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To cite this article: Y Su et al 2017 IOP Conf. Ser.: Mater. Sci. Eng. 254 042027

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Application of waterproof breathable fabric in thermal protective clothing exposed to hot water and steam

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Abstract. A hot water and steam tester was used to examine thermal protective performance of waterproof and breathable fabric against hot water and steam hazards. Time to cause skin burn and thermal energy absorbed by skin during exposure and cooling phases was employed to characterize the effect of configuration, placing order and properties of waterproof and breathable fabric on the thermal protective performance. The difference of thermal protective performance due to hot water and steam hazards was discussed. The result showed that the configuration of waterproof and breathable fabric presented a significant effect on the thermal protective performance of single- and double-layer fabric system, while the difference between different configurations in steam hazard was greater than that in hot water hazard. The waterproof and breathable fabric as outer layer provided better protective performance of fabric system. Additionally, the thermal energy absorbed by skin during the cooling phase was affected by configuration, thickness and moisture regain of fabric. The findings will provide technical data to improve performance of thermal protective clothing in hot water and steam hazards.

1. Introduction

Workers in oil and gas industries are subjected to two kinds of thermal hazards: hot water and steam [1]. Hot water is frequently heated to 80-90 $^{\circ}$ C under pressure, and steam temperature is more than 100 $^{\circ}$ C, which results in the steam burn or scald burn injuries [2]. For providing effective protection against hot water and steam, worker is required to equip with personal protective clothing to resist heat and mass transfer.

Thermal protective performance provided by protective clothing against hot water and steam is determined by various factors, such as fabric's basic properties, air gap size and exposure condition [3-6]. As reported in standard ASTM F2701-08, a hot liquid splash tester was developed to evaluate the protective performance of materials used for protective clothing. The bench top tester was further improved by Lu et al. [4] to precisely investigate the influencing factors of the protective performance against hot liquid splash, such as liquid type, temperature, flow rate and impingement angle. The result demonstrated that mass transfer rate and amount determined the thermal protective performance of the clothing, depending on the air permeability of clothing system [7]. The improved tester was also employed by Mandal et al. [5] to analyze the relationship between the fabric properties and thermal

Content from this work may be used under the terms of the Creative Commons Attribution 3.0 licence. Any further distribution of this work must maintain attribution to the author(s) and the title of the work, journal citation and DOI. Published under licence by IOP Publishing Ltd 1 protective performance, indicating that the air permeability and thickness of fabric were the crucial influencing factor of thermal protective performance in hot liquid splash.

There has no international standard for characterizing the steam protective performance of fabric or clothing until now. Some preliminary studies have been carried out to develop a suitable assessment method for evaluating and improving thermal protection of clothing exposed to pressurized steam. Ackerman et al. [8] established a horizontal bench top tester that can differentiate the thermal protective performance of fabrics under steam exposure with a pressure from 69 to 620 kPa. It was found that the fabric's thickness, density and air permeability were the important fabric characteristics in providing protection against pressurized steam [5, 9]. In addition, some researchers developed vertical test device to evaluate the steam protective performance of fabric. For instance, Derscuell and Schimid [10] established a vertical test device that can adjust the splashing distance and pressure of steam to simulate different exposure conditions. Su and Li [11-12] developed a new test device considering the combined effect of steam and radiant heat transfer on thermal protective performance of clothing system. For evaluating the effect of body shape on thermal protective performance of clothing, Sati et al. [1] presented the test device of a cylindrical shape to study heat transfer in the fabric while exposing it to moderately high-pressure steam (69 kPa and 207 kPa). Moreover, a thermal manikin in a steam climatic chamber was employed to evaluate the thermal protective performance of clothing against steam exposure [10]. The results demonstrated that steam penetration and heat transfer in protective clothing mainly depended on resistance to water vapor diffusion, air permeability, thermal insulation and total heat loss.

It was found that hot liquid and steam penetration in protective clothing presented an important effect on thermal protective performance. Therefore, for improving thermal protective performance of protective clothing, impermeable fabric should be selected. It is generally that waterproof and breathable membrane, while allowing penetration of water vapor to increase heat loss due to sweat evaporation, provides the great resistance to water water [13]. Its impermeable property can enhance performance of thermal protective clothing exposed to hot water and steam hazards. The previous studies also proved that thermal protective clothing entrapping with waterproof and breathable fabric provided excellent thermal protection [5, 9].

However, there are few studies to further investigate the properties of waterproof breathable fabric on thermal protective performance against hot water and steam hazards. Therefore, the aim of the research was to examine the effect of properties of waterproof and breathable fabric on thermal protective performance against hot water and steam. The relationship between configuration of waterproof and breathable fabric and thermal protective performance was analyzed. The difference of hot water and steam hazard was discussed for explaining the protective mechanism and exploring the similar protective measures for two thermal hazards. The findings in this study would be useful in developing waterproof and breathable fabric used for the protection of hot water and steam.

2. Materials and methods

2.1. Materials

Two kinds of waterproof and breathable fabric with different type of substrates were selected for moisture barrier in this study (A1 and A2). Two kinds of composite fabric with different basic properties were used for outer shell (B1 and B2). The basic specifications of testing samples are listed in Table 1. Single-layer fabrics were assembled into double-layer fabric system. Different sides of waterproof and breathable fabric can be inserted into double-layer fabric system: configuration \Box and \Box . The configuration \Box of fabric system A1+B1 means that membrane side of waterproof and breathable fabric is exposed to hot water or steam, while the substrate side of waterproof and breathable fabric is exposed to hot water or steam for the configuration \Box of fabric system A1+B1.

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 2 kPa according to ASTM D 737. The oven was used to measure moisture regain of all samples in a constant atmosphere (20 °C temperature, 65%)

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IOP Conf. Series: Materials Science and Engineering 254 (2017) 042027 doi:10.1088/1757-899X/254/4/042027

relative humidity). The contact angle between the fabric's surface and distilled water drop was measured using video based optical contact angle system (OCA 25, DataPhysics instruments, Germany) in accordance with ASTM D 5725-08 at standard condition. In addition, surface morphology of microporous membranes was examined using a scanning electron microscope (FEI Quanta 250 FE-SEM, Oregon, USA) after sputter-coating with Iridium to increase image clarity. **Table 1.** Basic physical properties of protective fabric.

Fabric code	A1		A2			
	membrane	substrate	membrane	substrate	BI	В2
Fiber content	PTFE	PBI/ Kevlar	PTFE	Polyester	Nomex/ Kevlar /P-140	Nomex/ Kevlar
Fabric structure	Nonwoven	Twill	Nonwoven	Plain	Twill	Plain
Thickness (mm)	0.27		0.21		0.66	0.54
Mass (g/m ²)	187.48		123.13		260.07	248.03
Moisture regain	0.95%		0.07%		2.98%	1.65%
Air permeability (cm ³ /s/cm ²)	0.48	0.062	0.33	0.055	262.2	125.2
Contact angle (°)	90.91	141.63	79.38	125.76	0	143.79

2.2. Hot water and steam hazard simulation

Hot water and steam hazard tester (Iowa State University, USA) was employed to evaluate the thermal protective performance of protective fabric system under hot water and steam splash, as shown in Figure 1. Hot water splash tester is composed of a temperature controlled water reservoir, a water nozzle, a sensor board and a data acquisition system. Similarly, steam splash tester is composed of a steam generator, a delivery spout, a heat exposure cabinet, specimen fixed component and a data acquisition system. Water temperature can be set between ambient temperature and 100 °C with a temperature controller. The steam temperature ranges from 100 to 150 °C by controlling the electrically heated super heater in a small 3 kW boiler with an added super heater. The sample restraint of different thicknesses could be used to adjust the distance between steam nozzle and test specimen. The flow rate of water and steam during the exposure is controlled using a flow control valve. The temperature of splashing hot water or steam was measured by a T-type thermocouple (OMEGA: TC-GG-T-30) fixed near the nozzle. 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]. Three skin-simulant sensors are embedded in the sensor board in order to measure skin temperature at different positions for water flow. 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],

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

where , k and c_p are respectively the density, thermal conductivity and 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.



Figure 1. Schematic diagram of hot water (left) and hot steam (right) testers

3. Results and discussion

3.1. Difference of hot water and steam hazard

The average temperature of hot water flowed through water nozzle during the exposure is 85 °C, while the steam average temperature reaches to 104.34 °C. For evaluating the difference between hot water and steam hazard, skin-simulant sensor without the cover of fabric system was exposed to two heat exposure conditions. Table 2 shows times to 2nd and 3rd degree burn in hot water and steam hazard. It is clear that the time to 2nd and 3rd degree burn caused by steam exposure is significantly lesser than that caused by hot water exposure (P<0.05). The maximum difference between two heat exposures is 5.26 times for 2nd degree burn and 1.55 times for 3rd degree burn. It indicates that workers exposed to steam hazard confront with the larger risk comparing to hot water hazard. Theoretically, the thermal energy absorbed by skin in hot water and steam can be calculated by the below equations, respectively,

$$Q_l = \frac{m_l C_l \left(T_l - T_{skin}\right)}{A} \tag{2}$$

$$Q_{s} = \frac{m_{s}C_{l}(T_{s} - T_{skin})}{A} + \frac{m_{s}(h_{1} - h_{2})}{A}$$
(3)

where m_l and m_s are the mass of water water and from the water vapor to the water water (g), C_l is the specific heat of water water (4.192 kJ/kg/K), T_l , T_s and T_{skin} are the temperature of the liquid water, the steam and the skin surface (°C), h_l and h_2 are the water vapor enthalpy (2676.3 kJ/kg) and the water water enthalpy (419.06 kJ/kg) at 100 °C, respectively [16]. By comparing the two equations, it is clear that the thermal energy in steam exposure consists of mass transfer and phase change, while the thermal energy in hot water exposure is only dependent on mass transfer. For the same mass of hot water water, Additionally, steam is condensed on the surface of skin which can release a considerable amount of thermal energy according to the second term of right side in equation (3). Thus, the thermal energy absorbed by skin is obviously larger in steam exposure. The difference between two heat exposures is determined by the temperature and the phase change of hot water and steam.

Table 2. Thermal protective performance in hot water and steam hazards.

	Steam	Water-top	Water-middle	Water-down
Time to 2nd degree burn (s) (SD)	0.42 (0.033)	1.55 (0.020)	1.58 (0.033)	2.21 (0.059)
Time to 3rd degree burn (s) (SD)	6.12 (0.761)	8.21 (0.033)	8.21 (0.022)	9.46 (0.120)
Total thermal energy (kJ/m ²) (SD)	507.90 (14.201)	403.17 (3.189)	385.17 (2.538)	372.27 (9.148)

Figure 2 shows the variation of heat flux on the skin surface under hot water and steam hazards. The overall trend in the heat flux presents a consistency between two heat exposures. However, there

is an obvious difference for peak heat flux between hot water and steam exposures. The peak heat flux in steam exposure is 205.79 kW/m² which is far more that in hot water exposure (60.54 kW/m²). Furthermore, the heat flux arrives at the maximum value in 1.3 s of hot water exposure, while the heat flux for steam exposure reaches the peak value at 0.3 s. It means that steam exposure possesses not only more thermal energy, but also larger heat transfer rate comparing to hot water. After around 1.3 s of heat exposure, the heat flux for two heat exposures is almost equal. The average heat flux of hot water and steam at the end of heat exposure are 12.33 kW/m² and 11.99 kW/m², respectively. During the cooling phase, no significant difference between two heat exposures was observed. However, the heat flux for steam exposure is less than 0 kW/m² at the beginning of cooling period. The reason might be that some condensed water on the surface of skin for steam hazard was evaporated to take away thermal energy. The flow water for hot water hazard hardly stayed on the surface of sensor board due to its angle of inclination.



Figure 2. Heat flux histories over time in hot water and steam exposure

3.2. Effect of waterproof and breathable fabric on thermal energy

Figure 3 presents thermal energy absorbed by skin for different fabric systems during hot water and steam exposures. A significant difference between hot water and steam exposures was observed (P<0.05). The minimum and maximum differences between two heat exposures are 1.82 times and 8.67 times, respectively. This is far more than the difference between two heat exposures for the skinsimulant sensor without the cover of fabric system (see Table 2). It indicates that the fabric system can increase the difference of thermal protective performance between hot water and steam exposures. It might be attributed to the reason that the waterproof and breathable fabric resists the penetration of liquid water, but allows the water vapor transmission [13]. Thus, the waterproof and breathable fabric possesses better thermal protective performance in hot water exposure. The difference between two heat exposures depends not only on the stored thermal energy and phase change of hot water and steam, but also on the property of fabric system. Regarding different position of sensors, no obvious difference is observed based on the results of analysis of variance test (P>0.05). However, it is found that the difference of fabric system with configuration \Box is larger than fabric system with configuration \Box . This is because the membrane side exerts a less resistance to the flow of hot water on the fabric surface while the substrate side can allow the penetration of hot water. Furthermore, its rough surface resists the water flow on the fabric surface which can increase the retention time of water on the top and middle sensors.

When the waterproof and breathable fabric in different configurations was exposed to hot water and steam, the thermal energy for configuration \Box is significantly lesser than that for configuration \Box

(P<0.05). The larger difference between two configurations was observed for steam exposure. In steam exposure, the maximum different is 1.89 times for fabric system B2+A1, while the maximum different in hot water exposure reaches 1.65 times for fabric system A1. As discussed above, the waterproof and breathable fabric can provide better thermal protective performance in hot water exposure, which reduces the effect of configuration on thermal protective performance. Additionally, thermal protection against hot water and steam is influenced by the properties and position of fabric system. For steam hazard, the maximum thermal protection provided by fabric system is fabric system A1+B1 with configuration \Box , while the fabric A1 with configuration \Box possesses the worst thermal protection. The configuration of waterproof and breathable fabric is key influential factor for singlelayer fabric. However, the position of waterproof and breathable fabric embedded in fabric system is more important for double-layer fabric. The fabric properties present a minor effect on thermal protective performance due to the less difference of basic properties between the selected fabrics. For the hot water hazard, the best thermal protection is same with the steam hazard, while the fabric system A2 with configuration \Box shows the least thermal protection. The effects of configuration and position of waterproof and breathable fabric on the thermal protection present a consistent change with the steam hazard, but the influencing extent shows a decreasing trend. In general, the same improvements can be used to increase thermal protective performance for hot water and steam exposure.



Figure 3. Thermal energy absorbed by skin for different fabric systems during hot water and steam

exposure Figure 4 shows the change of thermal energy for different fabric systems during the cooling phase. When the thermal energy is more than 0 kJ/m², it means that skin surface during the cooling phase continues to absorb thermal energy stored in fabric system. In contrast, the skin releases thermal energy toward external environment. It is clear that the thermal energy absorbed by skin in steam hazard is larger than that in hot water hazard, except for fabric system B2+A1 with configuration \Box . Comparing with cooling phase without fabric system, the existence of fabric system increases the difference between two kinds of thermal hazard. The reason might be that more thermal energy in fabric system is stored before cooling phase for steam hazard. Single-layer fabric discharges more thermal energy to skin surface for steam hazard while more thermal energy within double-layer fabric is absorbed by skin for hot water hazard. This phenomenon is dependent on the amount of penetration of hot water and steam and thermal storage of fabric system. More steam is penetrated through singlelayer fabric so that the thermal energy from steam condensation continues to be transferred to skin during the cooling phase. With regard to hot water hazard, less water is transmitted in fabric system due to the existence of waterproof and breathable fabric. The thermal energy absorbed by skin is from thermal storage in fabric system. However, the thicker fabric system can store more thermal energy so that double-layer fabric system releases more thermal energy during the cooling phase [17].

Besides, the configuration of waterproof and breathable fabric presents different effects on thermal energy in hot water and steam hazards. The fabric system with configuration \Box discharges more thermal energy than the fabric system with configuration \Box under steam hazard, except for fabric A1. However, more thermal energy under hot water hazard is observed for fabric system with configuration \Box . For configuration \Box , the less thermal energy is transmitted to skin during steam exposure, thus reducing the increase of skin temperature. After the end of steam exposure, temperature difference between skin and fabric system enhances heat transfer. However, the storing amount of hot water in fabric system increases stored thermal energy, determining the difference between two configurations in hot water exposure. In addition, the thermal energy absorbed by skin is affected by fabric properties. It is found that the fabric system A1 discharges more thermal energy during the cooling phase than the fabric system A2. The fabric system A1 is characterized by the larger thickness, mass and moisture regain, indicating that the fabric system A1 can store more thermal energy. The fabric system containing fabric B1 can present higher thermal energy absorbed by skin comparing to the fabric system containing fabric B2, identically depending on the thickness, mass and moisture absorption. Therefore, the thermal energy absorbed by skin during the cooling phase is determined by the amount of mass penetration and stored thermal energy that is affected by configuration, thickness, mass and moisture absorption of fabric.



Figure 4. Thermal energy absorbed by skin for different fabric systems during cooling phase

4. Conclusions

Waterproof and breathable fabric was used for design of thermal protective clothing to improve protection against hot water and steam hazards. The effect of the waterproof and breathable fabric on thermal protective performance was analyzed using a hot water and steam tester. Thermal energy absorbed by skin was employed to examine the thermal protective performance of the waterproof and breathable fabric during the exposure and the cooling phases.

The configuration of waterproof and breathable fabric presented a significant effect on protective performance of different fabric systems exposed to hot water and steam hazards. The difference between two configurations was more obvious for steam hazard, which could be attributed to the lesser steam protective performance provided by the waterproof and breathable fabric. The position of

waterproof and breathable fabric also affects the thermal protective performance in hot water and steam hazards. The waterproof and breathable fabric should be treated as outer layer to resist the penetration of hot water and steam into fabric system. Secondly, a small amount of penetrating water and steam should be absorbed by the inner-layer fabric with thicker and larger moisture regain. Additionally, the thermal energy absorbed by skin during the cooling phase was determined by the amount of mass penetration and stored thermal energy that is affected by configuration, thickness, mass and moisture absorption of fabric. Two thermal hazards possessed different extent of risk, while the thermal protection in two thermal hazards was both influenced by configuration, position and fabric properties. The similar protective measures can be taken to improve protective performance of protective clothing against hot water and steam hazards.

Acknowledgments

The authors would like to acknowledge the financial support from the National Nature Science Foundation (Grant NO. 51576038), Donghua University PhD Thesis Innovation Funding (NO.16D310701), and Shanghai Municipal Natural Science Foundation (Grant NO. 17ZR1400500).

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