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Evaluating the Moisture Transfer Property of the Multi-layered Fabric System in Firefighter Turnout Clothing

Abstract

The multi-layered fabric system used on firefighter turnout clothing consists of an outer shell, moisture barrier, thermal barrier and comfort lining. Heat and moisture transfer property requirements in firefighter turnout clothing standards are different in the US, EU and China. In this research the water vapour permeability of component fabric samples and the total water vapour permeability of a four-layered fabric assembly were measured according to GA10-2002 (Standard for Fire Fighting Protective Clothing in China). It was found that the moisture transfer property of the fabric assembly could not be exactly reflected only by the water vapour permeability of single-layered fabrics, e.g. the moisture barrier. The heat and moisture transfer property of firefighter turnout clothing should be determined by the whole heat and moisture transfer property of the fabric assembly, for example, the total heat loss (THL), water vapor resistance, etc.

Key words: *firefighter turnout clothing, heat transfer property, moisture transfer property, water vapour permeability, multi-layered fabrics.*

Introduction

Firefighter turnout clothing is the basic personal protective ensemble for firefighters when they fight against fire or participate in emergency rescue. Therefore, for firefighter protective clothing, the thermal protective performance (TPP) is of primary importance, while the comfort and heat stress of firefighters should be a consideration only [1].

It is universally agreed that physical activity while wearing firefighter turnout clothing generates excess body heat, which, if not allowed to evaporate or dissipate, is then cumulatively stored by the body. Cumulated heat results in an increase in the body's core temperature [2], and excessive heat stress weakens firefighters' operational capability [3, 4]. Thus the heat and moisture transfer property is a key issue for firefighter protective clothing.

Up till now, sweating thermal manikins have been used for evaluating the heat and moisture transfer property of firefighter turnout clothing, but it is complex and costly. Consequently, taking universal application into consideration, some countries have established their own standards for firefighter turnout clothing, which are different with respect to evaluating the heat and moisture transfer property [5-8]. In NFPA1971 Standard (Protective Ensembles for Structural Fire Fighting and Proximity Fire Fighting) of the US, total heat loss (THL) is adopted. Total heat loss is the amount of conductive (dry) and evaporative (wet) heat loss that occurs through the multi-layers of a turnout ensemble [2]. Different from THL, other measurements are adopted in EU and Chinese standards (***Table 1***).

From ***Table 1***, it can be seen that, different from standards in the US and EU, in Standard GA10-2002 the water vapour transmission of the moisture barrier is tested as an index to evaluate the moisture transfer property of firefighter turnout clothing. Although testing the WVTR of a single moisture barrier by the cup method in a steady state is much simpler than to measure the total heat loss or water vapour resistance of a turnout ensemble's multi-layers using a sweating hot plate, the latter ones can be a better way to evaluate the effect of the heat and/or moisture transfer property of firefighter turnout clothing.

In Standard NFPA1971-2007, the total heat loss of a multi-layered fabric system required is at least 205w/m^2, much higher than that of 130w/m^2 in Standard NFPA1971-2000 , which indicates the importance of firefighter turnout clothing's heat and moisture transfer property, and hence it is given more regard. The requirement for water vapour resistance in Standard EN469-200 is to test the turnout ensemble's multi-layer assembly. Indices related to the heat and moisture transfer property in Standard GA10-2002 include the WVTR for the moisture barrier and the weight of the complete component assembly and so on. The WVTR for the moisture barrier required is no less than 5000g/ (m$^2 \cdot$ 24h).

Table 1. *Requirement for the heat and moisture transfer property of firefighter turnout clothing in different standards.*

Category	Standard title	Edition	Testing objects	Indices	Requirement	Testing apparatus
US	NFPA1971 Standard on Protective Ensembles for Structural Fire Fighting and Proximity Fire Fighting	2000	Multi-layered fabric assemblies	Total Heat Loss (THL)	≥130 w/m^2	Sweating hot plate
		2007			≥205 w/m^2	
EU	EN469 Protective clothing for firefighters – Performance requirements for protective clothing for firefighting	2005	Multi-layered fabrics assemblies	Water Vapour Resistance	30 m^{2}Pa/W	Sweating hot plate
China	GA10 Standard on Firefighting Protective Clothing	2002	Moisture barriers	water vapour transmission rate (WVTR)	≥5000 g/(m$^2 \cdot$ 24 h)	WVTR cup

***Table 2**. Details of fabrics in each component layer.*

No.	Material	Structure	Surface mass, g/m²	Thickness, mm	No.	Material	Structure	Surface mass, g/m²	Thickness, mm
A1	60% PBI, 40% Kevlar®	plaid	196.1	0.77	C1	100% Nomex®	nonwoven	90.0	3.34
A2	20% PBI, 80% Aramid	twill	206.5	0.76	C2	100% Nomex®	nonwoven	140.3	2.63
A3	95% Nomex®, 3% Kevlar®, 2% Carbon anti-sta	twill	212.1	0.55	C3	50% Nomex®, 50% Kevlar®	nonwoven	104.5	2.83
A4	95% Nomex®, 3% Kevlar®, 2% Carbon anti-sta	plain	150.0	0.50	C4	100% Tanlon®	nonwoven	203.1	3.41
A5	99% Kermel®, 1% Carbon anti-stat	twill	207.3	0.41	C5	100% Tanlon®	nonwoven	250.0	2.16
A6	95% Tanlon®, 5% Kevlar®	plain	260.0	0.87	C6	100% FR	nonwoven	255.2	2.56
A7	100% Tanlon®	twill	244.5	0.65	C7	100% Carbon	nonwoven	237.8	3.53
A8	100% Tanlon®	twill	260.0	0.79	C8	100% Tanlon®	nonwoven	188.4	2.85
A9	100% Tanlon®	twill	243.0	0.69	C9	100% Tanlon®	nonwoven	120.0	1.47
B1	100% Tanlon® + PTFE	laminated	85.0	0.78	C10	100% Tanlon®	nonwoven	160.0	1.58
B2	100% Nomex® + PTFE	laminated	151.2	0.29	D1	100% FR-Cotton	plain	108.5	0.22
B3	100% Aramid + PTFE	laminated	161.4	0.27	D2	100% FR-Cotton	plain	157.9	0.24
B4	100% FR-Cotton + PTFE	laminated	135.7	0.26	D3	100% FR-Cotton	plain	108.9	0.21
B5	100% FR-Cotton + TPU	coating	252.8	0.38					

In conclusion, the uncertainties about the heat and moisture transfer property related to firefighter turnout clothing performance are as follows: what the relationship between the WVTR for the moisture barrier and that for a multi-layered fabric assembly is; whether the WVTR for the moisture barrier can reflect the whole water vapour permeability of a multi-layered fabric system or not; whether the WVTR for the moisture barrier can be used as an evaluative index to describe the heat and moisture transfer property of a multi-layered fabric assembly or not. In this paper these issues are discussed by examining experimental data, and the relationship between the whole water vapour permeability of a multi-layered fabric system and that of each component layer is reviewed.

Experimental

Test fabrics

Various types of fabrics currently used in firefighter turnout clothing were selected as samples (***Table 2***), including 9 outer shells (A1~A9), 5 moisture barriers (B1~B5), 10 thermal barriers (C1~C10) and 3 comfort linings (D1~D3), in which Tanlon® is a trademark for polysulfonamide fiber.

According to Standard GA10-2002, the basic properties of each component sample were tested. For the outer shell, flame resistance, surface wetting, breaking strength, tearing strength, and heat durability were tested; for the moisture barrier, water penetration resistance and heat durability were tested; resistance to flame and heat durability were tested for the thermal barrier; and flame resistance was tested for the comfort lining.

Water vapour permeability of single-layered fabric

As stipulated by GB/T12704 – 1991 (Textiles test method for water vapour transmission of fabrics in the Chinese Standard) [9], the cup method was used to measure the water vapour permeability of single-layered samples. Calcium chloride anhydrous of 0.63mm~2.5mm diameter was used as a desiccant. The test specimen was sealed to the open mouth of the test dish containing the desiccant, where it is required that the distance from the surface of the desiccant to the lower surface of the specimen is about 3 mm. The cup assembly was placed in a controlled atmosphere (38°C, 90% RH) for 1 hour with a cover on the cup to ensure the assembly system was balanced. Then the cup assembly was moved to a drier with silica gel in a common temperature environment (21°C) for 30 minutes. The weight of the assembly (before test) was measured before placing the assembly into a controlled atmosphere without the cover. After 1 hour, the assembly was removed from the controlled atmosphere and the cover put on quickly to measure the weight of the assembly again (after test). Three specimens of each sample were tested by the method described above. Periodic weightings determined the rate of water vapour movement through the specimen from the controlled atmosphere into the desiccant. The water vapour transmission rate (WVTR) was calculated by the following formula:

$$WVTR = \frac{24 \times \Delta m}{S \times t} \qquad (1)$$

Where:

$WVTR$ – weight of water vapor permeability, g/ ($m^2 \cdot 24h$);
Δm – difference in weight of experimental assemble before test and after test, g;
S – area of the sample, m^2;
t – test time, h.

Total water vapour permeability of the multi-layered assemblies

As stated in GA10-2002, fabric samples were combined to make a four-layer fabric assembly for firefighter turnout clothing in order to measure the total water vapour permeability. Based on the test results of WVTR for single-layered samples, some component fabrics were selected from each layer to undertake a further orthogonal layout study to reduce test times for the multi-layered fabric assembly. The purpose of the orthogonal layout design was to make uniformity combinations of various samples in each layer and to reduce test times. In this study, two schemes of an orthogonal layout were designed to measure the total water vapour permeability of the multi-layered fabric assemblies.

Scheme of orthogonal layout representing all the samples selected

In the scheme of orthogonal layout representing all the samples selected , the best and worst sample of WVTR in each layer were determined as two levels, and another two samples were selected to make a four sample WVTR distribution as an arithmetical progression. The arrangement in this scheme was to show the effect of the difference between the levels in each layer (factor) on the whole water vapour permeability of the multi-layered fabric assembly. Finally, A1, A3, A5 & A9 were selected as outer shells; B1, B2, B3 & B4 were selected as moisture barriers; C1, C2, C5 & C7 were selected as thermal barriers; and D1 was selected as the comfort lining. In accordance with the orthogonal layout with 3 factors and 4 levels [10], component fabrics were combined to measure the assemblies' WVTR.

Scheme of orthogonal layout excluding the difference between the levels in each component fabric

From each layer of the outer shell, moisture barrier and thermal barrier, two sample fabrics were selected. The difference in the two sample fabrics' WVTR is almost same among the different components. This scheme was to show the effect of the different component layers on the whole water vapour permeability of the multi-layered fabric assemblies. A1 & A3 were selected as outer shells; B3 & B4 were selected as moisture barriers; C1 & C2 were selected as thermal barriers; and D1 was selected as the comfort lining. In accordance with the orthogonal layout with 3 factors and 2 levels, the component fabrics were combined to measure the assemblies' WVTR.

Results and discussion

The test results are reported in ***Tables 3, 4*** & ***6*** as an average of at least three independent replications.

Test results of single-layered samples

Test results of the water vapour transmission of single-layered samples are shown in ***Table 3***. The WVTR of all the moisture barrier samples met the requirement of 5000 g/$(m^2 \cdot 24h)$ in GA10-2002, except B5.

After a variance analysis of the single-layered samples' WVTR, it was seen that the water vapour permeability of the 4 component layers were significantly different ($p = 0.001<0.05$). Furthermore, when a dependent sample T test was performed on each component layer's WVTR, it was observed that the thermal barrier was significantly lower than that of the other 3 layers, whereas the outer shell, moisture barrier and comfort lining had no distinct dissimilarity.

Table 3. *Water vapour transmission test results of single-layered samples.*

Outer shell	WVTR, g/($m^2 \cdot 24$ h)		Moisture barrier	WVTR, g/($m^2 \cdot 24$ h)		Thermal barrier	WVTR, g/($m^2 \cdot 24$ h)		Comfort lining	WVTR, g/($m^2 \cdot 24$ h)	
	Mean	Std.		Mean	Std.		Mean	Std.		Mean	Std.
A1	7445.15	0.05	B1	9030.43	0.05	C1	7501.77	0.03	D1	8747.35	0.02
A2	7303.61	0.04	B2	8973.82	0.05	C2	6426.04	0.04	D2	8832.27	0.01
A3	8690.73	0.03	B3	7105.45	0.04	C3	7020.52	0.04	D3	8152.87	0.01
A4	7558.39	0.05	B4	8407.64	0.05	C4	6454.35	0.04			
A5	8351.03	0.05	B5	2292.99	0.01	C5	7218.68	0.04			
A6	7360.23	0.02				C6	7020.52	0.05			
A7	8888.89	0.04				C7	6765.75	0.02			
A8	7558.39	0.04				C8	7303.65	0.01			
A9	9030.43	0.04				C9	7728.24	0.05			
						C10	7530.08	0.03			

Table 4. *Test results of orthogonal layout with 3 factors and 4 levels.*

No.	A	B	C	Error	Fabric assemblies	WVTR, g/($m^2 \cdot 24$ h)		No.	A	B	C	Error	Fabric assemblies	WVTR, g/($m^2 \cdot 24$ h)	
						Mean	Std.							Mean	Std.
Z1	1	1	1	1	A1+B1+C1+D1	6510.97	0.04	Z9	3	1	3	4	A5+B1+C5+D1	6142.96	0.03
Z2	1	2	2	2	A1+B2+C2+D1	5803.26	0.02	Z10	3	2	4	3	A5+B2+C7+D1	5605.10	0.01
Z3	1	3	3	3	A1+B3+C5+D1	5888.18	0.03	Z11	3	3	1	2	A5+B3+C1+D1	5406.94	0.03
Z4	1	4	4	4	A1+B4+C7+D1	5605.07	0.04	Z12	3	4	2	1	A5+B4+C2+D1	5888.18	0.05
Z5	2	1	2	3	A3+B1+C2+D1	6001.42	0.02	Z13	4	1	4	2	A9+B1+C7+D1	6142.96	0.03
Z6	2	2	1	4	A3+B2+C1+D1	6029.72	0.02	Z14	4	2	3	1	A9+B2+C5+D1	6001.42	0.02
Z7	2	3	4	1	A3+B3+C7+D1	5633.40	0.02	Z15	4	3	2	4	A9+B3+C2+D1	5690.02	0.02
Z8	2	4	3	2	A3+B4+C5+D1	5746.64	0.02	Z16	4	4	1	3	A9+B4+C1+D1	6001.42	0.05

Table 5. *Variance analysis of orthogonal layout with 3 factors and 4 levels.*

Factor	S (Sum of deviation Square)	f (Degree of freedom)	V (Mean square)	F (F-ratio)	Sig.
A	34058.42721	3	11352.80907	0.55	
B	457985.674	3	152661.891	7.39	**
C	88151.2234	3	29383.7411	1.42	
Error	185918.944	9	20657.6604		

*** Variance is significant at the 0.01 level (2-tailed).*

Table 6. *Test results of orthogonal layout with 3 factors and 2 levels.*

No.	A	B	A×B	C	A×C	B×C	Error	WVTR, g/($m^2 \cdot 24$ h)	
								Mean	Std.
Y1	1	1	1	1	1	1	1	5732.48	0.01
Y2	1	1	1	2	2	2	2	5726.82	0.05
Y3	1	2	2	1	1	2	2	5794.76	0.02
Y4	1	2	2	2	2	1	1	5794.76	0.01
Y5	2	1	2	1	2	1	2	5169.14	0.04
Y6	2	1	2	2	1	2	1	5562.63	0.02
Y7	2	2	1	1	2	2	1	5208.78	0.04
Y8	2	2	1	2	1	1	2	5763.62	0.04

Test results of multi-layered samples

Test results of orthogonal layout with 3 factors and 4 levels

As regards the test of the 3 factor and 4 level orthogonal layout, the results of WVTR for the multi-layered samples are shown in ***Table 4***. It was known by variance analysis (***Table 5***) that the moisture barrier contributed most to the multi-layered fabric system's WVTR. Because the disparity among the moisture barrier fabrics was bigger than among the other layers, the effect of a wide gap among the moisture barrier samples selected could not be excluded. The orders of the effect at various levels of these factors on the multi-layered samples concluded from the orthogonal layout were A9>A3>A1>A5, B1>B2>B4>B3, C5>C1>C2>C7. In addition, the orders of the outer shell and thermal barrier were different from those of the single layer WVTR test.

Table 7. *Variance analysis of orthogonal layout with 3 factors and 2 levels.*

Factor	S (Sum of deviation Square)	f (Degree of freedom)	V (Mean square)	F (F-ratio)	Sig.
A	226012.72	1	226012.72	99.26	**
B	17190.49	1	17190.49	7.55	
A×B	1523.614	1			
C	111079.6	1	111079.6	48.79	*
A×C	113764.2	1	113764.2	49.96	*
B×C	3486.982	1	3486.982	1.53	
Error	3030.198	1			
Error Δ	4553.812	2	2276.906		

*** Variance is significant at the 0.01 level (2-tailed).*
** Variance is significant at the 0.05 level (2-tailed).*

Table 8. *Correlation analysis of the WVTR of the fabric assemblies and component fabrics.*

		Assembly	Outer shell	Moisture barrier	Thermal barrier	Component with minimum WVTR
Assembly	Pearson Correlation	1	–.103	.566**	–.069	.064
	Sig. (2-tailed)		.631	.004	.748	.765
	N	24	24	24	24	24
Outer shell	Pearson Correlation	–.103	1	.088	.024	.051
	Sig. (2-tailed)	.631		.683	.910	.814
	N	24	24	24	24	24
Moisture barrier	Pearson Correlation	.566**	.088	1	.038	.223
	Sig. (2-tailed)	.004	.683		.860	.296
	N	24	24	24	24	24
Thermal barrier	Pearson Correlation	–.069	.024	.038	1	.958**
	Sig. (2-tailed)	.748	.910	.860		.000
	N	24	24	24	24	24
Component with minimum WVTR	Pearson Correlation	.064	.051	.223	.958**	1
	Sig. (2-tailed)	.765	.814	.296	.000	
	N	24	24	24	24	24

*** Correlativity is significant at the 0.01 level (2-tailed).*

Test results of orthogonal layout with 3 factors and 2 levels

Test results of the orthogonal layout [10] with 3 factors and 2 levels with respect to interaction are shown in ***Table 6***. The couple in the outer shell fabrics (A1 and A3), in the moisture barrier fabrics (B3 and B4) and in the thermal barrier fabrics (C1 and C2) had a very small WVTR difference, which was about 1100-1300 g/$(m^2 \cdot 24h)$. Based on this, a variance analysis was undertaken, shown in ***Table 7***, which indicated that the outer shell gave the greatest contribution of the 4 layers, while the outer shell, thermal barrier and the interaction of the two layers affected the whole WVTR of the multi-layered fabrics systems significantly. The order of the effect at various levels of these factors on the multi-layered fabric assembly concluded from the orthogonal layout were A1>A3, B4>B3, and C2>C1. In addition, the orders of the outer shell and thermal barrier were still different from that of the single layer WVTR test.

Correlation analysis of the WVTR of the fabric assemblies and component fabrics

Analysing the results of the two test schemes above, the total WVTR of the fabric assemblies was much lower than that of the single component fabrics. The total WVTR of the multi-layered fabric system had a positive correlation with the moisture barriers' WVTR at the 0.01 confidence level; however, the correlation coefficient was just 0.556, which meant that the linear correlation was not significant (***Table 8***). Therefore, it was not sufficient to evaluate the water vapour permeability of the multi-layered fabric system only using the WVTR of the moisture barrier. Besides, the correlation between the total WVTR of the multi-layered fabric system and the minimum WVTR of the component fabrics, which were mainly presented as thermal barriers, in each assembly was not significant either, having been judged by the correlation coefficient of 0.064. Therefore, the total water vapour permeability of the fabric assemblies was not determined by the minimum WVTR of the component fabrics in each assembly.

It could be concluded that water vapour permeation was a complicated process influenced by many factors, therefore it could not be evaluated by simply using any single component fabric's WVTR. When evaluating the heat and moisture transfer property of firefighter turnout clothing, the actual wearing status and choice of multi-layered fabric system as a test object should be carefully considered. If an experimental environment is accessible to simulate the coupling effect of heat and moisture transmission close to that in the wearing status, a sweating hot plate is the best way to measure the total heat loss or water vapour resistance of the multi-layered fabric systems of firefighter turnout clothing. Furthermore, the total heat loss (THL) adopted by NFPA1971-200 and the water vapour resistance adopted by EN469-2005 are more comprehensive and appropriate than the water vapor resistance of the moisture barrier adopted in GA10-2002.

Conclusions

In this study several representative outer shells, moisture barriers, thermal barriers and comfort lining fabrics were chosen from firefighter turnout clothing fabrics currently used, and their water vapour permeability was investigated in terms of Standard GA10-2002 . The experimental results demonstrated that the average WVTR of each component layer fabric had the following order: comfort lining > moisture barrier > outer shell > thermal barrier. In addition, the thermal barrier was different from the other 3 layers, playing a special role in the WVTR of the multi-layered fabric systems. However, the outer shell, moisture barrier and comfort lining had no distinct dissimilarity.

In view of the requirement for different component fabric combinations to be used in firefighter turnout clothing, orthogonal layout tests were undertaken. The results showed that the moisture barrier had the greatest effect on the WVTR of the multi-layered fabric systems. Excluding the dissimilarity between the various layers, the outer shell contributed the most of the four layers, while the outer shell, thermal barrier and their interaction affected the whole WVTR of the multi-layered fabric systems significantly. An integrated correlation was analysed for the whole WVTR of the fabric assemblies and various component layers, which showed that the total WVTR had a positive correlation with that of the moisture barrier, but with a low linear correlation coefficient of 0.556 at a 0.01 confidence level. Hence it was not sufficient to evaluate the water vapour permeability of the multi-layered fabric system with just the WVTR of the single moisture barrier.

The water vapour permeability of the multi-layered fabric system used in firefighter turnout clothing was complicated and influenced by many factors. Using a sweating hot plate to measure the heat and moisture transfer property of the multi-layered fabric system was a direct and reliable method for evaluating the comfort performance of the fabric assemblies. ❑

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