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Investigation of Material Combinations for Fire-fighter's Protective Clothing on Radiant Protective and Heat-Moisture Transfer Performance

Abstract

This paper describes an investigation into protective clothing for fire-fighters, made of different material combinations, based on the demand for radiant protective performance (RPP) and heat-moisture transfer properties, which are closely associated with comfort performance. The outer shell and thermal barrier were changed to measure their effects on radiant protection and comfort performance. Also, we compared clothing assemblies which incorporated moisture-permeable and moisture- impermeable barriers. It was our intention to match different material combinations of clothing assemblies, in order not only to provide effective radiant protection but also to maintain a balance between heat and moisture. This study shows the relative importance of the moisture vapour permeability of the moisture barrier on comfort performance in fire-fighters' protective clothing.

Key words: *fire-fighters' protective clothing, radiant protective performance, thermal insulation, moisture vapour resistance, material combinations, moisture barrier.*

Introduction

Fire-fighters look for a number of performance benefits in their equipment and clothing. Because the requirements for long-term wear, increased mobility, comfort and thermal protection can vary, it may be a challenge to find everything that is needed in one garment, especially when there are so many garments from which we may choose. In fact, two vital yet conflicting factors are maximising thermal protection from fire and minimising metabolic heat stress by designing the fire-fighter's clothing [1 - 4]. Fire-fighters must wear heavy protective clothing ensembles to protect them from thermal injury. They cannot work efficiently if they feel uncomfortable, even at the risk of becoming incapacitated due to excessive heat stress. For the fire-fighter's protective clothing, thermal protection is of primary importance, but its contribution to comfort and heat strain of the fire-fighter should simultaneously be a consideration. However, these two contradictory requirements will cause great difficulty in selecting suitable fabrics for uniforms.

The evaluation of regulations and practices, as well as the development of new prototypes for fire-fighters' clothing, should be based on these competing requirements. In this paper, a RPP tester set up according to standard NFPA 1977 [5] was used to measure the radiant protective performance of single-layer fabrics or multiple-layer fabric assemblies. Simultaneously, we used a sweating manikin to assess the thermal insulation I_t and moisture vapour resistance R_{et} of fire-fighters' protective clothing with different material configurations. Such data provides useful information to develop more protective, less stressful fire-resistant clothing system. We also discussed thermal protection and thermal strain on fire-fighters' clothing with different types of moisture barriers. Therefore, the purpose of this laboratory study is to examine different material combinations and optimise the overall material configurations in terms of protection and heat-moisture comfort performance.

Experimental

Test samples

Protective clothing for fire fighters is primarily designed to protect an individual from the thermal environment produced by fire. It affords protection from thermal radiation, hot gas convection caused by fire, and (to some extent) direct contact with hot surfaces. At present, protective clothing assemblies typically consist of a flame-resistant outer shell and an inner liner. The outer shell should resist ignition while being exposed to thermal radiation or a very short period of direct flame contact. The inner liner is generally composed of a moisture and thermal barrier. The moisture barrier should fully prevent the passage of any moisture, whether in the form of liquid or vapour.

As the heat and water vapour transmission in protective clothing is dependent on the permeability and the configuration of the samples, clothing assemblies with different structural characteristics were selected for this study, according to the practical use of protective clothing in China (Table 1).

Radiant protective performance (RPP)

The RPP tester was set up according to NFPA 1977, a standard for protective clothing and equipment for fire- fight-

Table 1. *Structural characteristics of clothing layers.*

Component	Sample No.	Material	Weight, g/m	Thickness, mm
Outer shell	A1	Panof	286.3	0.505
	A2	FR cotton	265.4	0.403
	A3	Aramid (twill)	212.3	0.435
	A4	Aramid (twill)	176.5	0.389
	A5	Aramid (twill)	205.9	0.393
Moisture barrier	B1	PTFE membrane	-	-
	B2	PVC coated cotton	-	-
Thermal barrier	C1	Cotton fibre (nonwoven)	158.9	3.68
	C2	Para-aramid fibre (nonwoven)	167.5	4.57
	C3	Far infrared fibre (laminated)	196.7	2.69
	C4	Space cotton (coating)	173.6	3.54
	C5	Polymer fibre (nnowoven)	203.5	7.89

ing [5]. The heat source was provided by five 500-watt quartz tubes. The temperature rise versus time and heat flux is measured using a copper calorimeter located behind the sample fabrics (ensembles) at a distance of 2.54 cm to the surface of the quartz tubes. The heat source is calibrated to 0.5 cal/cm^2·s. The exposure time for fabrics is 25 seconds for a single layer and relatively longer for multiplayer samples. The time T in seconds to cause a second-degree skin burn on each kind of protective clothing assemblies or a single-layer fabric is determined by overlaying the curve of the thermal response of the calorimeter with a curve obtained from standard ASTM D 4108 at the same scale. The RPP value is calculated according to the following equation:

$$RPP = 0.5 \times T \qquad (1)$$

where RPP stands for Radiant Protective Performance, and T is the required time to a second-degree skin burn.

The sweating manikin

The sweating manikin system developed by the China Donghua University is composed of the three following parts: the manikin body, the simulating sweating system, and the computer smart controlling system. The manikin was built according to the anatomy of Chinese male adults, including 16 temperature-controlled parts. The computer smart temperature controlling part has two kinds of controlling models, governed by using separate controlling systems, an invariable skin temperature, and an invariable heating power. The manikin is housed in a climatic chamber. The manikin surface is continuously fed by water in specially designed 'sweat glands'. The sweating rate is controlled in proportion to the skin water preservation.

Calculating clothing thermal insulation and moisture vapour resistance

When the manikin is not sweating, the total thermal insulation I_t, including the insulation of the clothing and the surface air layer, is calculated with the following equation:

$$I_t = A(T_s - T_a)/Q_s \qquad (2)$$

where T_s is the mean skin temperature (°C), T_a is the mean temperature (°C) of the environment. Q_s is the dry heat loss per m^2 skin area, and A is the total skin area, m^2.

When the manikin is sweating, the total evaporative resistance R_e, including the vapour resistance of the boundary air layer and the moisture vapour resistance of clothing, was calculated as follows:

$$R_e = A(P_s - P_a)/(Q_w - Q_s) \qquad (3)$$

where:

P_s - the water vapour pressure at the skin surface,

P_a - the water vapour pressure in the ambient air,

Q_w - the power input while the manikin is sweating.

Since the nonwoven material used to form the thermal barrier is difficult to stitch in order to make single-layer garments, the thermal insulation and the moisture vapour resistance of the thermal barrier is determined from clothing assembly. To measure the single-layer garment's heat-moisture comfort performance, the outer shell was made in the form of single-layer garments of a similar size to that in clothing assemblies, and the outer shell layer material, together with the thermal barrier layer material, was made into clothing ensembles excluding a moisture barrier. First, the insulation I_a from the unclothed manikin to the ambient air was measured, assuming that I_a is equivalent to resistance at the surface of clothed body. The effective clothing assemblies' (outer shell + thermal barrier) thermal insulation I_{cle} is the insulation from the skin to the clothing surface, excluding the effect of the increased surface area of the clothed body.

$$I_{cle} = A(T_s - T_a)/(Q_s - I_a) \qquad (4)$$

Then, the effective thermal insulation of single-layer clothing made of outer shell material is described as follows:

$$I'_{cle} = I'_t - I_a \qquad (5)$$

where I'_{cle} and I'_t are the effective and total insulation of the single-layer outer shell material. We assume that there is no air gap between the outer shell and thermal barrier. Therefore, from Equation 4 and 5, the effective thermal insulation of single-layer thermal barrier material is calculated as follows:

$$I'_{cle} = I_{cle} - I'_{cle} = I_t - I'_t \qquad (6)$$

Thus, we have

$$I'_t = I_t - I'_t + I_a \qquad (7)$$

where I'_t is the total thermal insulation of the single-layer thermal barrier.

Similarly, for the single-layer thermal barrier, moisture vapour resistance R'_{et}, equals

$$R'_{et} = R_{et} - R'_{et} + R_a \qquad (8)$$

where R'_{et} *and* R_a are the effective moisture resistance of the thermal barrier, and the resistance of the surface air layer.

Results and discussion

Test results of single-layer material

Radiant protective performance (RPP)

Many researchers have studied the thermal protective performance (TPP) of single layer heat-resistant fabrics [6 - 8]. However, the latest NFPA standard recommends the RPP test as a standard method for evaluating clothing materials for wildland fire-fighters. As mentioned earlier, the RPP test uses a bank of quartz lamps with a heat flux of 0.5 cal·cm^{-2}·s^{-1} as the radiant heat source. We measured the single-layer radiant protective performance for fabric or material used to make the outer shell and the thermal barrier.

As can be seen from Figure 1, the differences in the *RPP* values of the outer shell and thermal barrier materials are not significantly different. Sample A4 possesses poor radiant protective performance due to its low fabric density and loose weave. Simultaneously, we find that thick and heavyweight fabrics exhibit high radiant heat, indicating that, as expected, the radiant protection of fabrics improves as their thickness or weight increases. Sample C3 performs better than other samples as regards the thermal barrier feature. An aluminised layer on C3's surface acts as a good reflector of heat in exposure radiation. It is not surprising, therefore, that aluminised samples provided more protective insulation than the substrate material did.

Thermal insulation

Figure 2 shows that significant differences in thermal insulation I_t value exist between the outer shell material and thermal barrier materials. The higher thermal insulation value is due to a mass of stagnant air within the thermal barrier, which has a lower thermal conductivity than solid fibre does. However, the volume of stagnant air within the outer shell

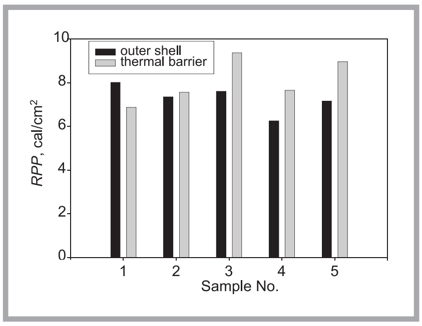

Figure 1. *Radiant protective performance for single-layer material.*

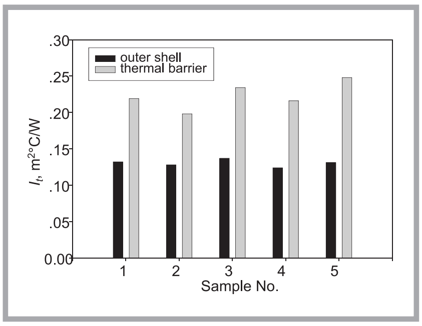

***Figure 2.** Thermal insulation value for single-layer material.*

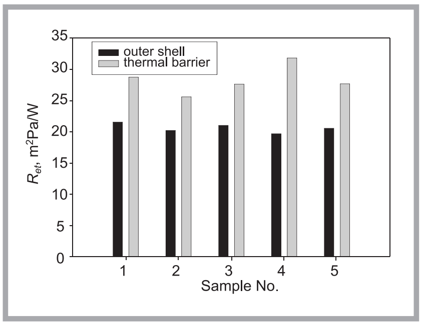

***Figure 3.** Moisture vapour resistance for single-layer material.*

material is low, and the conductive heat transfer through solid fibre is dominant.

As can be seen from Figure 2, sample C3 does not display the best thermal insulation performance among the samples of thermal barriers, even though it has the highest radiant protective capability (Figure 1). Therefore, the superiority or inferiority of materials cannot be determined in terms of a single index.

Moisture evaporative resistance

Material weight and thickness have a direct impact on the moisture vapour resistance value, as can be seen from Figure 3. For the same material, heavier or thicker samples lead to higher R_{et} values, such as for samples A3, A4 and A5. This can be explained by the fact that the passages among fibres decrease as the weight or thickness of materials increases, and the rate of moisture vapour transport decreases. The moisture vapour resistance of the material is also affected by the type fibre. For instance, sample C1 has a higher evaporative resistance than sample C2l which has a similar thickness. This is because hydrophilic cotton tends to absorb and retain moisture because of its fibre structure, and hydrophobic aramid fibres have a high wicking ability, and can evaporate moisture quickly without wetting the materials.

Analysis of material combinations

Variations in thermal comfort performance exist in a single-layer material of fire-fighters' protective clothing. Materials with good heat resistant capability do not always provide high evaporative resistance. However, excellent heat resistance and water permeability are necessary when fire-fighters wear protective clothing during physical exercise or fire-fighting. Therefore, it is desirable that the optimisation of the overall material configuration in terms of thermal protection and comfort performance is conducted by examining different combinations of existing materials. Sample C5 was excluded from consideration as a thermal barrier due to its very large thickness. For our study, only sample B1 was selected as a moisture barrier in the configuration study. It should be noted that an *RPP* tester was used to measure the radiant protective performance of fabric assemblies, and the sweating manikin was used to measure the heat-moisture transfer performance of clothing assemblies. The test results of these material combinations are shown in Table 2.

In our experiments, the results in terms of *RPP* value, thermal insulation and evaporative resistance varied, so it is difficult to describe the experiment accurately because of its multi-index characteristic, and we cannot analyse it by simple methods of intuition. Therefore we have adopted the integrated balance method to obtain reasonable conclusions. Firstly, we analysed each experimental index as a simple existing index, and then balance the analysed results synthetically.

The range of analysis results are shown in Table 3. For three indices related with radiant protective and comfort performance, the *C* factor is more important than the *A* factor according to their primary or secondary sequences. So the effect of the thermal barrier material is stronger than that of the outer shell material.

From Table 3 (see page 73), it can be seen that different levels of factors have different impacts on three indices (*RPP*, thermal insulation and moisture vapour resistance). The optimal level of the factor is determined by the times that [each level of each factor is selected as the optimal level by three factors]. Two levels of factor *A* and four levels of factor *C* are selected twice, respectively. Three levels of factor *A* and one level of factor *B* are selected only once. Thus, we can obtain the best combination of the experiments: A2, B1, and C4.

Obviously, the thermal barrier has a significant influence on the radiant protection, thermal insulation and evaporative resistance performance of fire-fighters' protective clothing when they are estimated by range analysis. The outer shell also affects heat and moisture transmission through protective clothing, but the effect is not as strong as that of the thermal barrier. However, its effect on radiant protection and moisture permeability cannot be ignored.

***Table 2.** Testing results of material combinations.*

No.	Outer shell	Moisture barrier	Thermal barrier	RPP, cal/cm²	Thermal insulation, m² ·°C/W	Evaporative resistance, m²· Pa/W
1	A1	B1	C1	14.82	0.345	45.21
2			C2	14.64	0.341	54.34
3			C3	15.25	0.298	52.47
4			C4	14.66	0.389	48.97
5	A2	B1	C1	14.16	0.276	47.52
6			C2	13.77	0.356	38.65
7			C3	14.55	0.321	48.52
8			C4	13.92	0.301	47.21
9	A3	B1	C1	12.88	0.402	40.24
10			C2	12.65	0.245	54.23
11			C3	13.59	0.317	51.68
12			C4	13.01	0.296	47.69
13	A4	B1	C1	13.43	0.416	46.03
14			C2	13.55	0.404	48.45
15			C3	14.27	0.347	41.73
16			C4	14.12	0.299	42.36
17	A5	B1	C1	15.67	0.374	47.65
18			C2	15.43	0.341	55.53
19			C3	15.97	0.287	54.21
20			C4	14.83	0.312	49.56

Table 3. *Range analysis results.*

Quantity, unit	No.	Outer shell A	Thermal barrier C	Factor sequence	Optimal level
Radiant protective performance *RPP*, cal/cm^2	K1	14.92	15.22	C>A	A3C4
	K2	15.15	15.41		
	K3	15.71	14.35		
	K4	15.51	15.84		
	K5	14.86	-		
	Range R	0.85	1.49		
Thermal insulation I_t, m^2 °C/W	K1	0.328	0.454	C>A	A2C1
	K2	0.388	0.346		
	K3	0.287	0.253		
	K4	0.343	0.386		
	K5	0.353	-		
	Range R	0.101	0.199		
Evaporative resistance R_{et}, m^2 Pa/W	K1	48.71	46.58	C>A	A2C4
	K2	44.31	50.29		
	K3	48.62	49.58		
	K4	49.57	45.12		
	K5	52.78	-		
	Range R	8.47	5.17		

Table 4. *Test results of protective clothing.*

Clothing assemblies	RPP, cal/cm^2	Thermal insulation, m^2·°C/W	Evaporative resistance, m^2·Pa/W
R1	12.88	0.402	40.24
R2	14.31	0.415	38.45
S	12.49	0.583	65.79

Effect of moisture barrier

To investigate the effects of the moisture barrier on thermal protection and clothing comfort including heat and mass transfer, the optimal combination of A3+B1+C1 containing the microporous membrane PTFE was selected to make protective clothing R based on the integrated balance analysis. R was tested under two conditions: R1 was brand-new; R2 had been worn during smoke-diving training and had been washed three times before the study. Another clothing ensemble system S (A2+B2+C3) was brand-new, including the impermeable moisture barrier B2. For RPP testing, the fabric assemblies were arranged in the same manner as a turnout suit, and fabric assemblies R (S) was also named.

The experimental results are listed in Table 4. The RPP value of clothing combination R2 is about 10% greater than that of the combination R1, and the *RPP* value of R1 was about 3% greater than that of the ensemble S. It seems that the differences in *RPP* value caused by the moisture barrier are not great in R1 and S fabric (clothing) assemblies. The differences in *RPP* values for clothing assemblies R are obvious before and after being washed. After three washing cycles, R2 shows increased *RPP* value, possibly caused by increased thickness due to the fuzzy surfaces created during laundering.

The total thermal insulation for clothing assembly R1 was 0.402 m^2°C/W, 0.415 m^2°C/W for R2, and 0.583 m^2°C/W for assembly S. S has not only the highest thermal insulation but also the highest moisture vapour resistance R_{et}. The impermeable moisture barrier (B2) incorporated in S is inferior to the moisture permeable barrier (B1) in R1 and R2, considering heating transfer. The impermeable moisture barriers in protective clothing show great resistance to evaporative vapour loss from the wearer, which was consistent with the results of other researchers [9]. When incorporated in clothing, moisture barriers have a strong effect on the moisture permeability of the fire-fighters' protective clothing.

Conclusions

Our work has resulted in the optimisation of a combination of materials for fire-fighters' protective clothing, and we have investigated the effects of the moisture barrier type on heat and moisture transfer through clothing assemblies. For a single-layer material, distinct differences in the value of thermal insulation and variations in radiant protection performance are not obvious between the outer layer material and the thermal barrier layer material. Material weight and thickness have a direct impact on the moisture vapour resistance value. The effects of the thermal barrier layer on radiant protective performance, thermal insulation and moisture vapour resistance are more intensive than that of the outer shell layer in clothing assemblies. Therefore, the effects of thermal barrier should be regarded as the key point in the design of the protective clothing for fire-fighters. The optimal combination of the materials selected by the research work described in the article is to take A2 as the outer shell layer and C4 as the thermal barrier layer. Finally, this study shows the relative importance of the moisture vapour permeability of the moisture barrier on heat and moisture transfer.

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