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Quantitative assessment of the relationship between radiant heat exposure and protective performance of multilayer thermal protective clothing during dry and wet conditions

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HIGHLIGHTS

- Thermal protective performance of multilayer protective clothing was studied.
- Two kinds of moisture barrier with different vapor permeability were compared.
- Moisture transfer affects the heat transfer of the multilayer clothing.
- A linear correlation between temperature of each layer and heat flux is found.

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ABSTRACT

The beneficial effect of clothing on a person is important to the criteria for people exposure to radiant heat flux from fires. The thermal protective performance of multilayer thermal protective clothing exposed to low heat fluxes during dry and wet conditions was studied using two designed bench-scale test apparatus. The protective clothing with four fabric layers (outer shell, moisture barrier, thermal linear and inner layer) was exposed to six levels of thermal radiation (1, 2, 3, 5, 7 and 10 kW/m^2). Two kinds of the moisture barrier (PTFE and GoreTex) with different vapor permeability were compared. The outside and inside surface temperatures of each fabric layer were measured. The fitting analysis was used to quantitatively assess the relationship between the temperature of each layer during thermal exposure and the level of external heat flux. It is indicated that there is a linear correlation between the temperature of each layer and the radiant level. Therefore, a predicted equation is developed to calculate the thermal insulation of the multilayer clothing from the external heat flux. It can also provide some useful information on the beneficial effects of clothing for the exposure criteria of radiant heat flux from fire.

1. Introduction

Radiant heat exposure hazards to people from a wildfire, a LNG fire, or a structure fire are the main thermal threats when fighting the fire [1–3]. With the duty of protecting property and rescuing trapped personnel, firefighters have to remain at a close distance from the fire front or enter into the fire. Therefore, firefighter protective clothing is used to protect the body from external heat exposure hazards. NFPA estimated that more than 78,150 firefighter injuries occurred annually in the line of duty during 1981–2009 [4].

While fighting fire, fire fighters are exposed to two thermal hazards of skin burns and heat stress [5,6]. The criteria for people exposure to radiant heat flux from fires were reviewed by Raj [7]. It was shown that the criteria for skin burn hazards were associated with the level of heat flux, the exposure time, and the effects of clothing on a person, etc. Barker summarized firefighter thermal environments with different levels of radiant flux and tolerance time, classified as routine, hazardous, and emergency [8]. Emergency conditions could occur during a flashover building fire, leading to skin burns in several seconds [8]. Two test methods are used to evaluate the thermal protective performance of protective clothing under emergency conditions. The two methods are thermal protective performance (TPP) for convective and radiant heat penetrating through a composite fabric system, and radiant protective performance (RPP) for a controlled radiant heat source to penetrate through protective clothing [8]. However, firefighters

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were frequently working with the thermal exposures in routine and hazardous conditions, not flashover conditions [9]. It was indicated that skin burn mostly occurred in the low level radiant flux ranging from 5 kW/m^2 to 20 kW/m^2 [10,11].

The thermal exposures hazards have great effects on the thermal protective performance of clothing. Some previous studies including the dry test [12–14], and the wet test [11,15,16] evaluated the thermal protective performance of clothing exposed to the low level thermal radiation. Including the effect of clothing, a series of field-scale tests with LNG fires were conducted by Raj [12] to measure the radiant heat attenuation factors for different types of civilian clothing. However, only one level of heat flux close to 5 kW/m^2 was used. The protective performance of civilian clothing was different from the clothing that firefighters dressed. From thermal manikin experiments exposed to thermal radiation, Emiel and Havenith [13] predicted a linear relationship between the heat loss and the radiation intensity. But the wet test with the manikin sweating was not considered. A test apparatus was developed by Song et al. [11] with the range of 6.3–8.3 kW/m^2 to evaluate the thermal protective performance of clothing, examine the effect of moisture, and predict the associated physiological burden within different fabric systems. It was shown that the protective performance of clothing was significantly affected by the stored thermal energy. Keiser and Rossi [16] investigated the temperatures inside the clothing layers, to analyze the evaporation process at 5 kW/m^2 during 10 min. The results showed that the moisture had a positive effect on thermal protection.

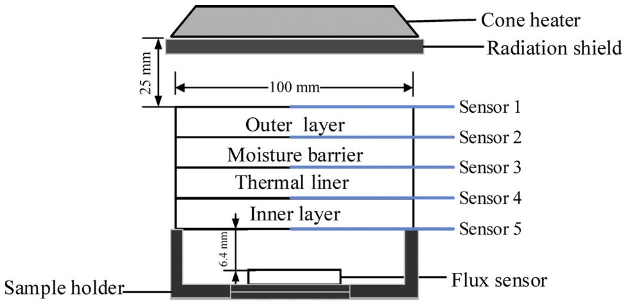
However, few studies were conducted to study the relationship between the thermal radiation and the protective performance of protective clothing. The elements that affected the exposure criteria of radiant heat flux from fires concentrated on the level of heat flux and the exposure time [9–11,14]. The effects of clothing on a person were discussed only with qualitative analysis by Raj [7,12]. There is still lack of quantitative assessment between the thermal radiation and the protective performance of protective clothing exposed to low level thermal radiation. The presence of clothing between the external radiation and the skin surface can reduce the actual heat flux entering the skin [12]. The thermal insulation of the clothing represents a quantitative assessment of the ability to heat exchange through the multi-layers of the clothing system [17]. However, the thermal insulation is mainly measured by a heat guard plate or a thermal manikin [17], which needs to measure the temperature of each layer and control the heat loss to the ambient environment. Therefore, it is time-consuming and not convenient for the scientific community of hazardous materials and thermal risk assessment.

The objective of this study is to investigate the effects of low level thermal radiation on the thermal protective performance of protective clothing during dry and wet tests. In addition, the fitting analysis was studied between the thermal radiation and the thermal protective performance of clothing. The thermal insulation of the clothing can be then predicted by the external thermal radiation, without being measured by a heat guard plate or a thermal manikin. The research findings might provide comprehensive understanding on the thermal protection of clothing from low level thermal radiation. It can also provide some useful information on the beneficial effects of clothing, to be used in the exposure criteria of radiant heat flux from fires reviewed by Raj [7].

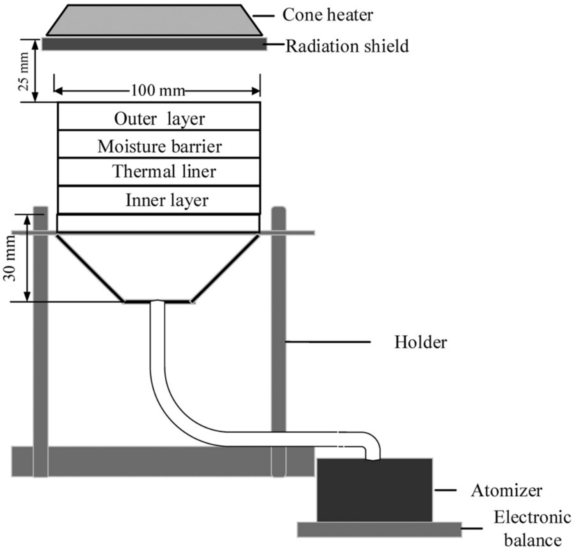
2. Experimental

2.1. Materials

Four-layer fabric system was used, including the outer shell, moisture barrier, thermal liner and inner layer. The four layers of fabric are sewed in sequence, seen in Fig. 1. Two kinds of composite fabric (PTFE and Gore-Tex) for the moisture barrier were applied with different water vapor permeability. The vapor permeability of PTFE and Gore-Tex was 5155 and 7513 g/m^2/24 h, respectively, according to ASTM E96 [18]. The selected sample fabrics used in each layer and their basic properties are listed in Table 1.



(a) Dry test



(b) Wet test

Fig. 1. Schematic diagram of the bench-scale test apparatuses for dry and wet tests.

2.2. Testing apparatus

To evaluate the thermal protective performance of multilayer fabric systems exposed to low level thermal radiation, two bench-scale test apparatuses were constructed with dry and wet tests. Those two apparatuses could well regulate the required measurement conditions of different levels of thermal radiation, as shown in Fig. 1.

These two apparatuses used the same heat source, i.e. a cone-shaped radiant electrical heater (Fire Testing Technology, UK) specified by ISO 5660-1 [19]. The radiant heater was widely used to provide the thermal radiation comparable with small to medium fire scenario [20]. A 12 cm × 12 cm testing sample of four-layer fabrics system was placed vertically downward of 25 mm from the cone heater, required by ISO 5660-1 [19]. The irradiance of the exposed sample surface was uniform within the central 5 cm × 5 cm area. A removable radiation shield protected the testing sample from the exposure before the exposure test.

For the apparatus used for the dry test (shown in Fig. 1(a)), a radiant flux sensor (Captec Entreprise, France; measuring accuracy: 1%) was placed on the center of the sample holder, to measure the

Table 1
Specification of the materials used for each layer.

Layer	Component	Weave type	Fabric weight (g/m^2)	Thickness (mm)	Thermal conductivity (W/m °C)
Outer shell	93% Nomex, 5% Kevlar, 2% P140	Twill	200	0.44	0.042
Moisture barrier I	50% Nomex, 50% Kevlar	Water thorn felt with PTFE	105	0.62	0.052
Moisture barrier II	Breathable film with nylon	Laminated with GoreTex	119	0.12	0.054
Thermal liner	Nomex	Needling nonwoven	150	2.60	0.071
Inner layer	50% Nomex, 50% FR-VISCOS	Plain weave	120	0.31	0.032

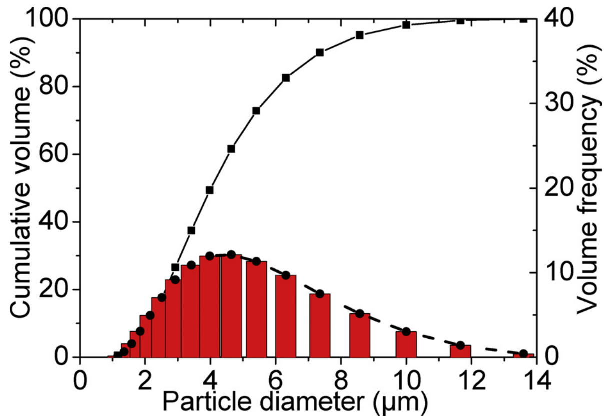


Fig. 2. The atomized droplet distribution measured in the experiment.

incident heat flux transmitted the sample. According to Torvi [21], the distance from the backside of the sample to the sensor was 6.4 mm. An asbestos pad was positioned under the radiant flux sensor to prevent heat loss from the sensor to the sample holder.

For the apparatus used for the wet test (shown in Fig. 1(b)), an atomizer with a heater was used to produce liquid droplets. Therefore, it was impossible to measure the transmitted heat flux through the clothing sample as the dry test. The liquid droplets out of the pipe (30 mm under the inside of the inner layer) was maintained at a constant temperature of 35 °C by the heater, measured by a type K thermocouple and controlled by a proportional-integral-derivative (PID) system. The size distribution of atomized droplets was measured by a laser particle size analyzer (Spraytec, Malvern Instruments Ltd, UK). The results of the volume frequency and the cumulative volume are shown in Fig. 2. It can be seen that the diameters of all the particles are less than 14 μm. The diameter with 97% of the cumulative volume is near 10 μm. The thickness of individual fibers is typically 15–30 μm in diameter, yielding yarns of 50–100 μm diameter and fabrics with thicknesses more than 100 μm [22]. Therefore, it can be assumed that the atomized droplets can simulate human sweating transferring from the human skin to the clothing system.

2.3. Protocol

The testing sample were preconditioned in a temperature and humidity chamber (20 ± 2 °C and 65 ± 3% RH) for 24 h, and then sealed in a plastic bag for another 24 h before the experiment. Thermocouples of Type K with the diameter of 0.4 mm (Omega Engineering, USA) were sewn on the center of each layer (shown in Fig. 1(a)), to measure the temperature distribution through the clothing, according to the research of Keiser et al. [16].

After the preparation of the multilayer fabric system with thermocouples, the sample fabric system was placed under the cone heater. It needed 3 min for the cone heater to reach up the temperature to produce the required thermal radiation (1, 2, 3, 5, 7 and 10 kW/m^2, respectively). The experimental data were obtained for a total test time of 40 min. After the controlled temperature of the cone heater achieved stable for 10 min, the radiation shield was removed quickly from the cone heater. The sample system was exposed to the preset radiant flux for 20 min. The radiation shield was then moved back without the radiation for the next 10 min as the cool-down period. The data of thermocouples and the radiant flux sensor were collected. The mean value of each sample was obtained from repeated three tests.

3. Results and discussion

3.1. Effect of thermal radiation on the protective performance of clothing

The effect of thermal radiation was firstly discussed with the multilayer clothing with the moisture barrier of PTFE during the dry and wet tests. The effects of moisture barrier with different vapor permeability were then studied with the multilayer fabric system with the moisture barrier of GoreTex.

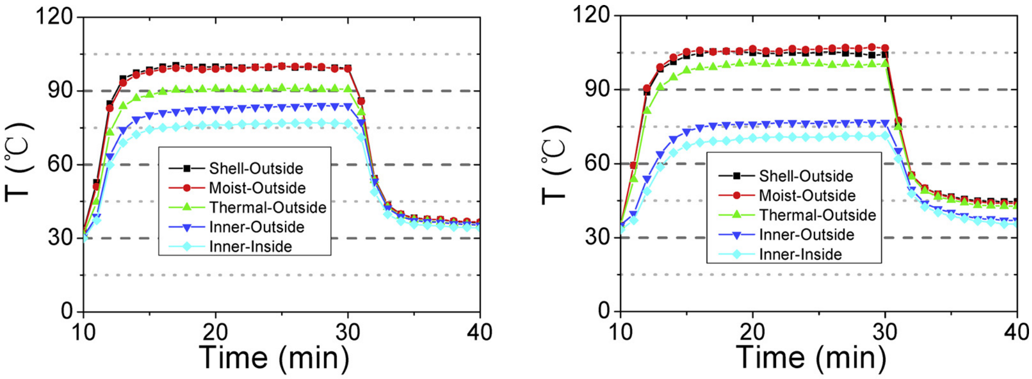
3.1.1. Effect of thermal radiation during dry and wet tests

Fig. 3 shows the temperature distribution of each layer with the moisture barrier of PTFE during the dry and wet tests exposed to 2, 5 and 10 kW/m^2, respectively. It can be seen that the thermal radiation greatly affects the heat transfer of multilayer clothing system during both the dry and wet tests. As expected, the temperature of each layer is increasing with the exposed thermal radiation. During the exposed period (10–30 min), the temperature distribution of each clothing layer can be divided in three different phases (shown in Fig. 3): an initial quick rising phase for the first 2 min, a second slow rising phase for the next 2–5 min, and a quasi-stable condition for the next 5 min (15–30 min).

For the outer shell, the difference of the outside and inside temperatures is very small. The outside temperature has not much difference at the dry and wet tests. Except the transmitted thermal radiation through the clothing layers, this phenomenon can be accounted for the designed function of the outer shell. The role of the outer shell is to provide resistance from flame, thermal and mechanical [17,23]. It can be seen from Table 1 that the thermal conductivity of the outer shell is less than the other layers, except the inner layer with wearing comfortable for the human body. However, the inside temperature is a litter higher than the outside temperature during wet test at each heat flux (see Fig. 3(b), (d) and (f)). This result might be associated with the effect of moisture transfer, which will be discussed later.

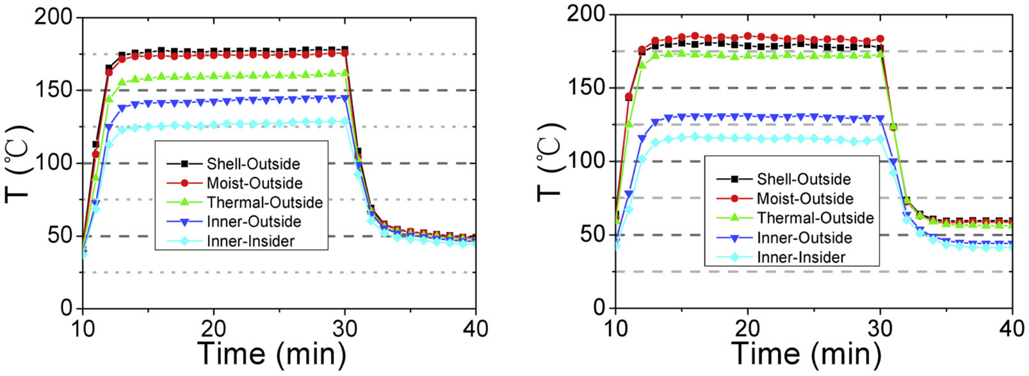
For the moisture barrier, the temperatures of the outside and inside face are less at the dry test than that at the wet test for the quasi-stable condition (15–30 min). During 15–30 min for dry test, the outside and inside temperatures reach up to 100 and 91, 175 and 161, and 262 and 239 °C with the heat flux of 2, 5 and 10 kW/m^2, respectively. For wet test, the temperatures arrive at 104 and 98, 183 and 172, and 275 and 252 °C with the three heat fluxes, respectively.

However, for the thermal liner, the inside temperature are more at dry test than that at wet test for the quasi-stable condition. The inside temperature reaches up to 84, 144 and 217 °C for the dry test, while it is 75, 130, and 206 °C for the wet test at 2, 5 and 10 kW/m^2,



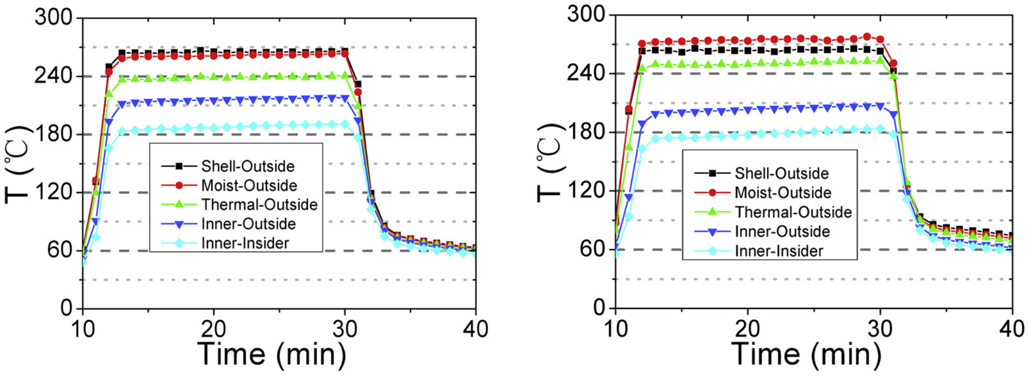
(a) Dry test exposed to 2 kW/m^2

(b) Wet test exposed to 2 kW/m^2



(c) Dry test exposed to 5 kW/m^2

(d) Wet test exposed to 5 kW/m^2



(e) Dry test exposed to 10 kW/m^2

(f) Wet test exposed to 10 kW/m^2

Fig. 3. Temperatures between the layers with the moisture layer of PTFE during the dry and wet tests, exposed to 2, 5 and 10 kW/m^2, respectively.

respectively. Therefore, the temperature difference between the outside and inside faces is 23, 42 and 46 °C for the wet test, which is more than that at the dry test (7, 17 and 22 °C at the three heat fluxes, respectively). That is to say, the protective performance of the thermal liner is improved with the moisture transfer. The liquid droplets from the atomizer transfer though the inner layer, and are absorbed in the thermal liner. The absorbed liquids will absorb a large amount of heat and cool the inside of the thermal liner. However, the absorbed water cannot pass though the moisture barrier, with vaporization by releasing heat to the outer layers. Therefore, the insider and outside temperatures of the moisture barrier will rise, in addition to the transmitted thermal radiation.

The inner layer has similar inside temperature distribution with that of the thermal liner both in the dry and wet tests. The inside temperature at quasi-stable condition is 77, 128 and 189 °C for the dry test, and 70, 114 and 181 °C for the wet test at 2, 5 and 10 kW/m^2, respectively. This inner layer can be cooled by the cooler liquid droplets and the absorbed water with absorbing heat.

For the cool down period, the temperatures of each layer are decreasing quickly within 3 min after ending the radiation, and reach near the values before the radiation (10 min). There is not much difference between the temperatures of each layer at the dry test. However, at the wet test, the temperatures of the outer shell and the moisture barrier are bigger than those of the thermal linear and the inner layer. The temperatures of the outer shell and the moisture barrier are near 45, 60 and 70 °C at 2, 5 and 10 kW/m^2, respectively. Because the moisture can transfer from the inner layers to the outer layers, but is blocked by the moisture layer. The vaporization within the membrane of the moisture layer can discharge heat to the outer layers. It should be noted that the stored heat by the outer layers during the cool down period can release to the human body when the clothing contacting with solid body, or the moving human body [10,11]. As a result, the stored heat can result in skin burn injuries or heat stain for human body [5,6].

3.1.2. *Effect of thermal radiation with different kinds of moisture barrier*

Fig. 4 shows the temperature distribution of each layer with the moisture barrier of GoreTex during dry and wet tests exposed to 2, 5 and 10 kW/m^2, respectively. It is also shown that the thermal radiation greatly affects the heat transfer of multilayer clothing system during both the dry and wet tests. For the dry test, the temperature distribution of each clothing layer can be divided in three different phases as the results for the sample with PTFE, during the exposed period (10–30 min). For the cool down period, the temperatures of each layer decreases also quickly within 3 min after the radiation, and near the value of 10 min. However, different phases occur when exposed to 2, 5 and 10 kW/m^2 during the wet test.

In the wet test during the exposure period (10–30 min) at 2 kW/m^2 (see Fig. 3(b)), the temperature distribution can be split into five different phases: an initial quick rising phase for the first 2 min, a slow rising phase for the next 2–7 min, a slight drop for the next 7–9 min, a second slight rise for the next 9–12 min, and a final stagnation phase for the last 8 min. For the phase of a slight drop, the outside and backside temperatures of the outer shell drop with a slighter gradient, compared with the temperature drop in the inner layers (Fig. 3(b)). It can be assumed that this is the time when moisture evaporates from the inner layers to the outer layers, cooling the inners layer. The cooling effect is not clearly visible for the outside and backside temperatures of the outer shell, for the external heat flux. After all the absorbed moisture changes from liquid state to vapor state (occurring at the second slight rise for the 9–12 min after the exposure radiation), the temperatures within the inner layers rise with a very small gradient.

In the wet test during the exposure period at 5 and 10 kW/m^2 (See Fig. 3(d) and (f)), the temperature distribution can be split into four different phases. The first two phases are the same as the dry test, i.e. an initial quick rising phase for the first 2 min and a slow rising phase for the next 2–5 min. Compared with the results about the third phase of a slight drop at 2 kW/m^2, it can be divided into two phases, i.e. a quasi-stable condition for the next 5–12 min, and a final bigger drop for the last 8 min. The drop gradient for the final phase from the outside layer to insider layer is 0.24, 0.09, 0.09, 0.25 and 0.48 and 1.33, 0.69, 2.13, 3.13 and 1.77 °C/min at 5 and 10 kW/m^2, respectively. During the final phase, moisture can absorb heat from the heated clothing and transmitted thermal radiation, evaporating from the inner layers to the outer layers to cool the multilayer clothing. Furthermore, water vapor transferring out of the outer shell can absorb thermal heat from the heat source for its high absorptivity [24]. Therefore, the heat source cannot provide the preset heat flux under the exterior of multilayer clothing. With the cooling effect of moisture evaporation and the reduced heat flux taken away by the water vapor, the temperatures of each layer are decreasing, especially within the inner layers. In addition, the amount of vapored water and the amount of reduced heat flux are more at 10 kW/m^2 than those at 5 kW/m^2. As a result, the drop gradients for the last two phases are bigger at 10 kW/m^2 than those at 5 kW/m^2.

For the cool down period, the temperatures of each layer are decreasing quickly within 3 min after ending the radiation, and reach near the values before the radiation (10 min) at ending the test (40 min). For the wet test during 4–6 min after ending the radiation, the temperatures of the outer shell and the moisture barrier are bigger than those of the thermal linear and the inner layer. This can be accounted for the stored heat by the outer layers during the cool down period [10,11]. The stored heat can release to the human body when contacting with solid, leading to skin burn injuries or heat stain for human body [5,6]. In addition, there is not much difference between the temperatures of each layer at 40 min for the dry and wet tests, respectively. Compared with the PTFE of less vapor permeability, the hot water vapor can transfer through the moisture barrier made of GoreTex to the outer layers. From the results of Fig. 4 and the above discussion, it can be seen that the moisture transfer is affected by the vapor permeability of the moisture barrier. At different levels of heat flux, the heat transfer within the clothing can be different with moisture transfer.

Table 2
Linear fitting results for the relationships between the heat flux and the temperatures of the fabric layers with PTFE.

Temperature of the fabric layers	*a*	*b*	*R*	Adj. R^2
Dry test with PTFE				
Shell-outside	22.12	57.56	0.989	0.972
Moist-outside	21.81	57.23	0.989	0.973
Thermal-outside	19.84	53.05	0.989	0.972
Inner-outside	17.78	48.55	0.991	0.978
Inner-inside	15.00	47.52	0.991	0.978
Wet test with PTFE				
Shell-outside	21.71	60.62	0.988	0.969
Moist-outside	22.88	60.41	0.988	0.970
Thermal-outside	21.15	56.16	0.981	0.952
Inner-outside	17.10	41.57	0.994	0.985
Inner-inside	14.82	38.72	0.992	0.979

3.2. *Fitting analysis for the effect of the thermal radiation*

From the results discussed in Section 3.1, it can be seen that the temperature distribution of each clothing layer reaches at a quasi-stable condition for 5 min after the thermal exposure (15–30 min), with PTFE at dry and wet tests, and with GoreTex at dry test. The clothing system with GoreTex at wet test is not included for there is no quasi-stable condition during the exposure time of 20 min. In this section, the fitting analyses are conducted between the temperature of each layer at the quasi-stable condition and the level of thermal radiation.

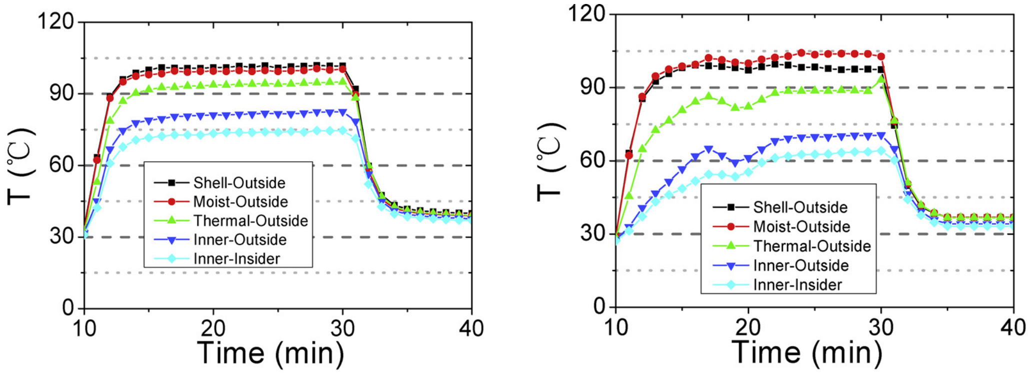
3.2.1. *Relationship between the heat flux level and the temperature of each layer*

It can be assumed as a linear regression with the effect of radiation, as below [13].

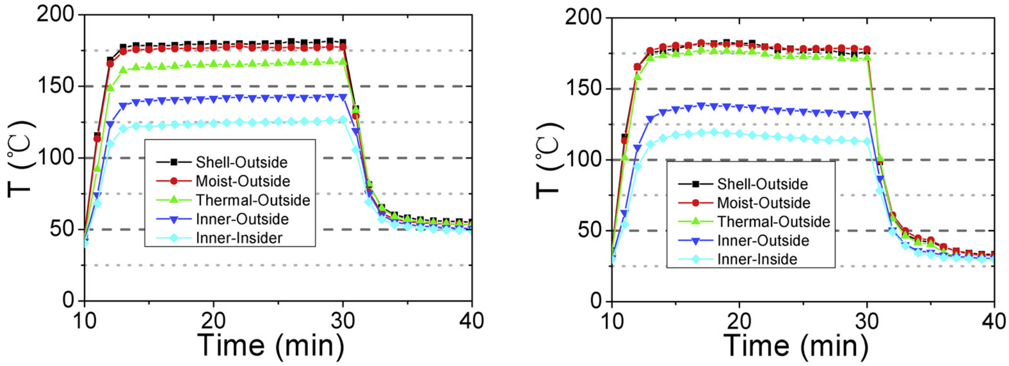
$$T_{\text{layer}} = a \times HL + b \tag{1}$$

where T_{layer} is the temperature of each clothing layer (°C). *HL* is the heat flux from the hot source, kW/m^2. *a* and *b* are the coefficients of the slope and intercept for the linear regression analysis, respectively.

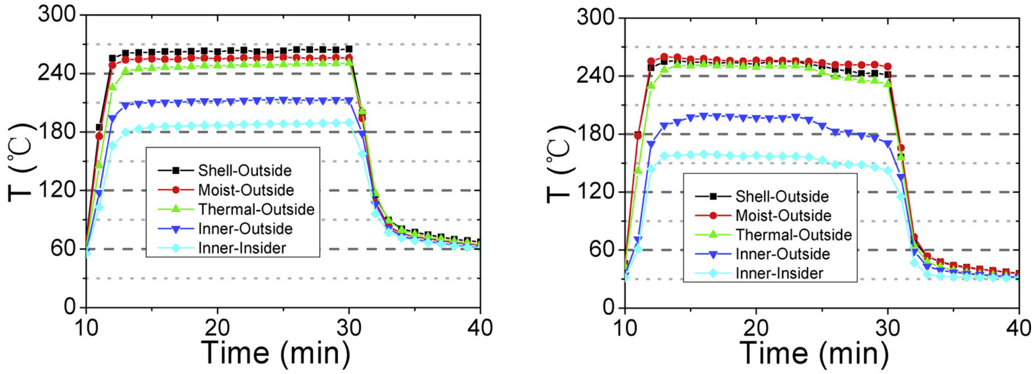
The correlation coefficient *R* and adjusted R^2-value are used to state the significance level and goodness of the linear fitting results. Six levels of thermal radiation (1, 2, 3, 5, 7 and 10 kW/m^2) were used for the fitting analysis. The linear correlation between T_{layer} and *HL* is shown in Table 2 for the clothing system with PTFE at the dry and wet tests. Table 3 shows the linear correlation between T_{layer} and *HL* for the clothing system with GoreTex at the dry test. It can be seen that the absolute value of R and the adjusted R^2-values are all more than 0.988 and 0.952 for all the layer temperatures. Therefore, there is a linear relationship between T_{layer} and *HL*, at the clothing system exposed to low level radiation.



(a) Dry test exposed to 2 kW/m^2 (b) Wet test exposed to 2 kW/m^2



(c) Dry test exposed to 5 kW/m^2 (d) Wet test exposed to 5 kW/m^2



(e) Dry test exposed to 10 kW/m^2 (f) Wet test exposed to 10 kW/m^2

Fig. 4. Temperatures between the layers with the moisture layer of GoreTex during the dry and wet tests, exposed to 2, 5 and 10 kW/m^2, respectively.

3.2.2. Calculation of clothing thermal insulation from external thermal radiation

The calculation of the clothing thermal insulation by a heat guard plate in room environments is from the temperature difference between the surface of the plate and the ambient air, and the electrical power, defined by the standard of ASTM 1868 [25]. However, this calculation method can't be used to calculate the clothing thermal insulation in hot environments, considering the difference of test conditions. The thermal insulations (I_T, °C m^2 W^{-1}) of the multilayer clothing exposed to low level radiation is determined from the heat loss within the multilayer fabric system, and the temperature difference between the outside surface of the outer shell and the inside surface of the inner layer [17], by:

Table 3
Linear fitting results for the relationships between the heat flux and the temperatures of the fabric layers with GoreTex.

Temperature of the fabric layers	*a*	*b*	*R*	Adj. R^2
Shell-outside	21.79	60.38	0.986	0.966
Moist-outside	21.13	60.35	0.984	0.960
Thermal-outside	20.40	54.87	0.991	0.978
Inner-outside	17.51	48.34	0.989	0.972
Inner-inside	15.21	44.92	0.990	0.976

$$I_T = \frac{T_{out} - T_{in}}{HL - R_1 - C} \tag{2}$$

where T_{out} and T_{in} are the outside surface temperature of the outer shell and the inside surface temperature of the inner layer (°C), respectively. R_1 is the incident heat flux measured by the radiant flux sensor (W/m^2). C is the heat loss by the natural convection

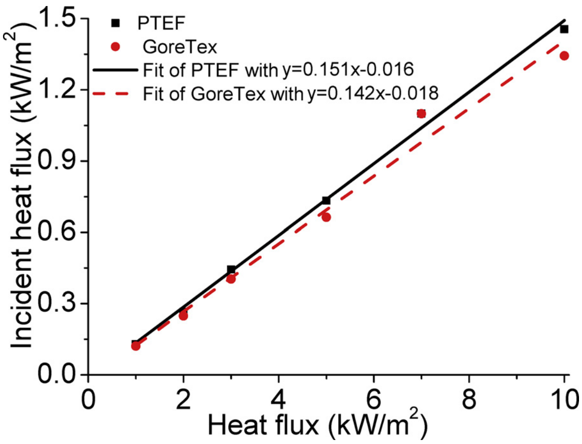


Fig. 5. Fitting analysis between the incident heat flux measured by the radiant flux sensor with the external heat flux.

within the air gap between the inner layer and the flux sensor (W/m^2), and calculated by:

$$C = h_c(T_{in} - T_{hf}) \tag{3}$$

where T_{hf} is the outside surface temperature of the radiant flux sensor (°C). h_c is the coefficient of convective heat transfer (W m^{-2} °C^{-1}), and provided by Incropera et al. [26]:

$$h_c = \begin{cases} 0.59k_a \dfrac{Ra^{1/4}}{L}, & Ra \le 10^9 \\ 0.1k_a \dfrac{Ra^{1/3}}{L}, & Ra > 10^9 \end{cases} \tag{4}$$

where k_a is the thermal conductivity of air (W/m °C^{-1}). L is the width of fabric system (10 cm). Ra is Rayleigh number [26].

Fig. 5 shows the linear fitting result between R_1 and HL. It can be seen that the absolute value of R and the adjusted R^2-values are all more than 0.979. It seems that the value of R_1 is linearly related to HL. Therefore, R_1 can be described by HL as follow.

$$R_1 = m \times HL + n \tag{5}$$

By filling Eqs. (1) and (5) into Eq. (2), a predicted equation can be made for I_T, with HL.

$$I_T = \frac{(a_{out} - a_{in}) \times HL + (b_{out} - b_{in})}{(1 - m) \times HL - n - C} \tag{6}$$

Using Eq. (6), the thermal insulation of the multilayer clothing exposed to low level radiation can be predicted at different levels of radiation. Fig. 6 shows the comparison between the calculated results of the thermal insulation with the measured results of [17] with five levels of radiation. It can be seen that the thermal insulation agrees well with the experimental results in terms of both the absolute value and the overall trend, with the average relative error of 8.1%.

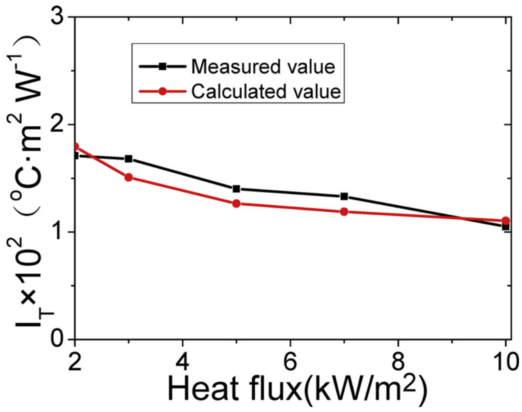


Fig. 6. The calculated results of the thermal insulation compared with the measured results [17].

In addition, the local thermal resistances of each fabric layer within the multilayer clothing can be calculated by the Eq. (6), with replacing for the temperature difference between the outside and the inside surface of each layer from Tables 2 and 3.

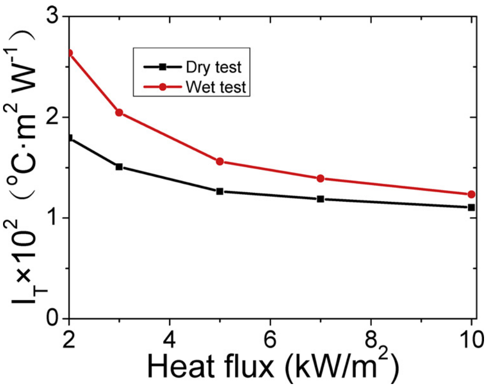


Fig. 7. The calculated results of the thermal insulation at the dry and wet test.

3.2.3. Comparison of clothing thermal insulation during the dry and wet conditions

For the wet test, however, it is hard to measure the incident heat flux and the air temperature below the inside of the inner layer (see Fig. 1(b)). It can be seen from Fig. 3 that the inside temperature difference of the inner layer with PTFE for quasi-stable condition at the dry and wet tests is near 7, 14 and 8 °C at 2, 5 and 10 kW/m^2, respectively. It is assumed that R_1 and C are same at the dry and wet tests. Therefore, Eq. (6) can be used to calculate the thermal insulation at the wet test.

Fig. 7 shows the comparison between the calculated results of the thermal insulation at the dry and wet tests. It can be seen that the thermal insulation is decreasing with the external thermal radiation. The heat conductivity and the radiation heat transfer coefficients of the fabric layer are rising with the increase of the temperature of the multilayer clothing [17]. Therefore, the thermal insulation is decreasing with the increase of the heat conductivity and the radiation heat transfer coefficients [21]. And it can also be shown that the differential coefficient of Eq. (6) is less than zero.

In addition, the thermal insulation at the wet test is more than that at the dry test. It can be explained by the results discussed in Fig. 3. The moisture transfer will affect the heat transfer of the multilayer clothing exposed to low level thermal radiation. The protective performance of the inner layers including the thermal linear and the inner layer can be improved with the moisture transfer, while the outer layers especially the moisture barrier will be heated by the external radiation and the released heat from the moisture transfer. Furthermore, the thermal insulation difference between the dry and the wet tests is smaller with the thermal radiation. It can be seen from Table 2 that the value of a for the outside of the outer shell is less than that for the outside of the moisture barrier (i.e. the inside of the outer shell). It can be assumed that there is a heat transfer with moisture transfer from the moisture barrier to the outer shell, which is needed to verify in future study.

The clothing thermal insulation of the multilayer clothing with GoreTex during the wet condition cannot be calculated using the Eq. (6), for there is no quasi-stable condition during the exposure time of 20 min. From the results of Fig. 4, it can also be seen that the moisture transfer is affected by the vapor permeability of the moisture barrier when the multilayer clothing is exposed to low level thermal radiation. At different levels of heat flux, the heat transfer within the clothing can be different with moisture transfer. Therefore, the vapor permeability of the moisture barrier might have influence on the clothing thermal insulation of the multilayer clothing exposed to low level thermal radiation. The thermal performance of the multilayer clothing with good vapor permeability should be evaluated by another way. And the analysis method of Eq. (6) can provide some suggestions for future study about the effects of clothing for the exposure criteria of radiant heat flux from fire.

3.3. Application of the predicted equation of thermal insulation in thermal radiation

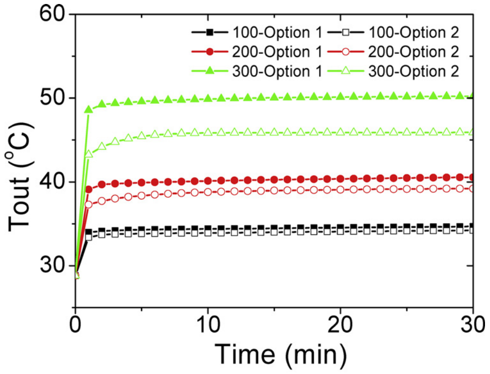
The UC Berkeley Comfort Model (UCB model) developed by Huizenga et al. [27] includes 16 body segments, each of which has four body layers (core, muscle, fat, and skin tissues) and a clothing layer. The UCB model has been validated against physiological responses in transient, non-uniform thermal environments [27]. A clothing model was developed by Fu et al. [28] and integrated with the UCB model. The evaporation transfer through and moisture absorption by clothing have been investigated. In this study, the developed clothing model [28] and the UCB model [27] were used to study clothing thermal response exposed to thermal radiation.

It is assumed that a clothed person is quietly standing in the center of a chamber (5 m length × 5 m width × 3 m height) at 30 °C, 50% RH and 0.1 m/s for 30 min. A 2 m × 2 m (width × height) radiant plate is used as the heat source on the north wall in the chamber. The human body faces the radiation source at the height of 0.5 m above the floor. The emissivity of the clothing and the heat source is set as 0.9 and 0.98, respectively. The method of view factors is used to calculate the radiative heat exchange between the clothing outer surface and the hot surface [27,28].

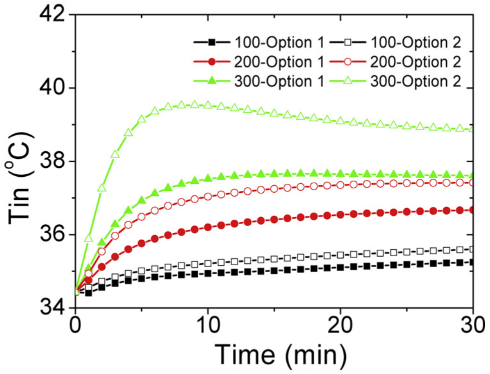
In order to investigate the effect of the results of the predicted equation (Eq. (6)) on clothing thermal response in low level radiation, the thermal insulation of clothing is obtained from the results in normal environments [29] (Option 1) and predicted by Eq. (6) under low level radiation (Option 2), respectively. The surface temperature is set as 100, 200 and 300 °C, to consider the effects of low level radiation on the clothing thermal response. Fig. 8 shows the calculated results of the outer and inner surface temperatures of clothing. It can be seen that both two surface temperatures increase with the temperature of the heat source. The outer surface temperature reaches at a quasi-stable condition for 5 min after the thermal exposure, which is similar with the results of Fig. 3. However, the inner surface temperature needs more time to reach a quasi-stable condition, for the inner layer contacts with the skin. The thermal regulation such as perspiration, vasodilatation and blood circulation, etc. slows down temperature increase of the human body and the inner layer.

From Fig. 8(b), the inner surface temperature is bigger when using Option 2. The thermal insulation measured in normal environments (Option 1) is about 8–15 times of that under the thermal radiation (Option 2) [17]. With less value of thermal insulation measured in low radiation, the inner surface temperature of the clothing is bigger under the thermal radiation. However, the outer surface temperature (Fig. 8(a)) is smaller using Option 2, which can be attributed to the sweating from the human body and the water absorption by the clothing.

The UCB model [27] and the clothing model [28] can predict the sweating rate of the human body and the mass of absorption water by the clothing, respectively. Fig. 9 shows the calculated results of those two rates at the same conditions of Fig. 8. It can be seen that these two rates are increasing with the temperature of the heat source. The maximum sweating rate of the human body is 35 g/m^2 [30]. When the temperature of the heat source arrives at 300 °C in this case study, the human physiological function will be disordered by severely dehydration as a result of water loss.



(a) Outer layer temperature



(b) Inner layer temperature

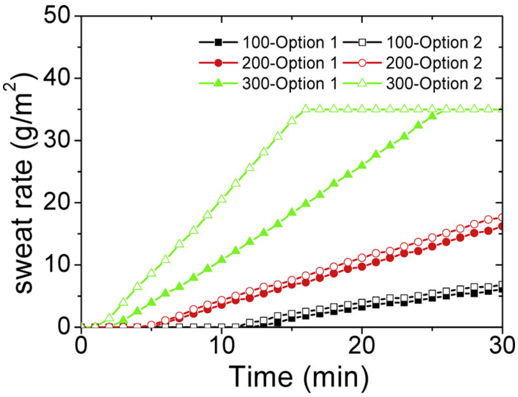
Fig. 8. Simulated results of the outer and inner surface temperatures of the clothing, when human body is exposed to a hot surface wall with different temperatures (unit: °C). (The thermal insulation of clothing is obtained from the results in normal environments [29] (Option 1), and predicted by Eq. (6) under low level radiation (Option 2), respectively.)

It can be seen from Fig. 9 that both two rates are bigger using Option 2. The water absorbed within the clothing can absorb heat from the hot environment. With a bigger water absorption rate using Option 2, the water within clothing can absorb more heat from the hot environment, thus a lower outer surface temperature appears as Fig. 8(a) shows. When the temperature of the heat source arrives at 300 °C, the time of human body to arrive at the limit of sweating rate is 16 min using Option 2 (Fig. 9(b)). The corresponding time is 26 min using Option 1. It indicates that using the thermal insulation measured in normal environment underestimate the time to reach the heat tolerance of the human body.

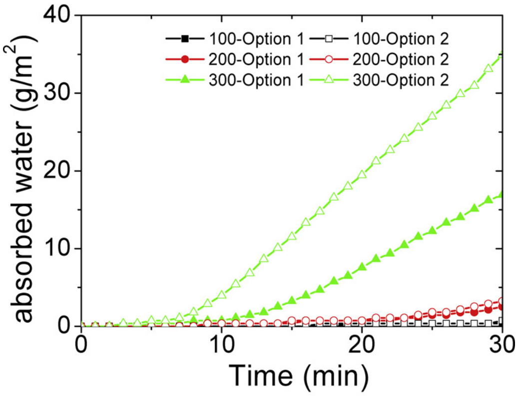
From the discussed above, this case study shows that the thermal radiation has impacts on the clothing thermal response, as the experimental results of Figs. 3 and 4. It also indicates that the obtained results from the predicted equation of thermal insulation affect the clothing thermal response and human thermal physiological response when the human body is subjected to external radiation.

3.4. Limitations and suggestions

For the wet test, condensed water can be seen on the sample holder during the measurement, which is not in contact with the clothing sample (seen in Fig. 1(b)). The experimental results of Keiser and Rossi [16] also showed that the moisture moved to the cap under and without contacting the inner layer. It may indicate a risk for steam burns under low level radiation during a fire duty, due to the moisture re-evaporation and condensation on the skin



(a) sweating rate of human body



(b) mass of absorbed water by clothing

Fig. 9. Simulated results of the sweating rate of human body, and mass of water absorbed by clothing, when human body is exposed to a hot surface wall with different temperatures (unit: °C). (Options 1 and 2 are same as those in Fig. 8.)

surface. The process of moisture movement toward the skin during radiation exposure should be noticed, although the moisture improves the thermal protection of clothing as Fig. 7 shows.

The thermal performance of clothing is also affected by the size and position of entrapped air gaps [31]. Wang et al. [31] found that the added moisture increased the thermal protection of clothing without air gap when exposed to 84 kW/m^2 heat source, which is similar with the results as Fig. 7 shows. However, the added moisture within the thermal liner weakened the positive effect of air gap size and position at high level of radiation [31]. The effect of moisture on thermal insulation depends on the level of thermal radiation [32]. In this study, the low level radiation (1–10 kW/m^2) was used to show the positive effect of moisture in thermal protection (Fig. 7). Therefore, the positive effect of moisture on thermal protection of clothing with air gaps exposed to low level radiation should be validated in future work.

Moisture transport within clothing is also affected by high atmosphere pressure from fire scenarios [33], body movement from fire-rescue operations [33], and external moisture source from a hose spray [15]. We neglected those effects in this study, which should be considered in real fire scenarios or other environment conditions with heat source or radiation.

4. Conclusions

In this paper, the effect of low thermal radiation on the heat transfer of multilayer thermal protective clothing was investigated, using bench scale thermal radiation tests. The outside and inside surface temperatures of each fabric layer were measured. The effects of vapor permeability were studied with two kinds of the moisture barrier (PTFE and GoreTex). The results show that the moisture transfer affects the heat transfer of the multilayer clothing exposed to low level thermal radiation. The protective performance of the inner layers including the thermal linear and the inner layer can be improved with the moisture transfer, while the outer layers especially the moisture barrier will be heated by the external radiation and the released heat by the moisture transfer. It can be also seen that the moisture transfer is affected by the vapor permeability of the moisture barrier.

In addition, the correlation between the temperature of each layer during thermal radiation and the level of heat flux was established by the linear fitting. A predicted equation is developed and validated to calculate the thermal insulation of the multilayer clothing from the low level thermal radiation. It can be seen that the thermal insulation is decreasing with heat flux. The thermal insulation at the wet test is more than that at the dry test under the low level thermal radiation. The predicted equation (Eq. (6)) supports an insight to the thermal insulation calculated from the external heat flux, without measuring the temperature of each layer. The beneficial effects of clothing for the exposure criteria of the low level radiation can be calculated from this predicted equation.

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