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A novel steam simulator was employed in this study to evaluate thermal protective performance of protective clothing while exposing to steam hazard. Single- and double-layer fabric systems were selected, and different configurations of moisture barrier were exposed to steam hazard for investigating the effect of configuration of protective fabrics on the thermal protective performance. The skin bio-heat transfer and Henriques burn integral models were used to predict the required times to reach 2nd and 3rd degree skin burn. The results demonstrated that the thermal protective performance of protective clothing under steam exposure was determined by the air permeability, the thickness, the mass, and the surface properties of fabric. Even though the moisture barrier provided excellent protective performance for steam exposure, the configuration of moisture barrier presented a decisive influence on the role of moisture barrier. The findings obtained in this study provide technical data for the performance improvement of protective clothing under steam hazard.

Keywords

Thermal Protective Performance, Steam Exposure, Protective Fabric, Configuration

Disciplines

Fiber, Textile, and Weaving Arts | Industrial and Product Design | Other Chemical Engineering | Thermodynamics

Comments

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Effect of Configuration of Protective Fabrics on Thermal Protective Performance under Steam Exposure ⋆

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Abstract

A novel steam simulator was employed in this study to evaluate thermal protective performance of protective clothing while exposing to steam hazard. Single- and double-layer fabric systems were selected, and different configurations of moisture barrier were exposed to steam hazard for investigating the effect of configuration of protective fabrics on the thermal protective performance. The skin bio-heat transfer and Henriques burn integral models were used to predict the required times to reach 2nd and 3rd degree skin burn. The results demonstrated that the thermal protective performance of protective clothing under steam exposure was determined by the air permeability, the thickness, the mass, and the surface properties of fabric. Even though the moisture barrier provided excellent protective performance for steam exposure, the configuration of moisture barrier presented a decisive influence on the role of moisture barrier. The findings obtained in this study provide technical data for the performance improvement of protective clothing under steam hazard.

Keywords: Thermal Protective Performance; Steam Exposure; Protective Fabric; Configuration

1 Introduction

Industrial steam extensively used in oil and gas sectors presents a potential hazard for workers, such as steam burns and fatalities, since the surrounding ambient air can be heated rapidly in a confined space if steam leaks [1-3]. Thermal protective clothing can provide effective protection by resisting heat transfer under steam hazards. As stipulated in standard NFPA 1971 and EN 469, a typical thermal protective clothing can be a one-layer coverall or composed of three different fabric layers, i.e., an outer shell, a moisture barrier, and a thermal liner. The role of outer shell is to provide flame resistance, protection against heat radiation, resistance to water, and certain

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levels of abrasion. As a middle layer, the moisture barrier is designed to not allow liquid water to penetrate from outside but promote water vapor transport outwardly from the wearer [4, 5]. Therefore, the common thermal protective clothing is generally designed for protection against flash fire and high- or low-intensity radiant heat exposure and behavior of clothing against steam exposure should be further examined [6-9].

There is no international standard for characterizing the steam protective performance of clothing or fabric until now. Some preliminary explorations were carried out to characterize the performance of thermal protective clothing exposed to a pressurized steam condition. For simulating hot steam conditions, some researchers developed the bench scale tests [10-12] as well as the full-scale thermal manikin tests [3, 11] to measure the protective capacities of fabrics and clothing under hot steam conditions. The horizontal bench top tests developed by Liu et al. [10] and Murtaza [12] were used to investigate the performance of protective fabrics under hot steam exposures. Liu et al. selected different steam pressures (50.6 and 152 kPa) to expose the protective fabrics for a fixed period of 20 s while Murtaza evaluated the performance of protective fabrics under steam pressure of 210 kPa at 150 °C for 10 s exposure. The main difference between two kinds of test approaches was the steam flow directions: upward and downward, respectively. Because different steam flow directions could affect the rate of heat and moisture transfer in protective fabric system. However, the horizontal steam flow more conforms to the actual fire ground according to the body standing state. Therefore, a vertical test device under steam exposure was developed by Derscuell and Schimid [11]. The device could change the steam splash distance and steam pressure to simulate different experimental conditions, but the major limitation of Derscuell and Schimid's work was that the heat flux sensors have relatively large error for higher skin temperature. Su and Li [13] developed a vertical test device and investigated the combined effect of steam and radiant heat exposures on protective performance of clothing. Additionally, Sati et al. [3] presented a test device of cylindrical shape to evaluate the effect of body shape on steam protection of clothing in moderately high-pressure steam (69 and 207 kPa). The fabric could be mounted with or without a space to provide an air gap between the cylinder and the fabric that simulated the real wearing state. A thermal manikin in a steam climatic chamber was employed to evaluate the protective performance of protective clothing against steam exposure [11]. The results demonstrated that the steam penetration and the heat transfer in protective clothing depended on fabric's properties, such as resistance to water vapor diffusion, air permeability, thermal insulation and total heat loss, as well as fabric coating/laminate.

Additionally, our previous work evaluated the thermal protective performance of protective clothing under steam exposure [14]. Further study was to analyze the effect of configuration of moisture barrier on the thermal protective performance of protective clothing under a pressurized steam. Therefore, different configurations of moisture barrier for single- and double-layer fabric systems were exposed to steamy condition. The times to cause skin burn and heat transfer in various fabric systems were analyzed in order to provide proper suggestions to improve the thermal protective performance of protection clothing in a steamy condition.

2 Experimental Part

2.1 Materials

Four types of fabrics currently used in thermal protective clothing were selected as samples. Two kinds of composite fabric with different air permeability were used for outer shell. Two kinds of waterproof and breathable fabric were selected for moisture barrier in this study. The basic specifications of testing samples were listed in Table 1. The thickness of test specimens was measured in accordance with standard ASTM D 1777-96. The fabric's air permeability was tested in a pressure drop of 2000 Pa according to ASTM D 737. The air permeability with different configurations of moisture barrier was also measured. The oven can be used to measure moisture regain of all samples in a constant atmosphere (20 °C temperature, 65% relative humidity). Single-layer fabrics can be assembled into double-layer fabric system. Different faces of moisture barrier can be inserted into double layer fabric system, as shown in Table 2. For example, the OS1+MB1-frontside fabric system (D1-F) means that outer shell is exposed to steamy condition and the substrate face of moisture barrier is contacted to skin-simulant sensor, while the membrane face of moisture barrier is directed to skin-simulant sensor for the OS1+MB1-backside fabric system (D1-B).

Table 1: Basic physical properties of single-layer fabric

Fabric code	Fiber content	Fabric structure	Thickness (mm)	Mass (g/m^2)	Air permeability (cm^3/s/cm^2)	Moisture regain
OS1	Nomex/Kevlar/P-140	Twill	0.66	260.07	262.20	2.98%
OS2	Nomex/Kevlar	Plain	0.54	248.03	125.20	1.65%
MB1-F	PTFE+PBI and Kevlar mixture	Twill	0.27	187.48	0.48	0.95%
MB1-B					0.06	
MB2-F	PTFE+Polyester	Plain	0.18	123.13	0.33	0.07%
MB2-B					0.05	

Table 2: Basic physical properties of fabric assembly

Fabric code	Configuration	Thickness (mm)	Mass (g/m^2)
D1-F	OS1+MB1-frontside	0.93	447.55
D1-B	OS1+MB1-backside	0.93	447.55
D2-F	OS2+MB1-frontside	0.81	435.51
D2-B	OS2+MB1-backside	0.81	435.51

2.2 Testing Apparatus and Method

The test apparatus of steam protective performance in this study was developed by Labs for Functional Textiles and Protective Clothing (Iowa State University, USA) [15], as shown in Fig. 1. This apparatus can control the required steam exposure conditions, such as steam pressure and steam flow. It includes a steam generator, a delivery spout, heat exposure cabinet, specimen fixed component and data acquisition system. The testing specimen was exposed to a saturated steam at a pre-set pressure produced by a small 3 kW boiler with an added super-heater. The steam temperature in steam generator ranged from 100 to 150 °C by controlling the electrically heated super heater. The pressurized steam was introduced to the surface of test specimen by a nozzle with an inner diameter of 4.6 mm. The T-type thermocouple (OMEGA: TC-GG-T-30) was fixed near the steam nozzle to monitor the steam temperature. The sample restraint of different thicknesses could be used to adjust the distance between steam nozzle and test specimen. The test specimen with a diameter of 190 mm was placed on a Teflon sample support with an embedded skin-simulant sensor that could measure the skin temperature rise versus time at the back of specimen. The air gap sizes between the fabric and skin surface can be adjusted by using spacer blocks with different thicknesses.

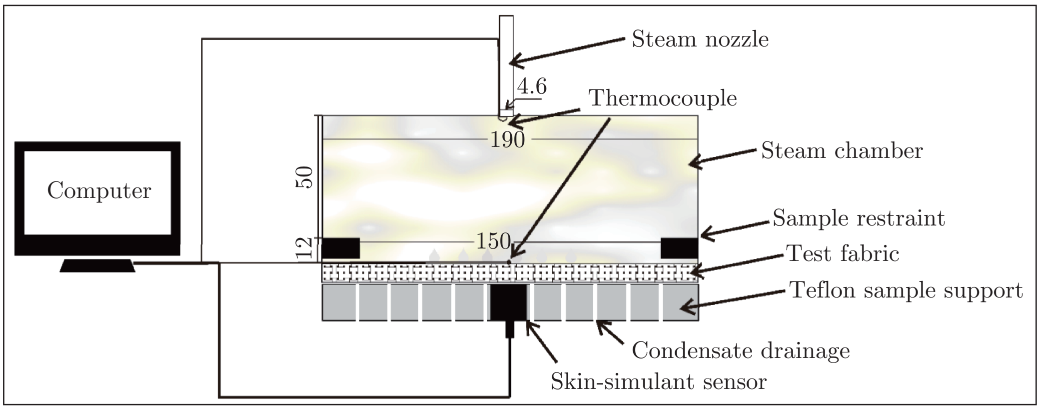

Fig. 1: Schematic diagram of thermal protective performance tester under hot steam

Skin-simulant sensor behind the test sample was used to record the change of skin temperature as the sensor housing is construct of Colorceran, an inorganic material having similar thermal physical properties with human skin [14]. The temperature data of skin's surface is employed to calculate heat flux ($q(t)$) absorbed by skin on the basis of Duhamel's theorem, given by [15]

$$q(t) = \sqrt{\frac{k\rho c_p}{\pi}} \left(\frac{1}{2} \int_0^t \frac{T_s(t) - T_i}{t^{\frac{1}{2}}} \right) \tag{1}$$

where ρ, k and c_p are respectively the density, the thermal conductivity and the specific heat of the skin simulant sensor, T_i is the initial uniform surface temperature and $T_s(t)$ is the surface temperature versus time t.

Before mounting the testing sample, it is essential to calibrate the exposure conditions. The steam pressure was set at 40 psi. These specimens were conditioned in a standard atmosphere (20 °C and 65% RH) for at least 24 hours before the experiments. The fabric specimens were exposed to the preset steamy condition for 20 s. After the exposure, these sensors continue to collect the thermal data for the next 40 s as the cool down period. The thermal response of skin surface could be employed to calculate times to 2 nd and 3 rd degree skin burn based upon Pennes bio-heat transfer model [16] and Henriques burn integral model [17]. Each specimen was tested three times and the average was obtained.

3 Results and Discussion

3.1 Effect of Fabric's Configuration on Skin Burn Time

In order to investigate the effect of fabric's configuration on skin burn time, different configurations of moisture barrier were exposed to a pressurized steamy conditions. Fig. 2 shows the predicted times to 2nd and 3rd degree skin burn with different fabric's configurations, and the standard errors of three tests for each fabric system are given. The protective levels provided by the selected fabric system ranged from 0.19 s to 7.43 s in steam exposure of 20 s. Most skin burns were caused by the transmitted thermal energy during steam exposure, not by thermal energy stored in protective fabric system, except for time to 3rd degree skin burn with D2-F fabric system.

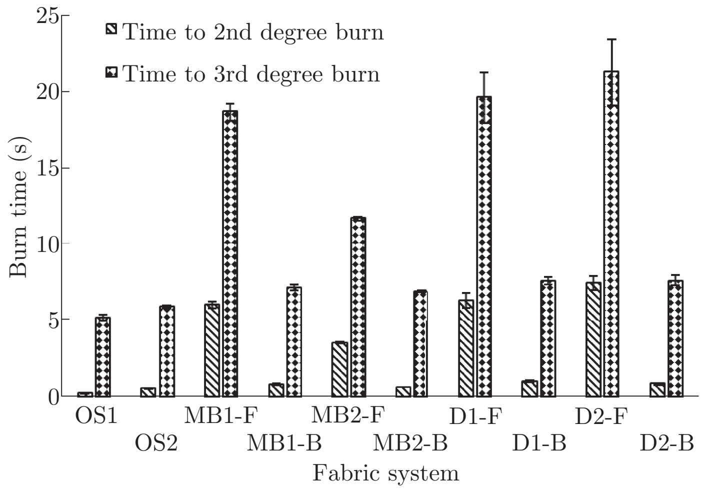

Fig. 2: Times to cause 2nd and 3rd degree skin burn with various protective fabrics

With regard to single-layer fabric, the lowest protective level was observed for the OS1 fabric with the highest air permeability. The protective levels of moisture barrier were obviously greater than that of outer shell, especially when the membrane face of moisture barrier was exposed to steam condition. The maximum differences between outer shell and moisture barrier for times to 2 nd and 3 rd degree skin burn were around 31.86 times and 3.66 times, respectively. But no significant relationship between air permeability and skin burn time was observed. It indicated that the air permeability of fabric was not the only factor influencing the steam protective performance. It was said that the moisture barrier provided a resistance to liquid water, but allowed the penetration of water vapor due to the pore size of moisture barrier [18]. For two kinds of moisture barrier, the time to skin burn when MB1 fabric was exposed to steamy condition was larger than that of MB2 exposed to steamy condition. This reason might be that the fabric's thickness and mass affected the protective level of moisture barrier. In addition, the MB2 fabric with higher moisture regain could absorb more steam penetrating through membrane, thus increasing the amount of stored thermal energy in the fabric. A significant difference was also found between different configurations of moisture barrier. This was because the membrane of moisture barrier has higher hydrophobic property than the substrate fabric of moisture barrier. Less condensate water was stored in moisture barrier when the membrane of moisture barrier was exposed to hot steam condition. Therefore, the thermal protective performance of protective clothing under steam exposure was determined by the air permeability, the thickness, the mass, and the surface properties of fabric.

Fig. 2 also shows the times to 2 nd and 3 rd degree skin burn with double-layer fabric system. Comparing to single-layer fabric, the protective performance provided by double layer fabric system did not present a significant increase. In contrast, some double layer fabric systems had a worse protective level under steamy condition. When the substrate face of moisture barrier was directed to outer shell (D1-B and D2-B), the times to 2 nd and 3 rd degree skin burn were far lesser than that of the substrate face of moisture barrier contacted with sensor (D1-F and D2-F). It was indicated that the position of membrane and substrate faces of moisture barrier exerted an important impact on the protective level afforded by the moisture barrier. The resistance to steam transfer in moisture barrier was mainly provided by the membrane of moisture barrier made of PTFE, while the substrate of moisture barrier could accumulate condensate water. If the membrane was connected with the skin-simulant sensor, the hot steam penetrated firstly through the substrate and following through the membrane. This could result in the production of more condensed water on the skin-simulant sensor. The substrate fabric of moisture barrier did not absorb steam through membrane, but accumulated a larger amount of thermal energy. Furthermore, the difference of skin burn time between different configurations of moisture barrier was more obvious for double-layer fabric. This was because hot steam penetrating through outer shell was easier to change into condensate in moisture barrier. In addition, the OS2 fabric with better protective level provided the greater protective performance for double-layer fabric system when D1-F and D2-F fabric systems were compared.

3.2 Effect of Fabric's Configuration on Skin Temperature

Figs. 3(a) and 3(b) illustrate the variation in the temperature of skin surface over time for single- and double-layer fabric systems, respectively. It was clear that the maximum temperatures for two kinds of outer shell during the exposure were respectively 103.39 °C and 101.13 °C, which were both close to the steam temperature flowed from the steam nozzle. This indicated that hot steam could quickly penetrate through outer shell. With the increase of exposure time, OS1 and OS2 fabrics took 3.9 s and 3.4 s to reach the peak temperature, respectively. Thus, the dominant heat transfer in the outer shell was steam heat transfer that could rapidly increase the skin temperature. However, there was a decreasing trend in the temperature of skin surface for outer shell after the peak temperature, since the condensation of steam occurred on the skin surface. The accumulated liquid water could evaporate to loss a portion of thermal energy, which resulted in the decrease of skin temperature.

For the moisture barrier, it was found that the skin temperature witnessed a continuous increase during steam exposure. The peak skin temperature during the steam exposure was less than that of the outer shell. The increasing rate of skin temperature decreased gradually over the

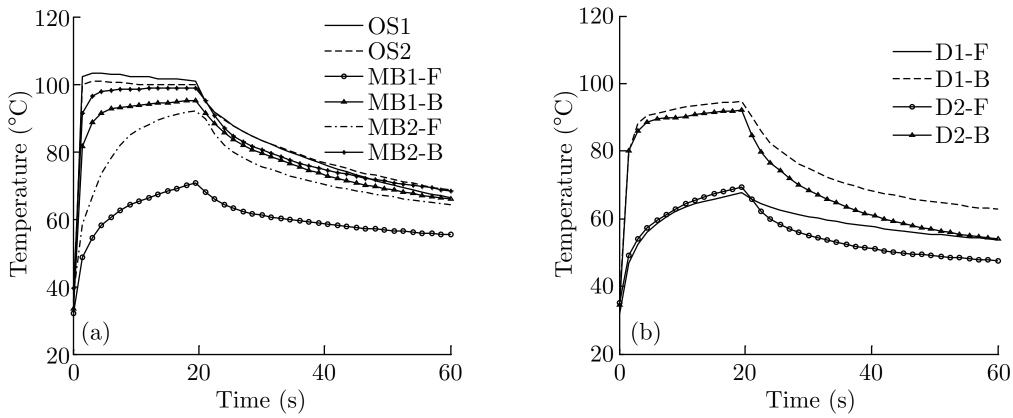

Fig. 3: Changes in the skin temperature versus time: (a) single-layer fabrics; (b) double-layer fabrics

exposure time. It could be inferred that conductive heat transfer played an important role in heat transportation of the moisture barrier. Due to the resistance to steam penetration, the thermal energy carried by steam was firstly stored in moisture barrier and then transferred to skin tissue by conductive heat transfer. The temperature gradient between outside and inside of moisture barrier was driving force to affect heat transfer rate. However, the increasing rate of skin temperature for MB1-B and MB2-B fabric system was larger than that for MB1-F and MB2-F fabric system. This indicated that the moisture barrier could provide higher resistance for steam transfer when the membrane of moisture barrier was exposed to steam condition. As a result, steam heat transfer in protective clothing has a higher heat transfer rate than conductive heat transfer.

After the exposure, the temperature drop on the skin surface was determined by the ambient temperature and the amount of condensed water. The lower ambient temperature quickened up the conductive heat transfer in the fabric system due to the increased temperature difference between the outer and inner side of fabric system. For the decreasing rate of skin temperature, the difference between two kinds of moisture barrier was caused by the thickness of moisture barrier, which is a key influencing factor of conductive heat transfer. Also, the liquid water on the skin surface could be evaporated to absorb thermal energy from skin tissue. It was for these reasons that the outer shell contained more liquid water presented a higher decreasing rate comparing with the moisture barrier. In addition, the heat transfer after the exposure was dependent on the stored thermal energy within fabric system. The discharge of stored thermal energy could exaggerate the skin burn as well [19].

Fig. 3(b) shows the changes in the skin temperature for double-layer fabric system. The change trend in all temperature curves showed a similar with MB1 and MB2 fabrics (see Fig. 3(a)). According to the above conclusion, the steam penetrating through the double-layer fabric system was mostly resisted due to the existence of moisture barrier. However, there was still significant difference when the moisture barrier was placed in different configurations. With regard to D1-F fabric system, hot steam could penetrate through the outer shell. A large amount of steam was resisted in the outer shell due to the waterproof membrane. Another small portion of steam transferred through the membrane of moisture barrier could be absorbed by the substrate of moisture barrier. Therefore, steam heat transfer just existed in the outer shell, while conductive heat transfer occurred in the membrane and the substrate of the moisture barrier. For OS+MB1-backside fabric system, hot steam could penetrate through the outer shell and the substrate of the moisture barrier so that hot steam was condensed within the outer shell and the substrate of the moisture barrier. Since the membrane of the moisture barrier was near to the skin surface, a small portion of steam could be condensed on the skin surface. In addition, the membrane of the moisture barrier was a thin PTFE membrane so that the released thermal energy from hot steam in the outer shell and the substrate was quickly transmitted to the skin surface in heat conductive way.

When the moisture barrier was entrapped between the outer shell and skin-simulant sensor in the same configuration, the skin temperature for double-layer fabric system experienced a similar change trend over the exposure time. The marginal difference was resulted from the basic properties of outer shell. For example, the OS2 fabric with lesser air permeability reduced the amount of steam penetration while the OS1 fabric with better moisture regain provided the larger capacity for storing more condensate water. After the exposure, it was obvious that the double-layer fabric system containing OS2 presented the greater decreasing rate of skin temperature. The OS1 fabric could store more thermal energy and condensate water, thus increasing the conductive heat transfer from the fabric system to skin tissue.

4 Conclusions

In this study, the thermal protective performance of single- and double-layer protective fabrics was examined under a pressurized steam exposure. The results showed that the moisture barrier exerted an important influence on the thermal protective performance provided by protective clothing. The maximum differences between outer shell and moisture barrier for 2nd and 3rd degree skin burn were around 31.86 times and 3.66 times, respectively. The thermal protective performance of protective clothing under steam exposure was determined by the air permeability, the thickness, the mass, and the surface properties of fabric. The steam heat transfer that existed in the outer shell or the substrate of moisture barrier could be a quicker heat transfer mode than the conductive heat transfer.

The configuration of moisture barrier presented a significant impact on the protective level of protective clothing, including single- and double-layer fabric system. The difference of skin burn time between different configurations of moisture barrier was more obvious for the double-layer fabric system. With regard to D1-F or D2-F fabric system, hot steam could penetrate through the outer shell. Besides, a large amount of steam was stored in the outer shell due to the waterproof membrane. For D1-B or D2-B fabric system, hot steam could penetrate through the outer shell and the substrate of moisture barrier so that hot steam was condensed within the outer shell and the substrate. Decreasing the amount of steam entering into fabric system, such as the steam condensation and penetration, contributed to the improvement of thermal protective performance under steam exposure. Therefore, the surface properties of moisture barrier is critical in determining the thermal protective performance of protective clothing under steam exposure. Further study should be conducted to examine the relationship between the protective level provide by moisture barrier and its transport properties in hot steam and even hot liquid hazards.

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