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ABSTRACT

Objectives. This study aimed to examine moisture distribution and transfer in firefighter protective clothing when moisture from the atmosphere and skin sweat were considered simultaneously. *Methods*. A self-developed test apparatus was used to simulate moisture transfer through the protective clothing under exposure to thermal radiation. The weights of each layer of fabric before and after heat exposure were measured to analyze the moisture distribution and transfer. *Results*. The moisture level in each layer of fabric before the exposure presented an increase over the initial moisture content. After dry heat exposure, the moisture content in each layer of fabric reduced gradually. However, the existence of hot steam increased the moisture content stored in the fabric system and accelerated the moisture transmitting to the skin surface. In addition, the amount of outward water evaporation for dry heat exposure was moderately more than inward water evaporation, while the amount of inward water evaporation was greatly more than outward water evaporation for wet heat exposure. *Conclusion*. Moisture transfer in the firefighter protective clothing was a two-way transmission during both heat exposures. Understanding moisture transfer helps to provide proper guidance to improve the thermal protection of clothing and reduce steam burns.

1. Introduction

Firefighters, as the first responders to fire disaster, usually come up against various thermal environmental conditions commonly identified as routine, hazardous and emergency [1]. A large number of firefighters suffer from fatal and non-fatal injuries annually in these fire hazards [2]. It is reported that emergency conditions, such as flash fire and high-intensify thermal radiation, are not common during firefighting and rescue work. In contrast, most firefighting assignments are performed at low-level thermal radiation for a long time exposure [3]. Even though the low-intensity radiation is not enough to lead to the degradation of flame-resistant fabric, the majority of skin burn injuries are caused in this environmental condition [4,5].

However, the thermal hazards confronted by firefighters are not just flame burns and heat stress, but also steam burns or scalds driven by moisture [6,7]. During firefighting work, the dousing water from a hose spray and the water from dew or rain can splash onto protective clothing, and be further transferred into the protective clothing [8]. For example, firefighters sometimes need to crawl through a puddle on the ground to carry out the rescue operation, which can moisten the protective clothing. In addition, the human body begins to perspire heavily when the skin temperature is more than 37 °C, and skin sweat has an upward trend with an increase of the skin temperature [9]. The water in the 'atmosphere–clothing–human skin' system can discharge or absorb thermal energy due to evaporation/condensation and absorption/desorption [8], which has an important effect on the thermal protective performance (TPP) of clothing and can result in serious steam burns [10].

In order to protect firefighters from extremely high-temperature and high-humidity conditions, firefighting protective clothing is fundamental equipment for increasing the firefighter's safety. According to Standard No. NFPA 1971:2018 [11], firefighting protective clothing comprises three layers, including an outer shell, a moisture barrier and a thermal liner. It is reported that the role of the outer shell is to resist flame and slow down heat transfer, while the design aims of the moisture barrier hopefully prevent atmospheric water and steam from penetrating through the protective clothing, and accelerate the outward evaporation of skin sweat [12,13]. If the moisture barrier could give full play to these functions as expected, skin steam burns would be minimized. However, recent studies reported that skin burns due to hot steam and hot water account for 60% of total burn injuries during firefighting [14]. This indicates that the protective clothing does not provide enough protection for steam burns or scalds. Thus, the moisture distribution and transfer in protective clothing should be further investigated in fire environments.

In previous studies, most researchers tended to use the standard TPP and radiative protective performance (RPP) test apparatus to characterize the performance of materials used in protective clothing. The whole performance of protective clothing was evaluated by full-scale manikins, such as the flame manikin, radiant manikin and hot water spray manikin [15]. These test apparatuses were used to mainly simulate radiant heat and flash fire, and did not investigate water from the atmosphere or simulate skin sweat. Therefore, some pre-wetting methods were employed to investigate moisture effects on the TPP of clothing [16,17]. Rationed distilled water was applied to the outer shell or the thermal liner, similar to the

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water absorbed by the clothing system from the atmosphere and skin sweat before exposure. In addition, a practical laboratory preconditioning protocol developed by Barker et al. [18] is widely used to reproducibly introduce moisture at levels and distributions that reasonably simulate moisture absorption in multilayer protective clothing exposed to perspiration from a sweating firefighter. The level and distribution of absorbed moisture vary depending on the type of thermal liner and the air permeability of the moisture barrier.

Lower air permeability of the moisture barrier and the thermal liner could provide higher thermal protection when these specimens were pre-wetted before exposure [19]. Keiser et al. [6] found that the evaporation rate in the outer shell was larger than that of the inner fabric, and the moisture distribution in the inner fabric was dependent on the transport and hygroscopic properties of the inner fabric and neighboring fabric. Su et al. [20] analyzed the effects of surface morphology, water repellency, air permeability, water vapor permeability and other characteristics on heat and moisture transfer in the moisture barrier. They found that the thickness, mass and moisture regain of laminated fabric exhibited different levels of positive correlation with the TPP of two configurations. When moisture was added to a fabric system, it both acted as a thermal conductor to present a negative effect and provided a positive effect owing to thermal storage of water and evaporative heat loss [21,22]. The main reasons were that moisture changed thermo-physical properties, such as thermal conductivity and specific heat capacity, as well as optical properties including the radiant absorption coefficient and transmissivity [23–25]. In addition, the moisture level and distribution in the protective clothing had different impacts on the TPP under various heat exposures. The moisture stored in the outer shell increased the TPP in low-intensity and high-intensity thermal radiations [16]. But the moisture within the thermal liner, while providing higher TPP in the low-level thermal radiation, also increased the rate of heat transfer to the skin tissues under the high-intensity thermal radiation [26].

Therefore, the moisture level and distribution play an important role in heat transfer in protective clothing. Although the moisture level and distribution in firefighter protective clothing before exposure have been investigated, there are few studies regarding analysis of the moisture flow direction during exposure, especially when hot steam and skin perspiration are considered simultaneously. Besides, the role of the moisture barrier should be further evaluated under the thermal and wet condition. Thus, the aim of this article was to investigate the level and distribution of moisture in firefighter protective clothing before and after exposure. The pre-wetting method was used to simulate different levels of skin sweat. These pre-wetted fabric systems were exposed to low-intensity radiation with/without hot steam, as a comparative

analysis. The weights of different fabric layers were measured precisely before and after exposure to study the moisture transfer direction and evaluate the role of the moisture barrier. The findings obtained from this study may contribute to improvements in the TPP of clothing by adjusting the content and flow direction of moisture.

2. Materials and methods

2.1. Materials

In this research, an outer shell, a moisture barrier and a thermal liner constitute the three-layer protective clothing, as the experimental specimen. Two kinds of thermal liner were selected in this study. These fabrics were characterized by flame resistance and heat insulation, and are widely used in firefighter protective clothing. All of the fabrics were conditioned and tested in a standard atmosphere with $65 \pm 2\%$ relative humidity (RH) and $20 \pm 2\,°C$ temperature. In accordance with Standard No. ASTM D1777:1996 [27], the thickness of test specimens was measured under a pressure of 1 kPa. The mass per unit area (g/m^2) was calculated as the mean of five specimens, following Standard No. ASTM D3776:1990 [28]. The moisture regain of fabric was measured using an oven-drying method. The air permeability was tested using a YG461E (Ningbo Textile Instrument Factory, China) fabric air permeability tester. The thermal resistance and evaporative resistance were measured by a sweating guarded hotplate tester according to Standard No. ASTM F1868:2017 [29]. The test results for the different layer fabrics are presented in Table 1.
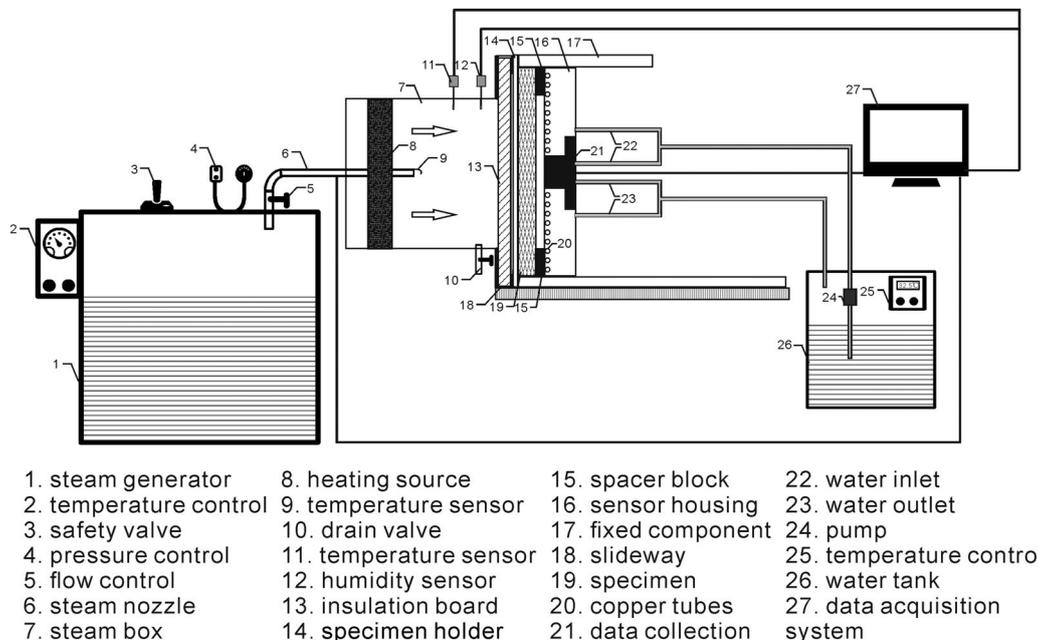
2.2. Test method

The bench-top tester in this research was used to evaluate the TPP in hot steam and thermal radiation, as shown in Figure 1 [30]. The test device is composed of a steam generator, a delivery spout, a steam box, a specimen fixed component and a data acquisition system. Steam from the steam generator is introduced from the delivery spout with an internal diameter of 11.5 ± 0.3 mm oriented toward the center of the measuring specimen. The steam flow rate is controlled by regulating the flow control valve. The steam pressure and flow in this study were, respectively, 0.05 MPa and 0.56 g/s. The impact pressure of the steam mainly depends on the flow rate of the steam, the diameter of the spout and the distance from the specimen under evaluation. The k-type thermocouple (HSTC-TT-K-24S; OMEGA, USA) is fixed near the steam nozzle to monitor the steam temperature. A black ceramic thermal flux source was used to produce the nominal radiant heat flux ($8.5\ kW/m^2$) according to Standard No. ASTM F2731:2011 [31].

Table 1. Basic physical properties of different layers of fabrics.

Layer	Component	Fabric structure	Thickness (mm)	Mass (g/m²)	Moisture regain (%)	Air permeability (cm³/s/cm²)	Thermal resistance (°C·m²/W)	Evaporative resistance (Pa·m²/W)
OS	100% Nomex	Twill	0.60	202.46	4.58	7.79	0.020	4.189
MB	80% Nomex/20% Kevlar (PTFE)	Water thorn felt with PTFE	0.90	106.38	2.80	0.61	0.032	4.318
TL1	100% Nomex + 50% Nomex/50%	Needle-punched	1.19	198.80	5.97	62.76	0.106	9.266
TL2	flame-resistant viscose	non-woven + plain	2.20	271.76	6.96	42.56	0.112	9.801

Note: MB = moisture barrier; OS = outer shell; PTFE = polytetrafluoroethylene; TL = thermal liner.

1. steam generator
2. temperature control
3. safety valve
4. pressure control
5. flow control
6. steam nozzle
7. steam box
8. heating source
9. temperature sensor
10. drain valve
11. temperature sensor
12. humidity sensor
13. insulation board
14. specimen holder
15. spacer block
16. sensor housing
17. fixed component
18. slideway
19. specimen
20. copper tubes
21. data collection
22. water inlet
23. water outlet
24. pump
25. temperature control
26. water tank
27. data acquisition system

Figure 1. Schematic of the thermal protective performance tester under hot steam and thermal radiation.

Table 2. Moisture content of the fabric system after pre-wetting.

Moisture addition (g) (moisture percentage)	Fabric code	Preset moisture content (g) (SD)		Moisture content after 12 h (g) (SD)	
		Dry condition	Wet condition	Dry condition	Wet condition
0	N1	0.52 (0.004)	0.52 (0.006)	0.52 (0.004)	0.52 (0.006)
	N2	0.70 (0.008)	0.71 (0.017)	0.70 (0.008)	0.71 (0.017)
2.5 (15%)	N1	2.57 (0.015)	2.54 (0.009)	2.39 (0.054)	2.33 (0.028)
	N2	2.51 (0.051)	2.53 (0.051)	2.23 (0.099)	2.23 (0.060)
8 (50%)	N1	7.98 (0.030)	7.99 (0.046)	7.63 (0.015)	7.75 (0.073)
	N2	8.01 (0.049)	8.04 (0.026)	7.60 (0.057)	7.71 (0.021)
16 (100%)	N1	16.01 (0.028)	15.95 (0.016)	15.05 (0.054)	15.42 (0.008)
	N2	16.02 (0.018)	16.01 (0.041)	15.67 (0.044)	15.76 (0.071)

Note: Fabric system N1 comprises fabric OS, fabric MB and fabric TL1; fabric system N2 comprises fabric OS, fabric MB and fabric TL2. MB = moisture barrier; OS = outer shell; TL = thermal liner.

In order to study the moisture level and distribution within multilayer protective clothing after heat exposure, four kinds of moisture levels were selected to simulate perspiration of different levels when firefighters are suppressing a fire (see Table 2). The first level was treated as the dry condition, as a comparison group. A 15% moisture content accounting for the weight of protective clothing was used to simulate body perspiration when firefighters work in a warm environment [18]. In terms of a specimen 152 mm×152 mm in size, 2.5 g water added into the thermal liner was equal to 15% by weight of specimen, as the second level. The third level was approximately 50% by protective clothing weight (8 g water), which was equal to a firefighter sweating at a rate of 1.5 L/h. The added water of the fourth level was around 16 g and corresponds to the maximum rate of skin sweat (3 L/h), which was near to the saturation condition (100%).

Based on the simulation methods of body sweats from Barker et al. [18] and Lu et al. [32], the pre-wetting procedure of skin sweat is shown in Figure 2. According to the specifications of the tester, the fabric specimens of size 152 mm×152 mm were conditioned in a standard atmosphere with 65 ± 2% RH and 20 ± 2 °C temperature. After 24 h, the weight of each layer fabric was measured (m_i). Secondly, the standard conditioned thermal liner was immersed in distilled water for at least 5 min

and then taken out. The fabric specimens were squeezed to remove the excess liquid water. Commercial blotting paper was used to repeatedly absorb the free water on the fabric surface to obtain a moisture content of 2.5, 8 and 16 g. According to the overlying order from above of the thermal liner, the moisture barrier and the outer shell, the fabric system was sealed in the plastic bag and then placed in the standard atmosphere for at least 12 h. The weights of the different layer fabrics (n_i) were measured again, which was used to calculate the actual moisture content (see Table 2). The pre-wetted fabric systems continued to be placed in the sealed bags for the experimental preparation. The fabric systems were respectively exposed to dry heat (thermal radiation) and wet heat (thermal radiation and hot steam) conditions for 300 s. A water-cooled Schmidt-Boelter thermopile type sensor (Medtherm Corporation, USA) was used to record the heat flux rise at the rear of the specimen over time. After the exposure, the specimens were also sealed in the plastic bags for 1 h of cooling, and the following moisture content in the different layer fabrics was measured (o_i).

In order to measure the water evaporation to the skin surface (*P*), the blotting paper was placed between the upper mounting plate and the heat flux sensor to absorb the water vapor penetrating through the fabric system (see Figure 3). On
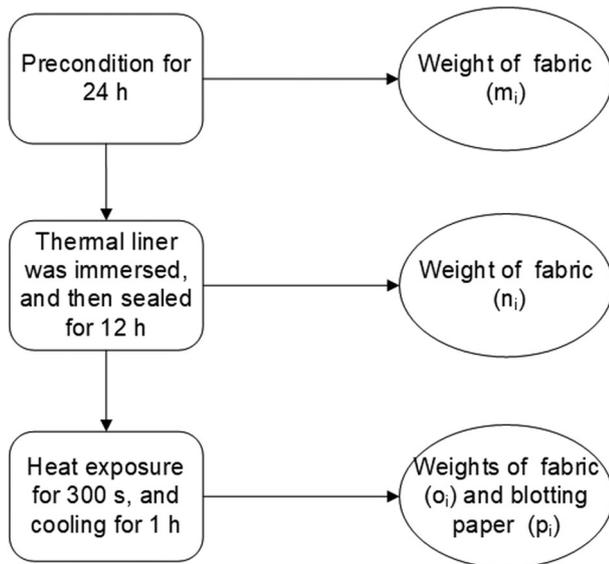
Figure 2. Method for simulating skin perspiration.

the basis of the tested moisture content in different phases, we can calculate the water distribution before ($n_i - m_i$) and after ($o_i - m_i$) the exposure, the moisture evaporation or absorption for each layer ($n_i - o_i$) and the water condensed on the skin surface (ΔP) during the exposure, which was defined as the inward evaporation. The outward evaporation was defined as the water vapor absorbed by the fabric system from the external environment during the wet heat exposure, which was equal to ($\sum_1^3 (n_i - o_i) - \Delta P$).

2.3. Data analysis

The analysis of variance (ANOVA) test for the test results was carried out using SPSS version 20.0 to analyze the difference of moisture content in different experimental conditions and fabric specimens. A paired *t* test was used to analyze the correlation between moisture content and moisture transfer. A *p* value of less than 0.05 was considered statistically significant.

3. Results and discussion

3.1. Moisture level and distribution in dry heat exposure

Moisture transfer in the multilayer fabric system is affected by skin sweat and hot steam from the external environment. The moisture within the fabric system was transferred to the skin surface through the air gap between the fabric system and the skin-simulant sensor (see Figure 1), or was evaporated into the atmosphere. Therefore, the moisture contents in the 'fire environment–fabric–skin tissue' system were changing values during the exposure. The flow direction and the amount of evaporation during the exposure were critical to further investigate the impacts of moisture on skin steam burns and thermal-moisture comfort, which contributed to improvement of the thermal-moisture protective performance by adjusting the flow direction of water.

Figure 4 shows the variation of moisture content in the different fabric layers before and after dry heat exposure. When the fabric system was exposed to the thermal radiation, the water in the fabric system was evaporated due to the temperature rise of the fabric system. The moisture content in all fabric systems after exposure showed a reduction. A significant positive correlation between the amount of water reduction and the initial moisture addition was observed ($p < 0.05$). Before the exposure, a lot of water was stored in the thermal liner. This was because the skin sweat was firstly absorbed by the thermal liner that neighbors the skin surface. Besides, the thermal liner containing 50% flame-resistant viscose has a good wetting property. The moisture content stored in the outer shell was marginally greater than in the moisture barrier as the moisture regain of the outer shell is superior to that of the moisture barrier (see Table 1). In addition, there was an increase in the amount of water in each layer of fabric when the initial moisture content increased. The total moisture content of the N2 fabric system was more than that of the N1 fabric system ($p > 0.05$). The reason for this might be that the thicker N2 fabric system absorbed more water to reduce water evaporation or drippage. After the exposure, the final water content in the outer shell was almost equal to 0 g as the evaporation rate of the outer shell was larger than that of the other layers [16,33]. The moisture content in the thermal liner was still the highest level. The reasons for this were not only its excellent hygroscopicity, but also the impeding role of the moisture barrier to moisture transfer.

The data presented in Table 3 indicate that the time to second-degree burn showed a decrease, firstly, and then an increase over the moisture content. Besides, the least time to second-degree burn was when the moisture addition to the fabric system was 8 g. The changing tendency of the burn time had good consistency with the results from Barker et al. [18] under a radiative heat exposure of 6.3 kW/m². The addition of moisture in the fabric system decreased the TPP.

On the basis of the moisture level before and after exposure, the amount of moisture change in different fabric layers was calculated, as presented in Table 4. With the increment
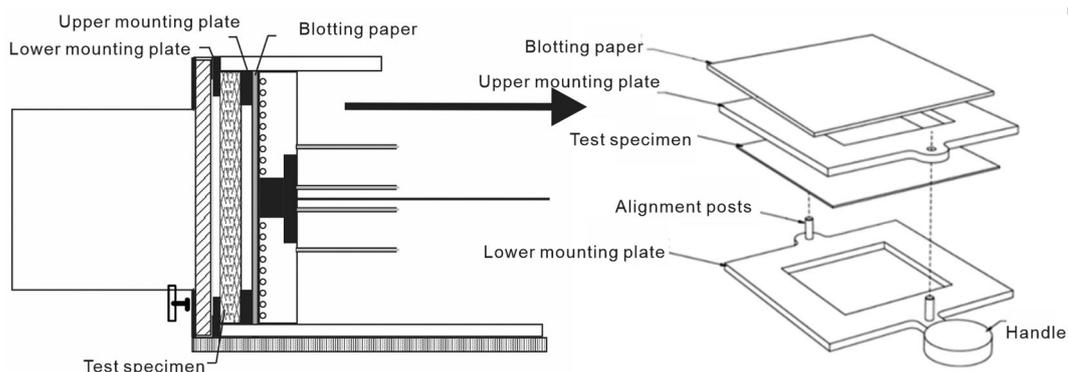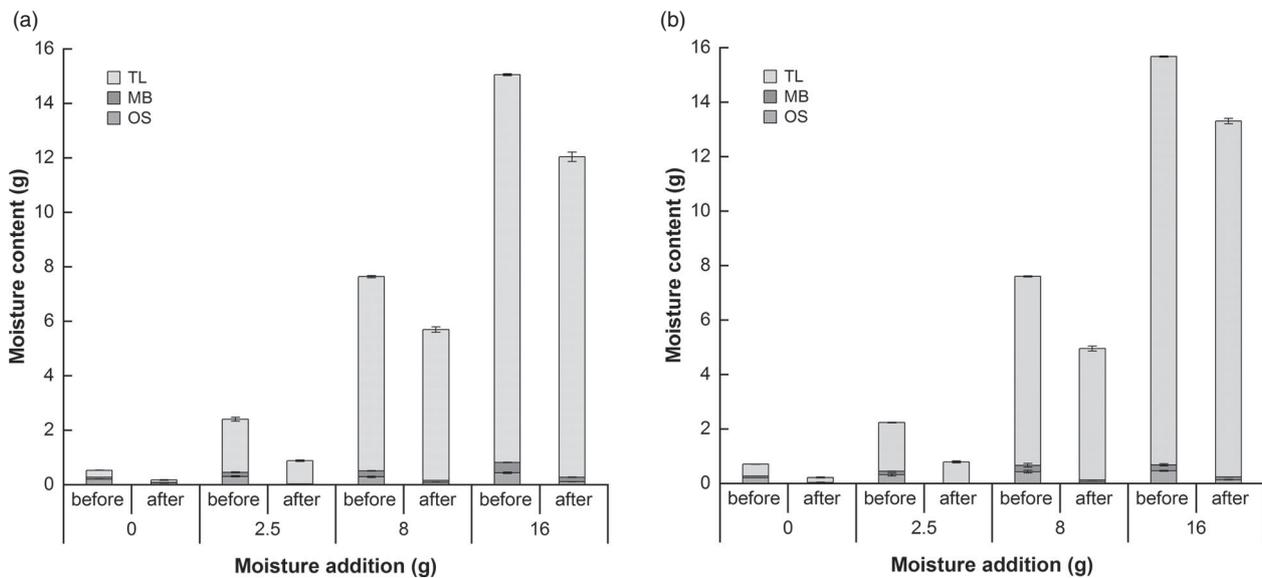

Figure 3. Test method of water evaporating to the skin surface.

Figure 4. Moisture content in each layer of fabric before and after dry heat exposure: (a) N1 fabric system; (b) N2 fabric system.
Note: MB = moisture barrier; OS = outer shell; TL = thermal liner.

Table 3. Change in time to second-degree skin burn for both heat exposures.

Fabric system	Moisture addition (g)	Time to second-degree burn (s)	
		Dry heat exposure	Wet heat exposure
N1	0	137.5	45.0
	2.5	115.8	45.1
	8	112.8	50.2
	16	131.8	62.1
N2	0	175.7	44.8
	2.5	162.4	46.1
	8	122.2	55.1
	16	140.4	69.1

Table 4. Amount of moisture change in each layer of fabric.

| Fabric system	Moisture addition (g)	Moisture change (g) (SD)		
		OS	MB	TL
N1	0	0.139 (0.0046)	0.052 (0.0030)	0.165 (0.0072)
	2.5	0.295 (0.0212)	0.132 (0.0177)	1.091 (0.0961)
	8	0.201 (0.0209)	0.153 (0.0082)	1.587 (0.0859)
	16	0.327 (0.0246)	0.217 (0.0094)	2.464 (0.1897)
N2	0	0.170 (0.0041)	0.072 (0.0026)	0.247 (0.0121)
	2.5	0.349 (0.0190)	0.128 (0.0111)	1.003 (0.1441)
	8	0.365 (0.0638)	0.176 (0.0180)	2.106 (0.0762)
	16	0.332 (0.0331)	0.117 (0.0178)	1.919 (0.0879)

Note: MB = moisture barrier; OS = outer shell; TL = thermal liner.

of moisture content applied in the fabric system, the moisture content in different fabric layers presented an overall increase, except for the N2 fabric system with 16 g. This was because the N2 fabric system did not reach a saturated state. The correlation coefficient between the total moisture change and the moisture change of the thermal liner was 0.998 ($p < 0.05$). Therefore, the variation of the total amount of moisture change in the fabric system was mainly determined by the thermal liner due to the greater hygroscopic property.

The percentages of moisture content in different fabric layers were compared before and after the exposure, as presented in Figure 5. It was found that the moisture content ratios in the outer shell and the thermal liner were significantly more than that of the moisture barrier when no water was applied to the fabric system. With the increase of the initial added water, there was a decreasing trend in the moisture content ratio of the outer shell and the moisture barrier. Even though the fabric system with the moisture addition was placed 12 h before exposure, a large portion of water was stored in the thermal liner due to the low air permeability of the moisture barrier (see Table 1). When the added water increased from 0 to 16 g, the moisture content ratio of the thermal liner for the two fabric systems ranged from 49.01 to 95.67%. It was reported that more than 75% of moisture was located in the innermost three layers under a standard environment with 65% RH and 20 °C temperature [6]. However, 50–80% of perspiration was stored in the innermost two layers under 30% RH and 30 °C temperature [7]. After the end of radiant heat exposure, the percentage of moisture content in the thermal liner increased from 54.74 to 98.27%, and increased with the initial water content. The moisture in the outmost two layers could be easily evaporated as the temperatures of the outmost two layers were larger than that of the thermal liner during the exposure. The reduction of moisture content in the outmost two layers indicated that the moisture barrier obviously slowed down the moisture transfer from the thermal liner to the outer shell. In addition, when 0 or 2.5 g water was added to the N2 fabric system before exposure, the moisture content ratios of the outer shell and the moisture barrier were both less than zero. But this phenomenon was not found in the N1 fabric system. Compared with the N1 fabric system, the thermal liner in the N2 fabric system has larger thickness and mass so that the thermal liner (TL2) decreased the heat transmitting to the skin. More thermal energy was stored in the outmost two layers of the N2 fabric system, which increased the temperature and the water evaporation of the outmost two layers. The variation tendency was similar to the fact that the increase of the air gap thickness improved the TPP, and increased the temperature of the fabric's backside [34]. Therefore, the water evaporation in the outmost two layers of the N2 fabric system was more than that of the N1 fabric system.

The reason why the moisture content ratio in the moisture barrier of the N2 fabric system with 0 g water showed a negative value was that the thermal degradation reaction

(a)

(b)
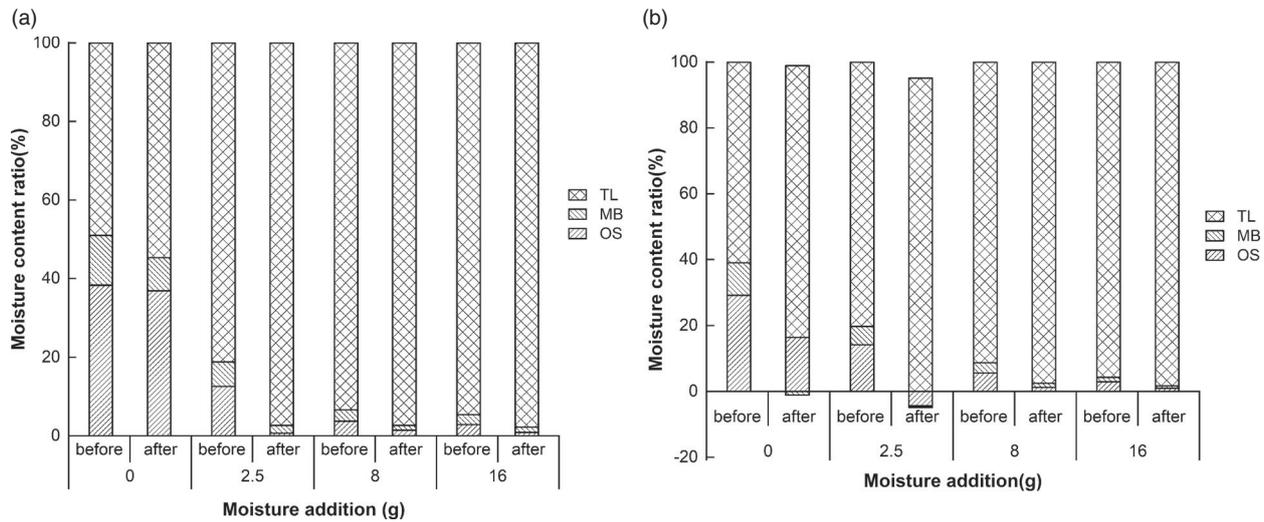
Figure 5. Moisture content ratio in each layer of fabric before and after dry heat exposure: (a) N1 fabric system; (b) N2 fabric system.
Note: MB = moisture barrier; OS = outer shell; TL = thermal liner.
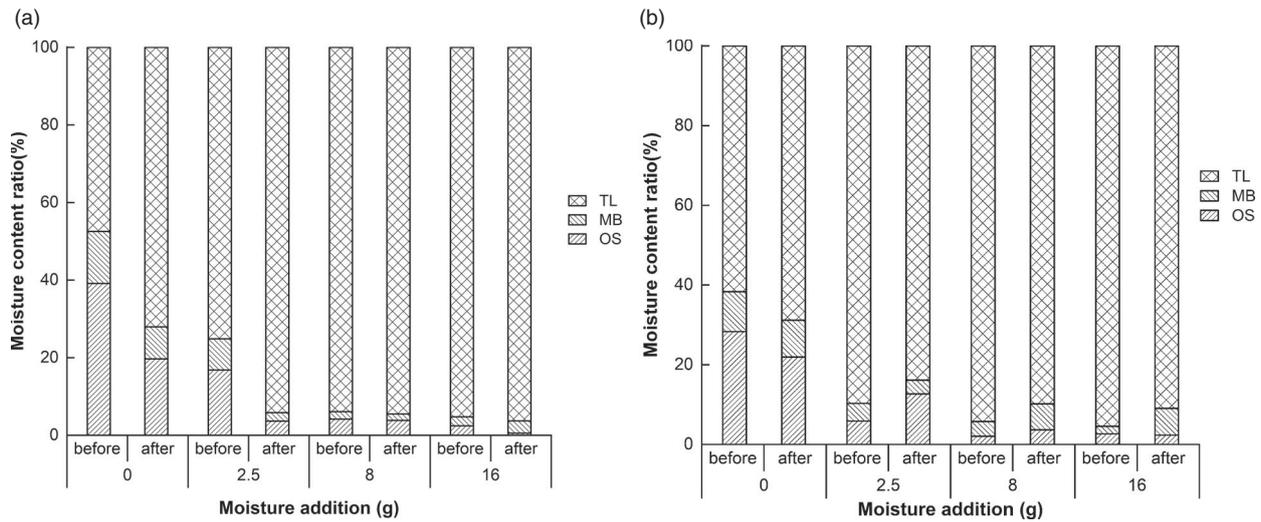
(a)

(b)
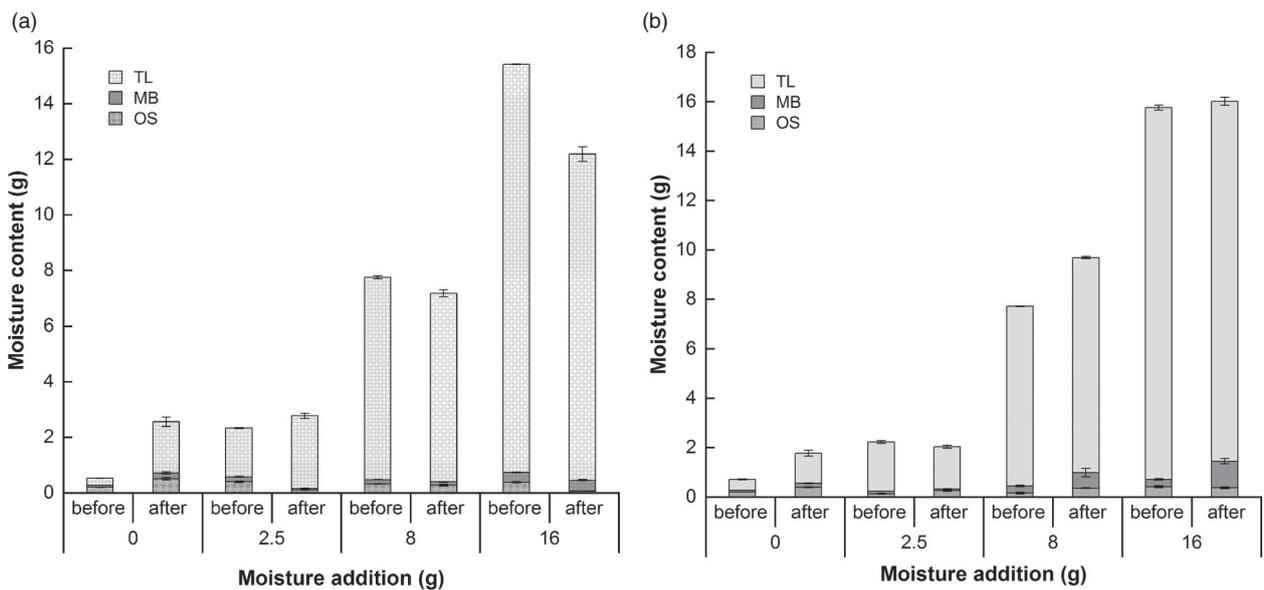
Figure 6. Moisture content in each layer of fabric before and after wet heat exposure: (a) N1 fabric system; (b) N2 fabric system.
Note: MB = moisture barrier; OS = outer shell; TL = thermal liner.

could happen in the moisture barrier. Even though the temperature in the fabric system was less than 450 °C in the radiant heat exposure of 8.5 kW/m² that was not enough to cause the decomposition reaction of Nomex and Kevlar fiber [35], the moisture barrier including the polytetrafluoroethylene (PTFE) film could be degraded partially under the radiant heat exposure. Besides, it was found that the heat exposure area of the PTFE film changed from white to claybank in color after the exposure, indicating the existence of thermal degradation. The fabric's thermal reaction due to the volatile products reduced the mass of the fabric [34]. When the N2 fabric system was initially treated with 2.5 g water, the final moisture content ratio in the outer shell and the moisture barrier was also less than zero. But this did not result only from the fabric's thermal degradation. This was also because the moisture in the N2 fabric system was mostly evaporated, including the 2.5 g of added water and the absorbed water during the 24-h precondition in a standard environment.

3.2. Moisture level and distribution in wet heat exposure

When the fabric system was exposed to wet heat (thermal radiation and hot steam), the skin sweat and hot steam totally determined the moisture transfer in the multilayer fabric system. Figure 6 shows the variation of moisture content in different fabric layers before and after wet heat exposure. The moisture level and distribution in each layer before the wet heat exposure agreed well with the dry heat exposure. After exposure, a significant difference between the two tested conditions was observed ($p < 0.05$). The moisture content with the fabric system in the dry heat exposure gradually reduced, which was dependent on the thermal radiation and the initial water content. But the presence of hot steam increased the moisture content in different fabric layers, especially for the N2 fabric system. The increased moisture contents of the thermal liner for the N1 fabric systems with 0 and 2.5 g water were, respectively, 0.1 and 0.5 g. This was because the thermal liner did not reach a saturated state before exposure (the moisture regain for the thermal liner at a saturated state is around 16 g). It was indicated that the moisture barrier did not completely prevent the penetration of hot steam. As the initial moisture addition for the N1 fabric system further increased, there was a decreasing tendency in the moisture content. When the initial moisture addition increased to 16 g, the moisture content located in the thermal liner showed the most obvious reduction. The thermal liner with 16 g water reached

Figure 7. Moisture content ratio in each layer of fabric before and after wet heat exposure: (a) N1 fabric system; (b) N2 fabric system.
Note: MB = moisture barrier; OS = outer shell; TL = thermal liner.
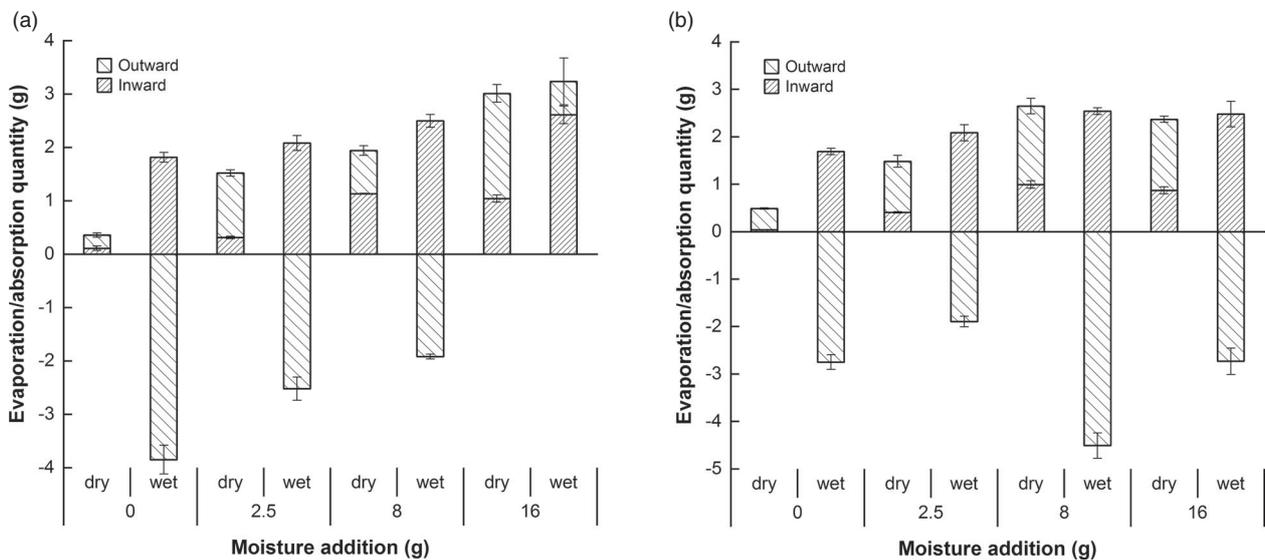
Figure 8. Relationship between outward and inward evaporation of moisture: (a) N1 fabric system; (b) N2 fabric system.

saturation so that the absorbed water could easily evaporate or drip off during exposure.

The data presented in Table 3 show that the time to second-degree burn under the wet heat exposure increased with the initial moisture content. The correlation coefficients for the N1 and N2 fabric systems were 0.977 and 0.994, respectively. This indicated that the increase of the initial moisture content improved the steam protective performance of the fabric system.

In the wet heat exposure, the moisture content ratio in each layer of fabric accounting for the total moisture content within the fabric system is presented in Figure 7. The moisture content ratio of the thermal liner witnessed an increase before and after exposure with the initial moisture content. Before exposure, the moisture content ratio in the thermal liner for the two tested N1 and N2 fabric systems ranged from 47.47 to 95.25% and from 61.67 to 95.47%, respectively. After exposure, there was an increase in the moisture content ratio for the thermal liner for the N1 fabric system. However, a decreasing trend in the moisture content ratio for the thermal liner of the N2 fabric system was observed, except for the N2 fabric system without added water. According to Figure 6, the thermal liners with 0 and 2.5 g water for the N1 fabric system still absorbed moisture during wet heat exposure. When the initial moisture

content increased to 8 and 16 g, the moisture content ratio for the thermal liner increased due to the water evaporation in the fabric system after exposure. The opposite variation in the N2 fabric system was attributed to the fact that the outer shell and the moisture barrier absorbed the atmospheric water. As Keiser et al. [6,26] reported, the moisture level and distribution in the multilayer fabric system mainly depended on the heat exposure condition, the skin sweating rate and the fabric's properties, while the moisture in the single-layer fabric was also affected by the hygroscopic properties of the neighboring layer. In other words, the thermal liner with good moisture absorption increased the water absorption of the outer shell and the moisture barrier.

3.3. Moisture transfer in the 'external environment–fabric–skin surface' system

On the basis of the aforementioned analysis, the fabric system presented a process of water evaporation or absorption during heat exposure with/without hot steam, which resulted in a variation of the total moisture content in the fabric system. The water evaporation was transmitted not only to the external environment but also to the skin surface, which could be respectively defined as outward and inward evaporation.
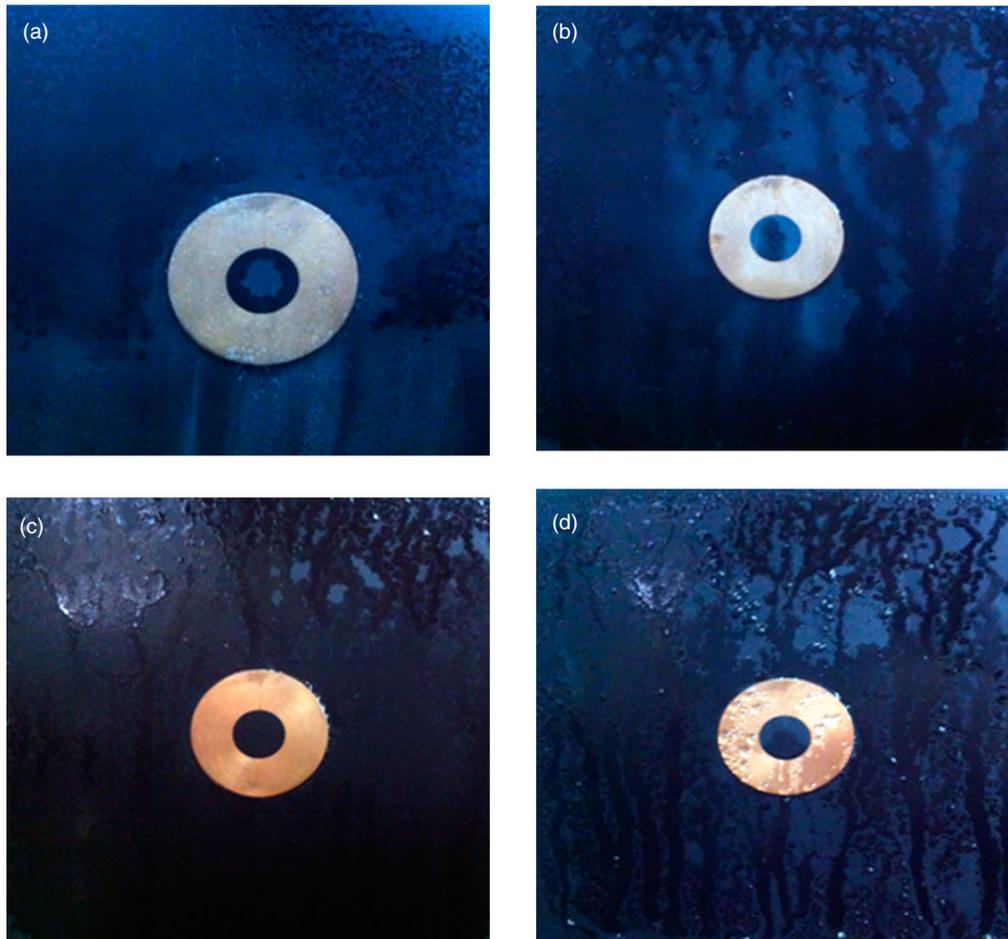
Figure 9. Moisture level on the surface of sensor for the N1 fabric system: (a) 0 g water; (b) 2.5 g water; (c) 8 g water; (d) 16 g water.

Furthermore, the fabric system absorbed the water vapor from the external environment during the wet heat exposure, which increased the mass of the fabric system. Thus, when the outward evaporation was less than zero, the fabric system absorbed the hot steam. Figure 8(a) and (b), respectively, show the relationship of outward and inward evaporation to the initial moisture content for the N1 and N2 fabric systems.

In the dry heat exposure, the moisture loss of the N1 fabric system after exposure increased over the initial moisture content. But the moisture loss of the N2 fabric system with 16 g water was less than that of the N2 fabric system with 8 g water. This was because the N2 fabric system after absorbing 16 g water did not reach saturation due to the good hygroscopicity of the thermal liner. Thus, the moisture stored in the N2 fabric system did not easily drip off compared with the N1 fabric system.

As shown in Figure 8, the outward water evaporation was marginally larger than the inward water evaporation. This indicates that the moisture in the fabric system was bidirectionally transferred during dry heat exposure. As the skin sweat was absorbed by the fabric system before the dry heat exposure, the moisture content in the fabric system was far higher than that in the external environment and the air gap. The temperature difference between the external environment and the air gap resulted in different evaporation rates for the inward and outward directions. With the increment of the initial moisture content, the inward evaporation of moisture in the fabric system presented an increase, firstly, followed by a decrease. The largest evaporation amounts for the N1 and N2 fabric systems with the 8 g initial moisture addition were equal to 1.13

and 0.99 g, respectively. The change tendency was also proved with the moisture level and distribution on the tested sensor after exposure, as shown in Figure 9. This was due to the existence of condensate water on the surface of the sensor, indicating the occurrence of skin steam burns. This was because the hot steam stored a large amount of thermal energy that was discharged quickly on the skin surface, and caused the steam burns [36,37]. Besides, the correlation coefficients between the inward evaporation and the time to skin burn were −0.371 and −0.974 for the N1 and N2 fabric systems, respectively. This indicated that the water evaporation to the skin increased the heat transfer and decreased the time to skin burn.

In addition, Figure 8 shows the outward and inward moisture evaporation during the wet heat exposure. Except for the N1 fabric system with 16 g water desorbing water owing to its saturation state, the other fabric systems absorbed hot steam from the external environment. Theoretically, the N1 fabric system with 0 g moisture addition absorbed more steam. However, the N2 fabric system with 8 g water absorbed the maximum steam during the exposure. It was indicated that the amount of absorbing water vapor was determined by the water storing capacity and the condensation rate, which depended not only on the hygroscopic properties, but also on the temperature in the fabric system. The amount of inward evaporation under the wet heat exposure was apparently larger than that under the dry heat exposure. Combining the variation of total moisture content in the fabric system, it was found that the initial moisture addition and the atmospheric water vapor totally determined the moisture content transferring to the skin surface. Therefore, the moisture stored

in the fabric system mainly flowed to the skin surface in the wet heat exposure, meaning that the typical protective clothing did not effectively protect workers from the thermal radiation and the hot steam condition. Steam burns in the wet heat exposure were more likely to occur compared to the dry heat exposure. Furthermore, the inward water evaporation of the fabric system increased with the initial moisture content, and then tended to a stable state. The difference of water evaporation between various initial moisture contents in the wet heat exposure was less compared to the dry heat exposure. It was speculated that the hot steam had an important effect on the moisture transfer from the multilayer fabric system to the skin surface and reduced the difference of water evaporation to the skin surface.

4. Conclusions

In this research, heat and moisture transfer in firefighter protective clothing under thermal radiation and hot steam was investigated to analyze the flow direction of water in the firefighter protective clothing and the protective role of the moisture barrier. It was found that the moisture levels in each layer of fabric before the exposure presented an increase over the initial moisture content. The moisture content was, in order from most to least, the thermal liner, the outer shell and the moisture barrier. After the dry heat exposure, the moisture content in each layer of fabric reduced gradually, which mostly depended on the sweat levels and the heat exposure condition. The moisture barrier did not completely prevent hot steam penetrating through the multilayer fabric system. In addition, the amount of outward water evaporation was moderately more than that of inward water evaporation. With the increase of the initial moisture content in the fabric system, the total water evaporation showed an increase while the inward water evaporation increased and then reduced. For the wet heat exposure, the amount of inward water evaporation was greater compared to the dry heat exposure. It was indicated that the dominant flow direction of water during the wet heat exposure was from the external environment to the skin surface. The findings in this study contribute to the development of new protective clothing for improving the TPP by adjusting the moisture transfer, and minimizing skin steam burns.

The study focused on the bench-top test of protective fabric, which had a certain difference with a full-scale manikin test of protective clothing. Further studies should be conducted to simulate skin sweat using the sweating thermal manikin, and to investigate the effect of moisture transfer on the TPP by connecting to the human body. In addition, the moisture transfer model in the protective clothing should be developed to further analyze the mechanism of moisture transfer in protective clothing.

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References

[1] Abbott NJ, Schulman S. Protection from fire: nonflammable clothing – a review. Fire Technol. 1976;12(3):204–218. doi:10.1007/BF02624796

[2] Karter MJ. Patterns of firefighter fireground injuries. Quincy (MA): National Fire Protection Association; 2009.

[3] Prasad K, Twilley WH, Lawson JR. Thermal performance of fire fighters' protective clothing: numerical study of transient heat and water vapor transfer. Gaithersburg (MD): US Department of Commerce, Technology Administration, National Institute of Standards and Technology (NIST); 2002. (NISTIR; 6881).

[4] Song G, Wei C, Gholamreza F. Analyzing stored thermal energy and thermal protective performance of clothing. Tex Res J. 2011;81(11):1124–1138. doi:10.1177/0040517511398943

[5] Song G, Paskaluk S, Sati R, et al. Thermal protective performance of protective clothing used for low radiant heat protection. Tex Res J. 2011;81(3):311–323. doi:10.1177/0040517510380108

[6] Keiser C, Becker C, Rossi RM. Moisture transport and absorption in multilayer protective clothing fabrics. Tex Res J. 2008;78(7):604–613. doi:10.1177/0040517507081309

[7] Mäkinen H, Smolander J, Vuorinen H. Simulation of the effect of moisture content in underwear and on the skin surface on steam burns of fire fighters. In: Mansdorf SZ, Sager R, Neilsen AP, editors. Performance of protective clothing, second symposium. Philadelphia, PA: American Society for Testing and Materials (ASTM); 1988. Standard No. ASTM STP 989. p. 415–421.

[8] Chitrphiromsri P, Kuznetsov AV. Modeling heat and moisture transport in firefighter protective clothing during flash fire exposure. Heat Mass Transf. 2005;41(3):206–215.

[9] Pan N. Sweat management for military applications. Manchester (UK): The Textile Institute and Woodhead Publishing; 2008, p. 137.

[10] Nazaré S, Madrzykowski D. A review of test methods for determining protective capabilities of fire fighter protective clothing from steam. Gaithersburg (MD): US Department of Commerce, Technology Administration, National Institute of Standards and Technology (NIST); 2015. (NIST Technical Note; 1861).

[11] National Fire Protection Association. NFPA1971: standard protective ensembles structural fire fighting proximity fire fighting. Quincy (MA): NFPA; 2018.

[12] Zhou L, Meng J. Current situation and development of waterproof and moisture permeable fabric. Prog Text Sci Technol. 2010;1:38–40.

[13] Aldridge D. Firefighter garment with combination facecloth and moisture barrier. Google Patents no. 5640718, United States; 1997.

[14] Kahn SA, Patel JH, Lentz CW, et al. Firefighter burn injuries: predictable patterns influenced by turnout gear. J Burn Care Res. 2012;33(1):152–156. doi:10.1097/BCR.0b013e318234d8d9

[15] Trent LC, Resch WA, Coppari LA, et al. Design and construction of a thermally-instrumented mannequin for measuring the burn injury potential of wearing apparel. Tex Res J. 1979;49(11):639–647. doi:10.1177/004051757904901104

[16] Lawson LK, Crown EM, Ackerman MY, et al. Moisture effects in heat transfer through clothing systems for wildland firefighters. Int J Occup Saf Ergon. 2004;10(3):227–238. doi:10.1080/10803548.2004.11076610

[17] Lee YM, Barker RL. Effect of moisture on the thermal protective performance of heat-resistant fabrics. J Fire Sci. 1986;4(5):315–331. doi:10.1177/073490418600400502

[18] Barker RL, Guerth-Schacher C, Grimes R, et al. Effects of moisture on the thermal protective performance of firefighter protective clothing in low-level radiant heat exposures. Tex Res J. 2006;76(1):27–31. doi:10.1177/0040517506053947

[19] Jensen RLJ. Thermal performance of firefighters' protective clothing. Minneapolis (MN): 3M; 1998. (Paper provided to industry).

[20] Su Y, Li R, Yang J, et al. Influence of transport properties of laminated membrane-fabric on thermal protective performance against steam hazard. Fibers Polym. 2019;20(11):2433–2442. doi:10.1007/s12221-019-1155-3

[21] Su Y, Li J, Song G. The effect of moisture content within multilayer protective clothing on protection from radiation and steam. Int J Occup

Saf Ergon. 2018;24(2):190–199. doi:10.1080/10803548.2017.1321890

[22] He J, Lu Y, Yang J. Quantification of the energy storage caused dual performance of thermal protective clothing containing with moisture exposed to hot steam. Energy Sci Eng. 2019;7(6):2585–2595. doi:10.1002/ese3.446

[23] Fu M, Yuan MQ, Weng WG. Modeling of heat and moisture transfer within firefighter protective clothing with the moisture absorption of thermal radiation. Int J Thermal Sci. 2015;96:201–210. doi:10.1016/j.ijthermalsci.2015.05.008

[24] Su Y, Li R, Song G, et al. Modeling steam heat transfer in thermal protective clothing under hot steam exposure. Int J Heat Mass Transf. 2018;120:818–829. doi:10.1016/j.ijheatmasstransfer.2017.12.074

[25] Su Y, Li J, Zhang X. A coupled model for heat and moisture transport simulation in porous materials exposed to thermal radiation. Transp Porous Media. 2020;131(2):381–397. doi:10.1007/s11242-019-01347-2

[26] Keiser C, Rossi RM. Temperature analysis for the prediction of steam formation and transfer in multilayer thermal protective clothing at low level thermal radiation. Tex Res J. 2008;78(11):1025–1035. doi:10.1177/0040517508090484

[27] American Society for Testing and Materials (ASTM). Standard test method for thickness of textile materials. West Conshohocken (PA): ASTM International; 1996. Standard No. ASTM D1777:1996.

[28] American Society for Testing and Materials (ASTM). Standard test methods for mass per unit area (weight) of fabric. West Conshohocken (PA): ASTM International; 1990. Standard No. ASTM D3776:1990.

[29] American Society for Testing and Materials (ASTM). Standard test method for thermal and evaporative resistance of clothing materials using a sweating hot plate. West Conshohocken (PA): ASTM International; 2017. Standard No. ASTM F1868:2017.

[30] Su Y, Li J. Development of a test device to characterize thermal protective performance of fabrics against hot steam and thermal radiation. Meas Sci Technol. 2016;27(12):125904.

[31] American Society for Testing and Materials (ASTM). Standard test method for measuring the transmitted and stored energy of firefighter protective clothing systems. West Conshohocken (PA): ASTM International; 2011. Standard No. ASTM F2731:2011.

[32] Lu Y, Li J, Li X, et al. The effect of air gaps in moist protective clothing on protection from heat and flame. J Fire Sci. 2013;31(2):99–111. doi:10.1177/0734904112457342

[33] Rossi RM, Zimmerli T. Influence of humidity on the radiant, convective and contact heat transmission through protective clothing materials. In: Johnson JS, Mansdorf SZ, editors. Performance of protective clothing. West Conshohocken, PA: American Society for Testing and Materials (ASTM); 1996. Standard No. ASTM STP 1237. p. 269–280.

[34] Yang L, Chen X, Zhou X, et al. The pyrolysis and ignition of charring materials under an external heat flux. Combust Flame. 2003;133(4):407–413. doi:10.1016/S0010-2180(03)00026-9

[35] Song G. Modeling thermal protection outfits for fire exposures [dissertation]. Raleigh (NC): North Carolina State University; 2002.

[36] Pruitt BA, Erickson DR, Morris A. Progressive pulmonary insufficiency and other pulmonary complications of thermal injury. J Trauma: Inj Infect Crit Care. 1975;15(5):269–379. doi:10.1097/00005373-197505000-00001

[37] Henriques Jr, FC. Studies of thermal injury; the predictability and the significance of thermally induced rate processes leading to irreversible epidermal injury. Arch Pathol. 1947;43(5):489–502.