be used in decreasing thermal stress on firefighters during rest periods (House et al., 1997; Carter et al., 1999; Selkirk et al., 2004). On the other hand, it has been reported that using immersion and fan techniques cause problems, such as time required, at exposure times, and usability is poor during an actual task (Ross et al., 2004). The question which must be considered next is its feasibility, and exposure times while using immersion and fan techniques.

According to McLellan and Selkirk (2004), it was possible to reduce thermal stress for the New York City Fire Department and the Toronto Fire City Services by firefighters' wearing short pants and T-shirts under a firefighting protective uniform. Moreover, Malley et al., (1999) reported the physiological responses when wearing short pants and T-shirts under a firefighting protective uniform, compared with wearing long pants and T-shirts. The former condition allowed the extension of subjects' exercise time. In Japan, for a typical wooden apartment building, in the case of semi-destruction by fire, it takes about one hour to extinguish the fire, and the average actual firefighting time is about 30 minutes (Nakahashi et al., 2003). The question then arises of using shorts instead of trousers, for those 30 minutes.

Additionally, Tochihara et al. (2005) reported that "high mobility" is more important than the other issues in a questionnaire survey of Japanese firefighters on firefighting protective clothing. Firefighting activities consist of carrying a hose, rescue tasks, hosing support, machine operation and support etc (Nakahashi et al., 2003; Tochihara et al., 2005), and executing these tasks may requires firefighters to carry tools or garments while performing various movements (Tochihara and Chou, 2007).

Hence, it is important to determine whether using short pants instead of trousers has an effect on physiological/subjective responses which could alleviate thermal stress and the mobility of firefighters in movements (such as arm raising, squatting, jumping, leg raising and rotation) which could enhance performance during a firefighter's exposure time of 30 minutes.

Only a few studies so far have discussed the benefits of wearing minimal clothing under firefighting protective clothing (Prezant et al., 2000, 2001; McLellan and Selkirk, 2004, 2006); little is known about wearers' physiological/subjective responses, such as thermal sensation, and mobility while wearing shorts/trousers under protective clothing with phase change materials (PCMs).

Therefore, the purpose of this study was to determine the effects of wearing trousers or shorts under firefighting protective clothing with PCMs on physiological/ subjective responses and the mobility of firefighters with a 30-minute exercise period which is the average Japanese actual firefighting task time.

4.2 Methods

4.2.1 Subjects

Experiment 1:

The physical characteristics of the 8 subjects (Fukuoka City firefighters) were as follows (means±SD): age 28.1±3.6 years; height 171.2±8.1 cm; weight 65.7±4.9 kg; body mass index 22.7±1.6 $kg \cdot m^{-2}$ and the maximal rate of oxygen consumption 52.4±10.9 $ml \cdot min^{-1} \cdot kg^{-1}$.

Experiment 2:

The physical characteristics of the 8 subjects (Fukuoka City firefighters) were as follows (means±SD): age 27.9±3.5 years, height 171.0±7.3cm, weight 67.0±6.6 kg, and body mass index 20.6±2.4 $kg \cdot m^{-2}$.

The subjects were informed of all details of the experimental procedures and the associated risks and discomforts. Each subject gave informed consent before participation. This study was accredited by the ethical committee of Kyushu University.

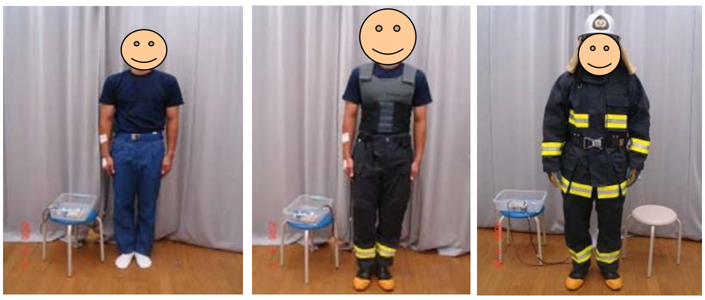
4.2.2 Clothing ensembles

Two conditions were designed in this study based on a combination of clothing and cooling devices (**Table 4.1**). FPC-S consisted of a firefighting protective clothing, PCMs, shorts, basic clothing, and self-contained breathing apparatus (SCBA). FPC-L, on the other hand, consisted of a firefighting protective clothing, PCMs, trousers, basic clothing, and SCBA. A T-shirt, underwear, socks, boots, gloves, and helmet were worn as basic clothing. The total weight for each conditions equipment was as follows- FPC-S: 8.9±0.2 kg and FPC-L: 9.0±0.1 kg. The weight of the SCBA was 9.5 kg. Shorts and trousers had the same clothing properties (**Figure 4.1**).

Table 4.1. Specifications of the two conditions. Values are means and SD

Condition	***Clothing***	***Cooling devices***	***Weight (kg)***
FPC-S	T-shirt + shorts+ firefighting protective clothing	Phase Change	8.9±0.2
FPC-L	T-shirt + trousers+ firefighting protective clothing	Materials -PCM (16)	9.0±0.1

(a)



(b)

Figure 4.1. Subject wearing (a) shorts (FPC-S); and (b) trousers (FPC-L) under firefighting protective clothing with phase change materials.

4.2.3 Experiment 1

Determination of the maximal rate of oxygen consumption

The maximal oxygen consumption ($\dot{V}_{O2peak}$) was measured in a room at 30ºC (with relative humidity of 60%) using an expiration gas analyzer (AE300s, Minato Electronics Inc., Japan) during exercise on a treadmill (STM-1250, Nihon Kohden Co. Ltd., Japan) wearing light clothing (a T-shirt and shorts). $\dot{V}_{O2peak}$ protocol was calculated using continuous incremental loading, based on Yamaji et al. (1992). The protocol consisted of an initial 5-minute rest period followed by 5 exercise periods, each of a 4-minute duration, for a total of 25 minutes. Heart rate was monitored continuously using a Dynascope DS-2151 (Fukuda Denshi Co. Ltd., Japan)

Thermal environments and experiment procedures

The pre-test room was used as a control and was kept at a constant air temperature (T_a) of 25ºC with a relative humidity (RH) of 50~60 %. The test-room was kept at a constant T_a of 30°C with an RH of 50%. Each subject rested in the pre-test room for 10 minutes before entering the test-room where the subject rested for another 10 minutes, followed by 30 minutes exercise on a treadmill and a 10-minute-recovery period. The exercise intensity was set at 4.8 $km \cdot h^{-1}$ at a 3% gradient (**Figure 4.2**).

Subjects underwent training, on different days, during which they were familiarized with running on the treadmill.

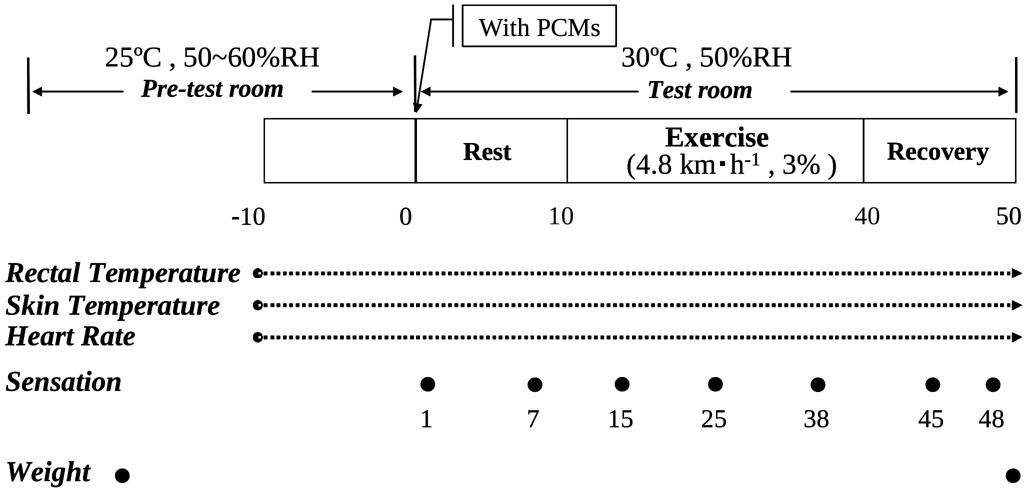


Figure 4.2. Experiment protocol 1 and measurement items

Physiological responses

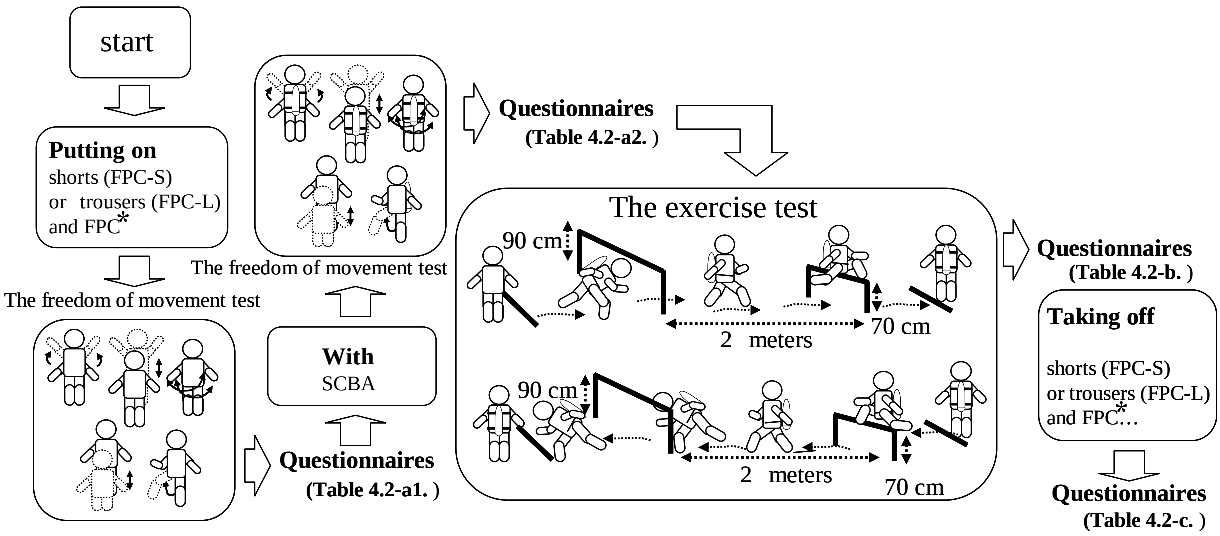
Rectal temperature (*Tre*) and skin temperatures were measured with thermistors. Each subject had a thermistor inserted to a depth of 15 cm into the rectum. The skin thermistors were placed on the right side of the body (head, abdomen, back, forearm, hand, thigh, calf and foot). The mean skin temperature ($\bar{T}sk$) was calculated using the Hardy and DuBois' equation (1938). *Tre* and $\bar{T}sk$ were collected on a portable data logger (Gram, LT-8A). Heart rate (*HR*) was monitored using a Dynascope DS-2151 (Fukuda Denshi Co. Ltd., Japan). Body weight loss was determined from the change in body weight (±1 g accuracy) (ID2, Mettler Instruments) between the start and end of the experiment.

Subjective responses

Subjective responses included thermal sensation, thermal discomfort (chest, back and whole body), humidity sensation and the rate of perceived exertion (*RPE*). The scale of thermal sensation (chest, back and whole body) was from slightly cold (-2) to very hot (9). The scale of thermal discomfort was from neutral (1) to very uncomfortable (8). The scale of humidity sensation was from slightly dry (-2) to very wet (7). The rate of perceived exertion was from extremely light (6) to extremely hard (20) (Borg, 1982).

4.2.4 Experiment 2

The subjects performed the freedom of movement test, the exercise test and answered a set of questionnaires (**Table 4.2-a1, Table 4.2-a2, Table 4.2-b, Table 4.2-c**) (Tochihara et al., 2006). The freedom of movement test included arm raising, squatting, jumping, leg raising and rotation (Huck, 1988; Havenith and Heus, 2004). The exercise test involved a 90 cm-obstacle and a 70 cm-obstacle. Each subject ran to duck under the 90 cm-obstacle, ran 2 meters, and then jumped over the 70 cm-obstacle to reach a set position. Next, the subject made a u-turn and ran to hurdle the 70 cm-obstacle, followed by running 2 meters and ducking under the 90 cm-obstacle and returning to the start position (**Figure 4.3**). This was one cycle of the exercise test. Each subject performed two cycles before the experiment for practice, and their three-cycle and five-cycle exercise times were recorded officially.



* Firefighting protective clothing (FPC)

Figure* 4.3. *Experiment protocol 2

Table 4.2-a1. ***Questionnaire used to determine subjective responses to FPC-S and FPC-L without SCBA***

1.	How does the clothing fit?									
	Too small	1	2	3	4	5	6	7	Too large
2.	What do you think of the length of trousers?									
	Too short	1	2	3	4	5	6	7	Too long
3.	What do you think of the length of sleeves?									
	Too short	1	2	3	4	5	6	7	Too long
4.	How well can you bend forward?									
	Difficult	1	2	3	4	5	6	7	Easy
5.	Was the clothing easy or difficult to wear?									
	Difficult to wear	1	2	3	4	5	6	7	Easy to wear
6.	How well can you open and close the fastener or magic tape?									
	Difficult	1	2	3	4	5	6	7	Easy
7.	How about the freedom of movement in this clothing?									
	Difficult to move	1	2	3	4	5	6	7	Easy to move
8.	How well can you lift your legs?									
	Difficult	1	2	3	4	5	6	7	Easy
9.	How well can you lift your arms?									
	Difficult	1	2	3	4	5	6	7	Easy
10.	Do you think that the clothing is baggy?									
	Very much so	1	2	3	4	5	6	7	Not at all
11.	How did you find the weight of the clothing?									
	Heavy	1	2	3	4	5	6	7	Light

Table 4.2-a2. **Questionnaire used to determine subjective responses to *FPC-S and FPC-L with SCBA***

1.	How does the clothing fit?								
	Too small	1	2	3	4	5	6	7	Too large
2.	How well can you bend forward?								
	Difficult	1	2	3	4	5	6	7	Easy
3.	How about the freedom of movement in this clothing?								
	Difficult to move	1	2	3	4	5	6	7	Easy to move
4.	How well can you lift your legs								
	Difficult	1	2	3	4	5	6	7	Easy
5.	How well can you lift your arms								
	Difficult	1	2	3	4	5	6	7	Easy
6.	Do you think that the clothing was baggy?								
	Very much so	1	2	3	4	5	6	7	Not at all
7.	How did you find the weight of the clothing?								
	Heavy	1	2	3	4	5	6	7	Light

Table 4.2-b. Questionnaire to determine feelings of movement for parts of body while wearing FPC-S and FPC-L with SCBA

1. How do you feel about movement at your?									
Neck	Very difficult	1	2	3	4	5	6	7	Normal
Arms	Very difficult	1	2	3	4	5	6	7	Normal
Elbows	Very difficult	1	2	3	4	5	6	7	Normal
Wrists	Very difficult	1	2	3	4	5	6	7	Normal
Lower back	Very difficult	1	2	3	4	5	6	7	Normal
Hips	Very difficult	1	2	3	4	5	6	7	Normal
Inner thighs	Very difficult	1	2	3	4	5	6	7	Normal
Knees	Very difficult	1	2	3	4	5	6	7	Normal
Ankles	Very difficult	1	2	3	4	5	6	7	Normal

Table 4.2-c. Questionnaire to determine subjective responses to taking off FPC-S and FPC-L

1. Did you feel sweaty in the clothing?									
Very	1	2	3	4	5	6	7	Not at all
2. Was the clothing easy or difficult to take off?									
Difficult	1	2	3	4	5	6	7	Easy
3. How did you find the weight of the clothing?									
Difficult to move	1	2	3	4	5	6	7	Easy to move

4.2.5 Statistical analysis

The effects of trousers or shorts under firefighting protective clothing on all measurements were examined by a one-way analysis of variance (ANOVA) with repeated measurements for rest, followed by exercise and recovery in turns of 10 minutes each for a total of three separate cycles (experimental conditions: FPC-L and FPC-S; time). Also, all questionnaire results were examined by t-test (statistical significance set up $p<0.1$). The values were presented as mean values with standard deviation (SD).

4.3 Results

4.3.1 Experiment 1

Physiological responses

Rectal temperature for 8 subjects across time in the two conditions is shown in **Figure 4.4**. No significant differences in mean *Tre* in all conditions from the beginning to the end of the experiment were measured. Similarly, although the mean skin temperature of FPC-S and FPC-L slightly increased, there were no significant differences between the two conditions (**Figure 4.5**). Heart rate for the four conditions did not reveal any significant differences. Before the end of exercise, the mean HR were 168.6±10.3 beats·min^{-1} (with FPC-S) and 176.1±8.8beats·min^{-1} (with FPC-L). The values for in body weight loss between the FPC-S and FPC-L were 1141.5±247.4g and 1103.1±183.1g, respectively which were not significance different.

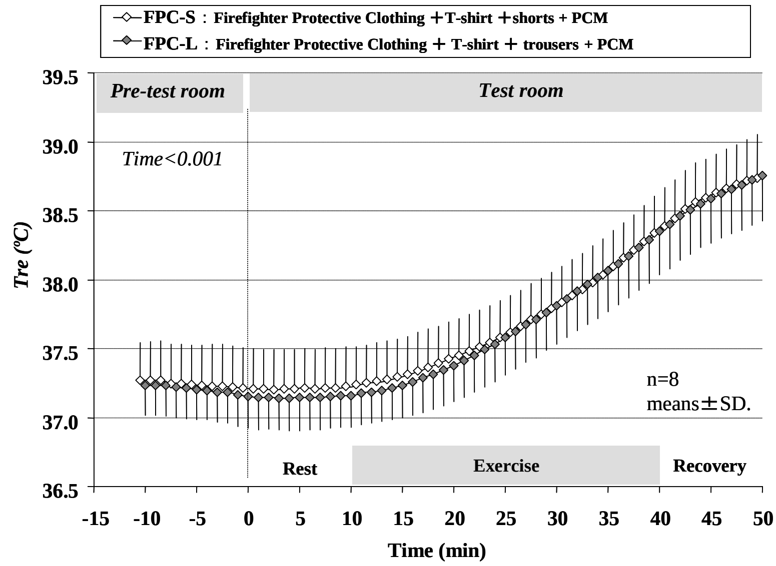


Figure 4.4. Time courses of rectal temperature with shorts (FPC-S) and trousers (FPC-L) under firefighting protective clothing with phase change materials. Values are means and SD.

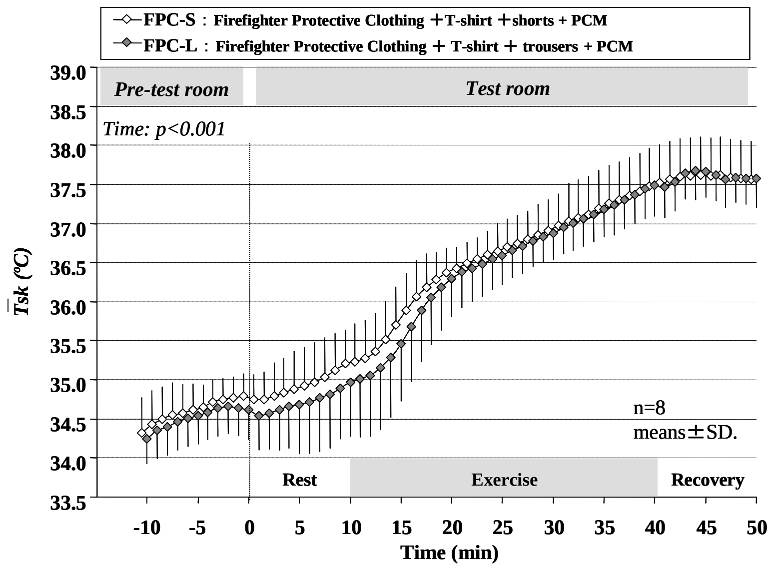


Figure 4.5. Time courses of mean skin temperature with shorts (FPC-S) and trousers (FPC-L) under firefighting protective clothing with phase change materials. Values are means and SD.

Subjective Responses

No significant differences in thermal sensation on the chest, back and whole body after entering the room were observed (**Figure 4.6**). Similarly, the thermal discomfort sensation showed that FPC-L was equally uncomfortable on the chest and back during the exercise and the recovery period. Humidity sensation did not show any changes from the beginning to the end in all conditions.

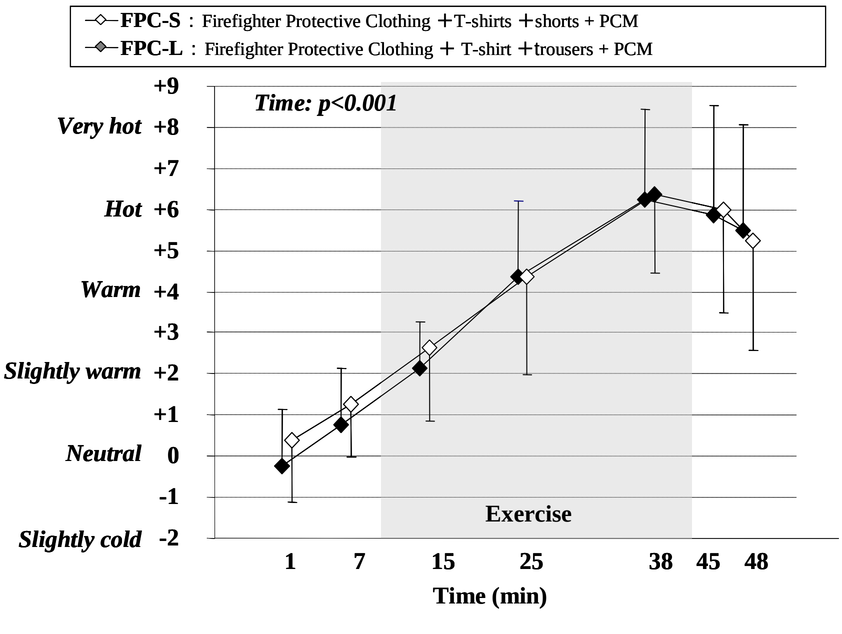


Figure 4.6. Time courses of the whole body thermal sensation for shorts (FPC-S) and trousers (FPC-L) under firefighting protective clothing with phase change materials. Values are means and SD.

4.3.2 Experiment 2

Eight subjects completed the freedom of movement test, the exercise test and answered the questionnaires. To the question "How do you feel while wearing FPC-S and FPC-L without SCBA?" (**Table 4.2-a1**), subjects replied that FPC-S's freedom of movement was greater than FPC-L's; however there were no significant differences between the conditions (Q.7). On the other hand, with FPC-S it was significantly easier to raise the legs than with FPC-L ($p < 0.065$) (Q.8) (**Figure 4.7**). To the question "How do you feel while wearing FPC-S and FPC-L with SCBA?" (**Table 4.2-a2**), there were no significant differences between the conditions (**Figure 4.8**). Subjects found SCBA was heavier with both FPC-S and FPC-L. To the question "How do you feel about moment at your…" (**Table 4.2-b**), subjects replied that with FPC-S the inner thighs and knees were easier to move than with FPC-L, but no significant differences between the two conditions were found (**Figure 4.9**). The mean exercise times of the three-cycle exercise test were 21.1±5.3 sec (with FPC-S) and 23.8±3.8 sec (with FPC-L). The mean exercise times of the five-cycle exercise test were 37.0±7.9 sec (with FPC-S) and 40.6±6.3 sec (with FPC-L). The three-cycle and five-cycle exercise times, however, were not significantly different between the two conditions. Similarly, there were no significant differences between the two conditions in the "How do you feel after taking off FPC-S and FPC-L" questionnaire (**Table 4.2-c**).

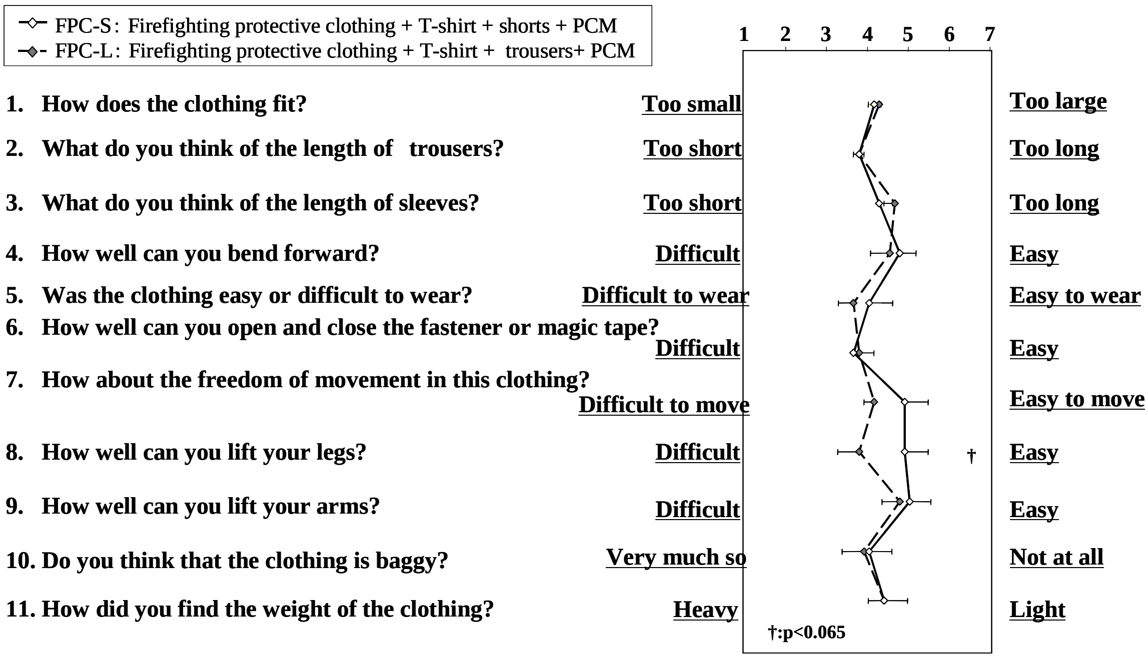


Figure 4.7. "How do you feel while wearing FPC-S and FPC-L without SCBA?" with shorts (FPC-S) and trousers (FPC-L) under firefighting protective clothing with phase change materials. Values are means and SD.

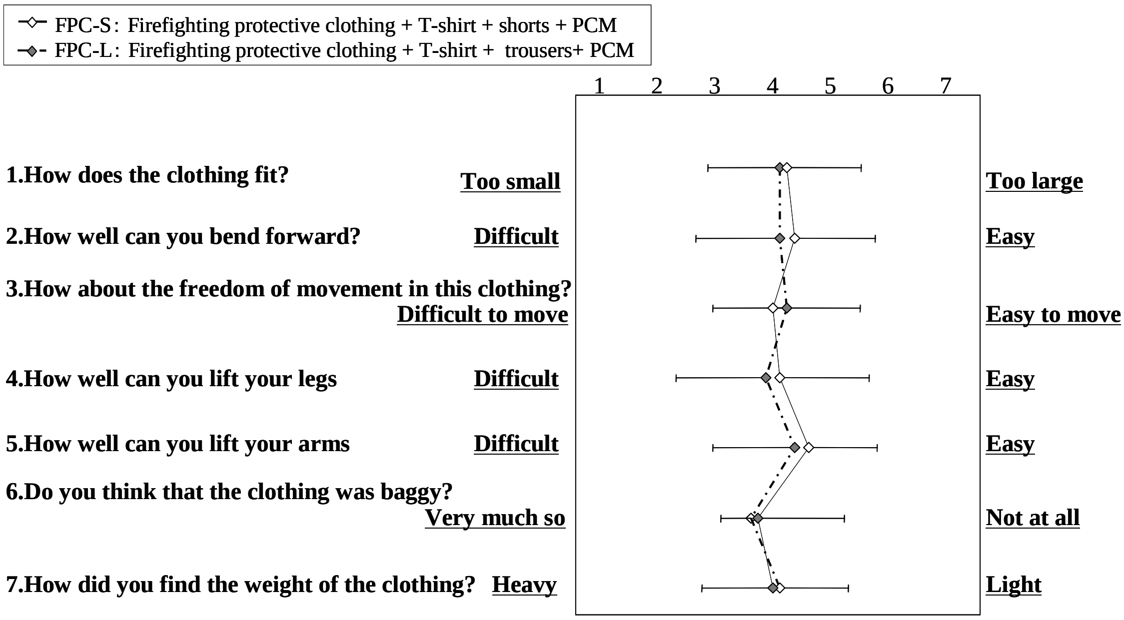


Figure 4.8. "How do you feel while wearing FPC-S and FPC-L with SCBA?" of shorts (FPC-S) and trousers (FPC-L) under firefighting protective clothing with phase change materials. Values are means and SD.

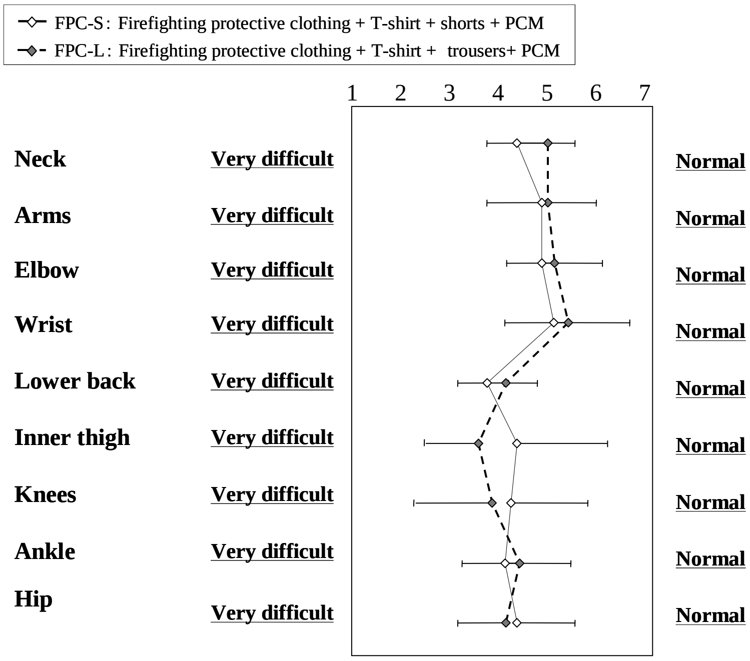


Figure 4.9. The feeling of movement from parts of body while wearing with SCBA with shorts (FPC-S) and trousers (FPC-L) under firefighting protective clothing with phase change materials. Values are means and SD.

4.4 Discussion

Chapter 4 examined physiological and subjective responses and the mobility of firefighters wearing trousers or shorts with phase change materials and firefighting clothing during a 30-minute exercise at 30 ºC with 50% RH.

In the last few years, several articles have been devoted to the study of using immersion and misting fan techniques to decrease the thermal stress of firefighters (Selkirk et al., 2004; House et al., 1997). Ross et al. (2004) reported that Toronto firefighters used cooling by forearm immersion in 17 ºC water when exchanging their self-contained breathing apparatus during an actual task. The questions which must be considered next are usability and exposure times, in addition to forearm immersion techniques (Ross et al., 2004).

According to McLellan and Selkirk (2004), it was possible to reduce thermal stress for the New York City Fire Department and the Toronto Fire City Services by wearing short pants and T-shirts under firefighting protective uniforms. The former study by Malley et al. (1999) had firefighters exercise (running on a treadmill at $4.8 km \cdot h^{-1}$~$6.4 km \cdot h^{-1}$) at room temperature, and although exercise time was significantly extended from 15 minutes to 17 minutes when shorts were worn, there was no effect on the *HR*, *Tre* and oxygen consumption increase over this short duration of activity. Based on Chou et al. (2008), using PCM was effective in reducing heat stress during a 30-minute exercise at 30 ºC with 50% RH. This study had subjects running at high speed during an exercise time of 30 minutes while wearing shorts with PCM at 30ºC and 50% RH, and there were no significant differences in physiological and subjective responses between shorts and trousers.

In addition, Tochihara et al. (2005) reported that a questionnaire survey on wearing protective clothing showed high mobility of protective clothing is more important than protection, safety, or comfort for Japanese firefighters. Firefighters work at varied tasks in varied environments (Lusa et al., 1994). Firefighting activities consist of carrying hoses, rescue tasks, hosing support, machine operation etc (Duncan et al., 1979; Nakahashi et al., 2003; Tochihara et al., 2005; Tochihara and Chou, 2007), and further, while carrying out these tasks firefighters also carry tools and/or garments and performing various movements (Tochihara et al., 2006; Tochihara and Chou, 2007). Thus, clothing affects firefighters' regular movements such as walking, crawling and bending forward during an actual task.

In experiment 2, freedom of movement was tested. Significantly greater mobility for raising the legs was found while using the 'FPC-S', as compared to the 'FPC-L' condition without SCBA. However, there was no significant difference between the two conditions with SCBA. In raising the legs with the SCBA, the SCBA was reported as “heavy”. Moreover, protective clothing covered the pants, which wrinkle up towards the joints during knee flexion while wearing trousers. Consequently, the mobility of firefighters wearing trousers is hindered, causing difficulty in movement. Thus, it affects firefighter’s regular movements such as walking, crawling and bending forward.

During the running exercise test, firefighters felt running and general mobility was easier for the inner thighs and knees using shorts compared to trousers. However, with FPC-S’ and ‘FPC-L’, there appeared no significant difference between the two conditions in a questionnaire survey. Therefore, this study confirmed that freedom of leg movement was better while wearing shorts under protective clothing with PCM for firefighters.

4.5 Conclusions

Chapter 4 of this study has documented that performance was improved in relation to mobility while wearing shorts under protective clothing with phase change materials, although it did not reveal any significant difference in reducing thermal stress in intense conditions while wearing shorts instead of trousers under protective clothing with PCMs.

• Chapter 5 General Discussion and Conclusions

Firefighting is a physically and psychologically demanding high-risk task (Davis et al., 1982; O'Connell et al., 1986; Romet and Frim 1987; Gledhill and Jamnik, 1992; Lemon and Hermiston, 1977; Holmer and Gavhed, 2007; Smith et al., 2001; Sothmann et al., 1992; von Heimburg et al., 2006; Eglin, 2007). When firefighters are performing strenuous tasks in high temperature environments, it is important to provide a high level of thermal protection with protective clothing (Pandolf and Goldman, 1978; Faff and Tutak, 1989; Nunneley, 1989; White and Hodous, 1989; White et al., 1991b; ISO11613, 1999; Graveling and Hanson, 2000). Whilst the functions of protective clothing have improved, there is the possibility that the physiological load on firefighters may increase in firefighting environments. Numerous studies have documented that strain and discomfort occur when wearing protective clothing in conditions of great thermal storage due to the body’s metabolism and exposure to heat (Smith et al., 1997; Smith and Petruzzello, 1998; Baker et al., 2000; Havenith and Heus, 2004). Moreover, Davis and Santa Maria (1975) mention that while wearing firefighting protective clothing under a moderate workload, a firefighters' working efficiency decreased by 33% before working at a strenuous firefighting activity. Alleviating physiological strain and discomfort could result in firefighter's increased ability to concentrate on efficient firefighting. Hence, it is important to consider factors related to clothing properties and also design ways of alleviating physiological strain and discomfort in firefighters' protective clothing. This study is comprised of two distinct parts that investigate the methods for alleviation of physiological strain and performance enhancement for firefighters while wearing firefighting protective clothing:

(1) It examines the specific clothing properties, such as clothing weight, clo-value and resistance to latent heat, which are factors pertaining to its physiological effect.

(2) It examines techniques such as cooling devices, fans, misting and wearing minimal clothing under protective clothing for the alleviation of physiological strain and to provide performance enhancement.

The objectives of this study were to investigate the relationship between clothing property factors and physiological effects, and techniques of alleviating physiological strain and enhancement of performance of firefighters on physiological and subjective responses while wearing firefighters' protective clothing.

In the first study, *"Effect of clothing properties on physiological and subjective responses of working firefighters' protective clothing"*, physiological and subjective responses of four kinds of firefighters' protective clothing and a light work garment worn during physically demanding activities were ascertained by examining clothing properties such as clothing weight, clo-value and latent heat resistance, and factors related to physiological effects. In the first experiment, clothing surfaces coated with aluminized sliver (PC2) compared to other PCs were almost the same or even lower in terms of clothing weight and clo-value. The latent heat resistance of PC2 was the greatest. Physiological and subjective heat strain in PC2 was greater than that of other PCs. Moreover, it was shown that the physiological strain of firefighting protective clothing, as shown in the difference between *Tre* and $\bar{T}sk$, depends more upon resistance to latent heat than upon clothing weight and clo-value. This study suggests that, when wearing firefighters' protective clothing, latent heat resistance is more closely related to the physiological effects than clothing weight or clo-value.

In the second study, "*Physiological and subjective responses to cooling devices on firefighting protective clothing*", two kinds of cooling devices (ICE and PCM) for reducing physiological load based on subjects' physiological and subjective responses under the condition of exercising on a bicycle ergometer whilst wearing firefighting protective clothing at 30 ºC with a 50% relative humidity were examined. In the second experiment, an increase in *Tre* for PCM(5)(cooled in a 5ºC refrigerator) and PCM(20)(kept at 20ºC) which was less than that for CON and ICE was observed. The increases in $\bar{T}sk$ were reduced by using cooling devices, but the cooling effects of PCMs were greater than ICE. The subjects with CON felt hotter and wetter than those in the other conditions. The larger surface cooling area, higher melting temperature and softer material of PCMs caused a decrease in *Tre* and $\bar{T}sk$ for PCM(5) and PCM(20) which was more than that for CON and ICE. Furthermore, PCM(20) does not require refrigeration. These results suggest that PCM(20) is more effective than other cooling devices in reducing the physiological load while wearing firefighting protective clothing at 30°C with a 50% relative humidity.

In the final study, "*Effects of wearing trousers or shorts under firefighting protective clothing on physiological and subjective responses*", the wearing of shorts in place of trousers under firefighting protective clothing using PCMs for the alleviation of thermal stress and performance enhancement of firefighters on physiological and subjective responses during 30 minutes exercise at 30 ºC with a 50% relative humidity was examined. The results indicated no significant differences in physiological and subjective responses between shorts and trousers. In the part of the experiment regarding movement, the results indicated that greater mobility in raising the legs was found while wearing shorts, compared with wearing trousers without SCBA. Although using shorts did not reveal any significant difference in reducing thermal stress in intense conditions over 30 minutes, freedom of leg movement was greater while wearing shorts under protective clothing.

These studies clarified that the coated outer surfaces of firefighting protective clothing caused firefighters the highest physiological and subjective heat strain. The various clothing properties affected the physiological effect upon physiological and subjective responses. Specifically, latent heat resistance was more closely related than clothing weight or clo-value to the physiological effect.

The experiment investigated the use of cooling techniques and shorts in place of trousers for the alleviation of thermal stress of firefighters. These studies clarified that PCMs were more effective than ICE, due to their larger surface cooling area, higher melting temperature, softer material and lack of a cover which reduces absorption capacity and causes a decrease in *Tre* and $\bar{T}sk$. Specifically, PCM kept at 20°C was more effective than other cooling devices in reducing the physiological load while wearing protective firefighting clothing. In addition, the studies show that PCMs were effective in reducing heat stress for 30 minutes during 55%$\dot{V}_{O2peak}$ exercise in our experimental condition, but new materials need to be developed for widespread use in actual firefighting activities with the following characteristics: (1) a high melting temperature (about 30°C) but with a greater latent heat capacity like ice, (2) nonflammability and (3) low production costs.

Future Research

Finally, the questionnaire survey on wearing firefighters' protective clothing showed high mobility of protective clothing is more important than protection, safety, or comfort. It is necessary to consider mobility for protective clothing design to enhance the performance of firefighters in the future. Cooling devices were also applied to alleviate firefighters' physiological load in this study. Better cooling devices and higher mobility with necessary protection, safety, and comfort for protective clothing are aspects for future study or development.

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Appendix A

Phase change materials (PCM)

Phase change materials provide high storage density and have small temperature variation from storage to retrieval (Farid et la., 2004; Mondal, 2008). **Figure B.1** shows pure paraffin waxes as PCM. Only technical grade paraffins can be used as pure paraffin waxes but they are very expensive (Farid et la., 2004). PCMs have a good crystallization process as well as an ability to absorb energy when they change from a solid to a liquid and vice versa.

Recently, the use of PCMs has been applied in many fields, such as in space suits, sport wear, medical applications, shoes and accessories, garments, home furnishings and cooling products (Mondal, 2008).

Figure B.1. A photograph of pure paraffin waxes as PCM (Sarı and Karaipekli, 2007)

Appendix B

How to calculate the theoretical heat absorption capacity of cooling materials

1. Ice-pack (ICE)

Melting temperature at 0°C and total weight at 1055 g

Heat capacity of H_2O is 75.15 $J \cdot k^{-1} \cdot mol$

Melting heat of H_2O is 6.01 $kJ \cdot mol^{-1}$ at 0 °C

(1) H_2O molar fraction

$1g \times 2 + 16g \times 1 = 18\ g \cdot mol^{-1}$

(2) Melting heat of H_2O

$6.01 kJ \cdot mol^{-1} \times 1\ mol \div 18\ g = 0.334\ kJ \cdot g^{-1}$

$0.334\ kJ \cdot g^{-1} \times 0.238\ kcal \cdot J^{-1} =$ **$79.5\ cal \cdot g^{-1}$**

where *1 cal = 4.2 J , 1 kcal =4.2 kJ

$1\ kcal \div 4.2\ kJ = 0.238\ kcal \cdot J^{-1} = 238\ cal \cdot J^{-1}$

(3) Melting heat for ICE

$1050g \times 79.5\ cal \cdot g^{-1} =$ **83.5 kcal**

where ICE total weight is **1050g**

(4) Heat capacity 0°C to 37°C

$(37°C-0°C) \times 1\ cal \cdot °C^{-1} . g^{-1} \times 1050g = 38.9\ kcal$

83.5 kcal + 38.9 kcal = 122.3 kcal

$122.3\ kcal \div 1.7\ m^2 = 71.9\ kcal \cdot m^{-2}$

$71.9\ kcal \cdot m^{-2} \times 4.2\ kJ = 302.2\ kJ \cdot m^{-2}$

where *1 cal = 4.2 J , 1 kcal =4.2 kJ

$1\ kcal \div 4.2\ kJ = 0.238\ kcal \cdot J^{-1} = 238\ cal \cdot J^{-1}$

Body surface area is $1.7\ m^2$

2. PCM(5)

Melting temperature at 28°C and total weight at 1344 g, at 5°C

(1) Melting heat for PCM

$1344g \times 35.1\ cal \cdot g^{-1}$ = **47.2 kcal**

where the melting heat of paraffin at 0°C $35.1\ cal \cdot g^{-1}$

(2) Heat capacity 5°C to 37°C

$(37°C-5°C) \times 0.69\ cal \cdot °C^{-1} . g^{-1} \times 1050g = 29.7\ kcal$

47.2 kcal + 29.7 kcal =76.9 kcal

$76.9\ kcal \div 1.7\ m^2 = 45.2\ kcal \cdot m^{-2}$

$45.2\ kcal \cdot m^{-2} \times 4.2\ kJ$ = **190.0 $kJ \cdot m^{-2}$**

where *1 cal = 4.2 J , 1 kcal =4.2 kJ

$1\ kcal \div 4.2\ kJ = 0.238\ kcal \cdot J^{-1} = 238\ cal \cdot J^{-1}$

Body surface area is $1.7\ m^2$

3. PCM(20)

The melting temperature at 28°C and total weight at 1344 g, at 20°C

(1) Melting heat for PCM

$1344g \times 35.1\ cal \cdot g^{-1}$ = **47.2 kcal**

where the melting heat of paraffin at 0°C $35.1\ cal \cdot g^{-1}$

(2) Heat capacity 20°C to 37°C

$(37°C-20°C) \times 0.69\ cal \cdot °C^{-1} . g^{-1} \times 1344g = 15.8\ kcal$

47.2 kcal + 15.8 kcal =63.0 kcal

$63.0 kcal \div 1.7\ m^2 = 37.1 kcal \cdot m^{-2}$

$45.2\ kcal \cdot m^{-2} \times 4.2\ kJ$ = **155.6 $kJ \cdot m^{-2}$**

where *1 cal = 4.2 J , 1 kcal =4.2 kJ

$1\ kcal \div 4.2\ kJ = 0.238\ kcal \cdot J^{-1} = 238\ cal \cdot J^{-1}$

Body surface area is $1.7\ m^2$

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