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Correlation of Bench Scale and Manikin Testing of Fire Protective Clothing with Thermal Shrinkage Effect Considered

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Abstract: Bench scale test and flame manikin test are two typical methods to evaluate the thermal protection provided by flame resistant fabrics or clothing. In this paper, the correlation between the test results of the two protocols was investigated. A group of fabrics commonly used in fire protective clothing were evaluated by a thermal protective performance (TPP) tester. Conditions with or without an air spacer were applied. Protective performance of the garments made of these fabrics with identical design feature was evaluated by a flame manikin testing system. Portable 3D body scanning technique was firstly used to characterize the air gap size change between the garment and manikin after flash fire exposure. The results showed that there was no significant correlation between the bench scale test and flame manikin test results in terms of TPP value and percent body burn. Thermal shrinkage which was not included in the bench scale test was demonstrated to be a key factor contributing to the weak correlation. It significantly decreased the air gap size between the garment and manikin and greatly affected the heat transfer after the flash fire exposure had ceased in the manikin test. Besides the TPP value, thermal shrinkage was suggested to be considered in the bench scale test as a parameter to predict the thermal protective property of flame resistant fabrics when made into garments.

Keywords: Bench scale test, Flame manikin test, TPP value, Percent body burn, Thermal shrinkage, Portable 3D body scanning technique

Introduction

Firefighters, soldiers and workers in the petroleum or metallurgy industries are always threatened by flash fire or high temperature. Fire protective clothing is needed to protect them against the heat hazards [1,2]. Qualified fire protective clothing should be flame resistant, thermal insulating and with good thermal dimensional stability [3,4]. A number of standards and apparatus to evaluate the thermal protective property of fabrics or clothing have been developed, which can be broadly classified into bench scale test and flame manikin test. Bench scale test is conducted on a sample of the fabric that an ensemble constructed from. Single or multilayer fabrics are exposed to high heat flux source and a heat senor is put on the back of the fabric to record the temperature change. The TPP value as described in the NFPA 1971 [5] or time to cause a 24 ^{o}C temperature rise as described in the ISO 9151 [6] is used as an criteria to evaluate the thermal protective property of the fabric sample. Flame manikin test as specified in ASTM F1930 [7] and ISO 13506 [8] is carried out based on an instrumented manikin. The manikin is human body like with more than one hundred of sensors equipped with. Under a simulated flash fire condition, the skin temperature change of the clothed manikin is recorded by these sensors. According to the temperature profile, the percent body burn suffered by the manikin is predicted. Because of the high cost and the complexity of flame manikin test, bench scale test is more widely used as it is simpler, quicker and less costly.

Flame resistant fabric and garment producers and end users are always interested in whether or not the performances measured in bench scale test are indicative of the performances in flame manikin test. The correlation between bench scale test and flame manikin test has been discussed in some literatures [9-11]. However, due to the insufficient sample size, the different exposure conditions (heat source, garment design) and analytical angles, there are no uniform conclusions on the correlation between the two test protocols. In these studies, the effect of air gap between the fabric and sensor was always considered. The heat flux sensor was placed in contact with the test specimen or with a distance of 6.4 mm behind the fabric to simulate the air gaps distributed between the garment and manikin. A 3D body scanner was also used to characterize the air gaps entrapped in the garment before exposure. The correlation between bench scale and full scale tests was discussed in light of air gap. However, it should be noted that, the air gap size remains constant throughout the bench scale test process, while it may be changed in the manikin test due to thermal shrinkage of the fabric. Therefore, not only the initial air gap size but also the air gap size after exposure should be considered when correlating the two test protocols.

The main objective of this paper is to identify whether or not the results of bench scale test can be used to predict the thermal protective property of flame resistant fabrics when made into garments providing the test conditions and garment

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designs are all identical. For this purpose, a group of flame resistant fabrics made of different fibers and with different textile properties were examined in both bench scale test and manikin test with controlled garment design. Correlation between the typical results of the two test protocols was analyzed in terms of TPP value and percent body burn. The air gaps entrapped in the protective clothing before and after exposure were measured by a portable 3D body scanner. Thermal shrinkage of the garment was identified by the air gap size change and its effect on the correlation between the two test protocols was investigated. The research findings were supposed to provide further understanding on the correlation between bench scale and full scale tests and give more references to the producer and end users for the evaluation and selection of flame resistant fabrics.

Materials and Experimental Protocols

Materials

Eight flame resistant fabrics typically used in fire protective clothing were employed in this study. The detailed information of all samples is shown in Table l. The thickness was measured according to ASTM D1777-96 [12] under a pressure of 1 kPa. The density was calculated by the weight divided by thickness. Garment samples of each kind of fabric were also prepared for the flame manikin test. They were all single layer coveralls with identical style and size, meeting the requirements specified in ISO 13506 for material evaluation. Both the fabric samples and garment samples were preconditioned in a climate chamber (20±2 ^{o}C and 65±5 % RH) for 24 h before the test.

Bench Scale Test

Thermal protective performance (TPP) test is the most significant and widely used bench scale test method for evaluating the protection of firefighter ensembles. In this study, a TPP tester in accordance with the NFPA 1971 standard was used to evaluate the performances of the candidate fabrics. The type of the tester was CSI-206 (Custom Scientific Instrument Corporation, USA), showing schematically in

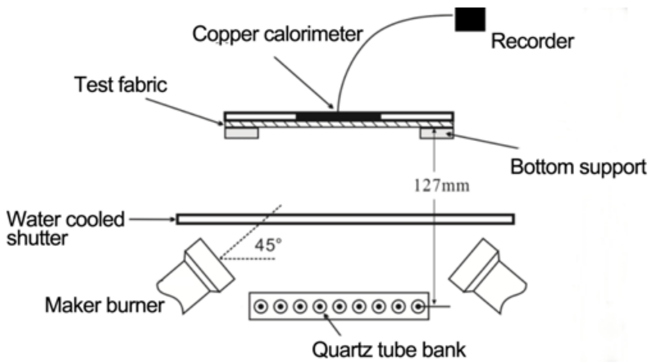

Figure 1. Schematic of TPP testing apparatus.

Figure 1. It consisted of two Meker burners and a bank of nine quartz tubes to provide a combined flame and radiant heat source. The fabric sample with a dimension of 15 by 15 cm was positioned horizontally on the supporter. A copper calorimeter was put on the back of the sample to measure the temperature change. A metal spacer was used to position the calorimeter above the fabric if an air gap is desired. The testing specimen was insulated from heat source before the test by an automatic water-cooled shutter to ensure accurate exposure time. Stoll curve [13] was applied to predict the time to second-degree burn. For this research, fabric samples were exposed to a heat flux of 84 kW/m^2, with 50 % radiative and 50 % convective heat flux, calibrated by a Hy-Cal radiometer (No.R8015-C15-072). Tests were conducted with zero or 6.4 mm air gaps. For each configuration, five specimens of each kind of fabric were tested. The typical result of TPP test was TPP value (the time to reach second-degree burn multiplied by 2.0).

Flame Manikin Test

A flame manikin testing system [14], meeting the technical requirements of both ASTM F1930 and ISO 13506, was employed to evaluate the thermal protection provided by the coveralls. The manikin was 5.74 feet tall with a size conformed to the average dimension of Chinese adult males. There were 135 heat flux sensors uniformly distributed over the manikin

Table 1. Description of the testing samples

Code	Composition	Weave	Weight (g/m^2)	Thickness (mm)	Density (g/cm^3)
F1	Nomex® IIIA	plain	166	0.33	0.50
F2	Nomex® IIIA	twill	198	0.42	0.47
F3	Nomex® IIIA	plain	250	0.52	0.48
F4	98/2 PSA/CF	plain	158	0.41	0.39
F5	93/5/2 PSA/Twaron®/CF	twill	196	0.57	0.34
F6	93/5/2 PSA/Kevlar®/CF	twill	261	0.52	0.50
F7	60/40 Kevlar®/PBI	plain	195	0.40	0.50
F8	PI	twill	211	0.54	0.39

CF is carbon antistatic fiber, PSA is polysulfonamide, PBI is polybenzimidazole, and PI is polyimide.

surface. Six groups of propane gas burners (12 in total) were mounted around the manikin to generate diffusion flames. Temperature at the manikin surface and its variation with time during a test were determined by a computer-controlled data acquisition system. The burn injury suffered by the manikin was calculated based on the work of Pennes [15] and Henriques [16]. For this research, the exposure conditions were conformed to the requirements specified in ASTM F 1930 and ISO 13506 for single layer garment test. The exposure time was 4 s and the average incident heat flux was 84 kW/m^2. No underwear was worn. Data acquisition was more than 60 s from the beginning of the exposure. Pictures were taken before and after the burns and video cameras in front of and behind the manikin captured the burn process. Three replicates of garment made of each kind of fabric were tested. The predicted percent body burn was used to analyze the thermal protective property of the candidate fabrics when made into garments.

Thermal Shrinkage Determination

Fire protective clothing made of inherent flame resistant materials is easy to shrink when exposed to flash fire, causing the size change of air gaps entrapped in the clothing.

Figure 2. The portable 3D body scanner and a scanning scene in the flame chamber.

In this study, a portable 3D body scanner (Fabrate, LLC, USA) was employed to measure the air gap size change (Figure 2). It consisted of four off-the-shelf Microsoft Kinect sensors. Each of the two sensors was mounted on one stand to acquire 3D data clouds of the front and back surfaces of a human body. The maximum precision of the sensor was 1 mm and it was not sensitive to light, color and texture condition. Together with the compact and portable characters of the system structure, it could be mounted into the flame chamber. To prevent the high ambient temperature during the exposure test, scanning sensors were put into two heat insulation boxes. With this portable body scanner, the nude manikin and clothed manikin before and after exposure were scanned. By superimposing the 3D images of clothed manikin over the nude manikin, the air gap size could be calculated. This was accomplished in the professional software Geomagic Control (Geomagic, USA). Two parameters, air gap thickness reduction (SR_{ag}) and air volume reduction (SR_v), were used to characterize the thermal shrinkage of the experimental garments after exposure.

Statistical Analysis

The SPSS software 16.0 was applied for the statistical analysis. One-way analysis of variance (ANOVA) was conducted on the protective performance and thermal shrinkage of the testing samples, followed by Dunnett T3 multiple comparison test. Spearman correlation was used to analyze the relationship between the results of TPP test and manikin test, thermal shrinkage and thermal protective property. $P<0.05$ was considered to indicate significant difference or correlation.

Results and Discussion

Performances Assessed in Bench Scale Test and Manikin Test

Table 2 shows the second-degree burn time and the TPP value in the bench scale test with or without an air gap. The

Table 2. Protective performance of fabrics in the bench scale test

Fabric code	No air gap		6.4 mm air gap	
	Second-degree burn time (s)	TPP value (cal/cm^2)	Second-degree burn time (s)	TPP value (cal/cm^2)
F1	4.0 (0.1)	8.0 (0.2)^d	6.4 (0.1)	12.9 (0.2)^c
F2	4.6 (0.1)	9.1 (0.2)^c	7.3 (0.1)	14.5 (0.1)^b
F3	5.4 (0.1)	10.6 (0.2)^{ab}	8.1 (0.1)	16.2 (0.2)^a
F4	4.5 (0.1)	8.9 (0.1)^c	6.4 (0.2)	12.7 (0.3)^c
F5	4.9 (0.2)	9.8 (0.4)^{abcd}	7.3 (0.1)	14.6 (0.1)^b
F6	5.7 (0.1)	11.3 (0.2)^a	8.1(0.1)	16.1 (0.2)^a
F7	4.1 (0.1)	8.2 (0.1)^d	6.9 (0.1)	13.6 (0.1)^c
F8	5.0 (0.1)	10.0 (0.1)^b	6.9 (0.1)	13.8 (0.2)^c

All values are means for five specimens with standard deviation in brackets. ^{a,b,c,d}In each column, means with the same superscript letter do not differ significantly when subjected to the Dunnett T3 pair wise multiple comparison test ($p<0.05$).

difference in the predicted protection provided by the candidate fabrics was significant in both the two test configurations (p<0.001). The multiple comparison test results showed that the candidate fabrics provided four levels of thermal protection in the contact test configuration and three levels of thermal protection in the spaced test configuration. In the contact test configuration, the TPP value was in the range of 8.0-11.3 cal/cm^2. F1 showed the smallest TPP value and F6 provided the best thermal protection. From Table 1, F1 ranked the smallest thickness and F6 had the largest gram weight. Statistical results showed that the TPP value had significant correlation with both fabric thickness (r=0.778, p<0.05) and weight (r=0.905, p<0.01). When there was 6.4 mm air gap, thermal protection of all the candidate fabrics was significantly improved (p<0.001). The TPP value was between 12.9 cal/cm^2 and 16.2 cal/cm^2. F3 and F6, which had the largest gram weight, provided the best protection. F1 and F4, which had the smallest gram weight, provided the least thermal protection. It showed that the fabric weight also had significant correlation with TPP in the spaced test configuration (r=0.905, p<0.01). The bench scale test results revealed that the air gap included between the fabric and sensor could slow down the heat transfer and significantly improve the TPP of fabric samples. While for the test configuration without air gap, it would take less time for the senor to reach second-degree burn. It was also anticipated that the garments with zero or smaller air gap size would develop more body burn in the flame manikin test.

The percent body burn and total absorbed energy during the flame manikin test for the experimental garments are shown in Table 3. The results showed that the tested garments made of different materials provided distinct thermal protection upon flash fire (p<0.001). Generally, the garment samples could be divided into four or five categories based on the protective performance. The total percentage of burn injury was in the range of 33.8-78.2 %. F4 developed the maximum percentage of burn injury (78.2 %) and F7 provided the best thermal protection (33.8 %). The total energy transferred through the garment to the manikin ranged from 138.8 to 200.4 kJ/m^2. And it had significant correlation with the total percentage of burn injury (r=0.976, p<0.01). However, unlike in the bench scale test, no significant correlation was observed between the thermal protective property and fabric weight or thickness. Although the gram weight and thickness of F2 was larger than that of F1, it generated 10 % more body burn.

Correlation of Bench Scale Test Results with Manikin Test Results

TPP value of a fabric is one indication of its protective ability in terms of the maximum amount of heat energy per unit area the fabric can withstand without causing second-degree burn. The predicted percent body burn indicates the area that manikin surface will suffer irreversible burn when dressed in protective garment under flash fire. Both TPP value and percent body burn are acknowledged as the most direct and effective parameters reflecting thermal protective property. Although the test protocol and evaluation standard of bench scale and flame manikin methods are different, we suppose that if the test condition and garment design are identical for all the samples, the one with higher TPP value should exhibit lower total percentage of burn injury. To verify this assumption, a correlation analysis between the TPP value and percent body burn was conducted based on the experimental results. Figure 3 shows the scatterplot between the bench scale test results and manikin test results. It was observed that the negative correlation between them was not significant. The statistical analysis results further confirmed that the percent body burn had no significant correlation with TPP value (r=-0.238, p>0.05 for contact test configuration; r=-0.405, p>0.05 for spaced test configuration). It indicated that the predicted burn injury did not absolutely decrease with the increase of TPP value as expected. In the bench scale test, for the aramid fabric F1 and F2, the TPP value of F1 was lower than that of F2 in both the contact and spaced test configurations. However, in the manikin test, the burn injury developed by F1 was 10 % lower than that of F2. For the fabric F7, although it had relative smaller TPP in the bench scale test, it provided the best thermal protection in

Table 3. Percent body burn and total absorbed energy of the tested garments

Fabric code	Second-degree burn (%)	Third-degree burn (%)	Total burn injury (%)	Total absorbed energy (kJ/m^2)
F1	55.0 (2.9)	4.4 (1.5)	59.3 (2.3)^{c}	174.0 (1.8)^{c}
F2	58.9 (1.3)	11.8 (0.8)	70.5 (2.0)^{ab}	200.3 (2.4)^{b}
F3	39.2 (0.5)	3.4 (0.2)	42.6 (0.5)^{d}	165.5 (0.2)^{cd}
F4	57.7 (2.4)	20.5 (3.2)	78.2 (0.9)^{a}	246.4 (2.5)^{a}
F5	63.9 (1.2)	9.5 (0.1)	73.3 (1.2)^{b}	200.4 (0.9)^{b}
F6	40.6 (3.2)	2.3 (1.3)	42.9 (2.4)^{d}	163.9 (1.0)^{d}
F7	33.8 (6.0)	0.0 (0.0)	33.8 (6.0)^{cd}	138.8 (0.8)^{e}
F8	54.7 (2.3)	1.1 (0.5)	56.0 (2.5)^{cd}	166.3 (2.9)^{cd}

All values are means for three specimens with standard deviation in brackets. ^{a,b,c,d,e}In each column, means with the same superscript letter do not differ significantly when subjected to the Dunnett T3 pair wise multiple comparison test (p<0.05).

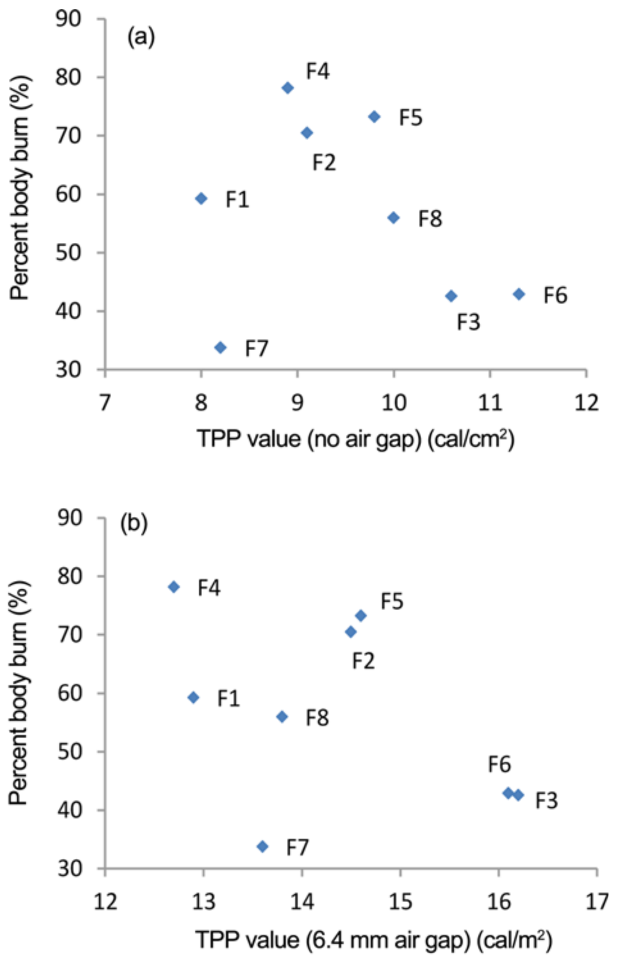

Figure 3. Scatterplot; (a) the results of bench scale test without air gap and flame manikin test results and (b) the results of bench scale test with air gap and flame manikin test results.

the manikin test. Base on the above analysis, when comparing a group of flame resistant fabrics, the thermal protective property of a fabric evaluated by the bench scale test is not absolutely indicative of its performance in the manikin test. By comparing the setup of the two tests, it was found that the major uncontrolled factor was the air gap size. In the TPP test, the fabric sample was fixed on the supporter and the air gap size between the fabric and sensor was constant throughout the test process. While in the manikin test, the fabric could shrink freely and the air gap size between the garment and manikin surface could be changed. Therefore, it is necessary to quantify the thermal shrinkage of garments made of different materials and investigate its effect on the manikin surface temperature change and thermal protective property.

Effect of Thermal Shrinkage on the Correlation between Bench Scale Test and Manikin Test

Thermal Shrinkage Magnitude of the Tested Garments

Figure 4 shows the 3D images of the nude manikin and the manikin dressed in F2 before and after exposure. It was obvious that the garment size was greatly reduced after a 4 s exposure to flash fire. By superimposing the clothed manikin over the nude manikin and adjusting the transparency of the 3D image of the clothed manikin, the ease allowance of the garment was also clearly shown in Figure 4. It could be seen that the garments made of Nomex shrank closely to the manikin body after exposure and the air space between the garment and manikin body was sharply reduced due to the decrease of ease allowance.

Table 4 shows the average air gap thickness and air volume of the tested garments before and after exposure and thermal shrinkage were also calculated. It was found that thermal shrinkage evaluated by average air gap thickness reduction (SR_{ag}) and air volume reduction (SR_v) had good consistency (r=0.976, p<0.01). The tested garments made of different materials generally showed significant difference in thermal dimension stability (p<0.001). F4 showed the largest thermal shrinkage with 58 % average air gap thickness reduction and 68.64 % air volume reduction. F7 and F8 showed good thermal dimensional stability with less than 5 % thermal shrinkage. For the PSA garments (F4, F5 and F6), thermal shrinkage decreased with the increase of fabric weight. For the Nomex garments F1 and F2, F1 exhibited a more compact fabric structure with larger density than that of F2, which might account for the lower shrinkage of F1. And for the fabrics with similar gram weight, PSA fabrics generally showed more severe shrinkage compared with other kinds of fabrics. It indicated that fabric thermal dimensional stability depended on several parameters, such as the fiber type, the fabric construction or the combined effect of these parameters.

Correlations among Thermal Shrinkage, Temperature Change and Thermal Protective Property

Before discussing the effect of thermal shrinkage on

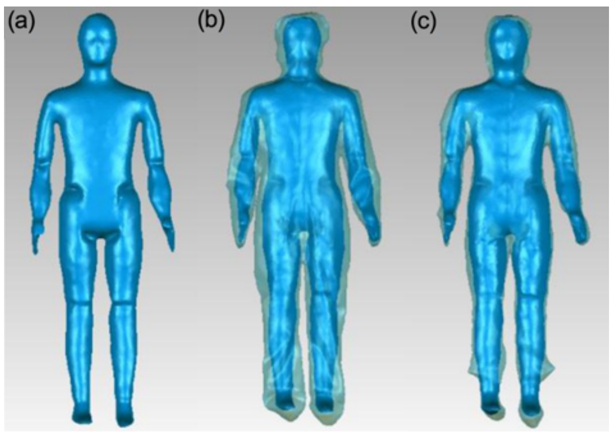

Figure 4. 3D images of the nude manikin and manikin dressed in garment F2 (Nomex® IIIA, 198 g/m^2); (a) nude manikin, (b) clothed manikin before exposure, and (c) clothed manikin after exposure.

Table 4. Thermal shrinkage of the experimental garments characterized by average air gap thickness reduction (SR_{ag}) and air volume reduction SR_v

Code	Average air gap thickness (mm)			Air volume (dm^3)		
	Before exposure	After exposure	SR_{ag} (%)	Before exposure	After exposure	SR_v (%)
F1	25.00 (0.93)	14.84 (0.58)	40.58 (4.54)^c	42.51 (1.13)	22.22 (1.26)	47.76 (1.68)^c
F2	24.42 (0.53)	11.66 (0.62)	52.28 (1.69)^b	40.65 (1.80)	14.70 (0.33)	63.77 (2.28)^b
F3	24.75 (0.77)	17.95 (0.70)	27.50 (0.99)^d	43.32 (0.80)	30.91 (0.52)	28.63 (1.67)^d
F4	24.59 (0.73)	10.31 (0.78)	58.00 (3.97)^a	42.19 (1.11)	13.22 (0.57)	68.64 (2.00)^a
F5	24.93 (0.37)	11.18 (0.59)	55.18 (1.68)^{ab}	43.39 (1.09)	15.63 (0.04)	63.97 (0.99)^b
F6	25.76 (0.45)	19.34 (0.53)	29.94 (2.01)^d	44.02 (1.25)	32.81 (0.70)	25.45 (0.73)^e
F7	26.17 (0.54)	25.09(1.16)	4.15(2.62)^e	43.64 (0.40)	43.01 (0.80)	1.43 (2.02)^f
F8	25.94 (1.74)	25.75 (1.89)	0.76 (0.68)^e	45.16 (1.96)	44.12 (2.15)	2.31 (0.77)^f

All values are means for three specimens with standard deviation in brackets. ^{a,b,c,d,e,f}In each column, means with the same superscript letter do not differ significantly when subjected to the Dunnett T3 pair wise multiple comparison test (p<0.05).

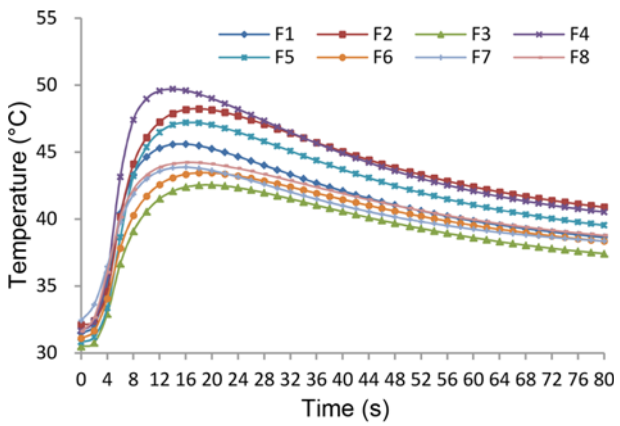

Figure 5. Temperature change of the manikin surface in an exposure test.

thermal protective property, the temperature change of manikin surface in the exposure test was examined, as shown in Figure 5. It was observed that, the temperature responded slowly during the 4 s exposure and continued to rise for a period of time after the gas burners were turned off; at the time of 12-18 s, the temperature rose to the peak and then began to decrease slowly. Generally, the temperature change could be classified into three periods, the temperature rise during the 4 s exposure (R1), the temperature rise from the point of exposure stop to the peak value (R2) and the temperature decline from the peak value to the last point of record (R3). Table 5 presents the temperature change rate in each period. The correlations of thermal shrinkage and percent body burn with temperature change are shown in Table 6. It was found that both the average air gap thickness reduction (SR_{ag}) and air volume reduction (SR_v) had significant correlation with the temperature change in R2 and R3 but no significant correlation with that in R1. According to the video taken in the manikin test, thermal shrinkage generally started 2 s later after the initiation of the exposure, for which there was no significant correlation between thermal shrinkage and the temperature change during the exposure. From Table 6, it was also observed that the percent body burn was related closely to the temperature change after the exposure had

Table 5. Temperature change rate in different periods (°C/s)

Fabric code	R1	R2	R3
F1	0.91 (0.37)	0.96 (0.07)	0.11 (0.00)
F2	0.62 (0.36)	1.00 (0.04)	0.12 (0.00)
F3	0.61 (0.03)	0.60 (0.01)	0.08 (0.00)
F4	1.05 (0.52)	1.40 (0.08)	0.14 (0.00)
F5	0.64 (0.45)	1.11 (0.06)	0.12 (0.00)
F6	0.74 (0.01)	0.64 (0.02)	0.08 (0.00)
F7	1.01 (0.65)	0.64 (0.15)	0.09 (0.00)
F8	1.10 (0.01)	0.66 (0.01)	0.09 (0.00)

All values are means for three specimens with standard deviation in brackets. R1 is temperature rise rate during the 4 s exposure, R2 is the temperature rise rate from the point of exposure stop to the peak value, and R3 is the temperature decline rate from the peak value to the last point of record.

Table 6. Spearman correlation among thermal shrinkage, temperature change and percent body burn

	TPBI	SR_{ag}	SR_v	R1	R2	R3
TPBI	1.0	0.833*	0.905**	0.095	0.958**	0.885**
SR_{ag}	0.833*	1.0	0.976**	-0.286	0.778*	0.788*
SR_v	0.905**	0.976**	1.0	-0.238	0.814*	0.788*

*Significant at 0.05 level and **significant at 0.01 level. TPBI is total percentage of predicted burn injury, SR_{ag} is thermal shrinkage characterized by air gap thickness reduction, SR_v is thermal shrinkage characterized by air volume reduction. R1 is temperature rise rate during the 4 s exposure, R2 is the temperature rise rate from the point of exposure stop to the peak value, and R3 is the temperature decline rate from the peak value to the last point of record.

ceased but had no significant correlation with the temperature change during the exposure. This was understandable. From Figure 5, the average temperature of the skin was below 44 ^{o}C at the end of the 4 s exposure, which indicated that a number of sensors had not reached the temperature threshold to cause irreversible burn injury. Based on the above analysis, the percent body burn mainly depended on the temperature change after the exposure had ceased, whereas the heat transfer in this period was significantly affected by thermal shrinkage. Therefore, thermal shrinkage must affect the thermal protection provided by the tested garments. From Table 6, both SR_{ag} and SR_v had significant correlation with percent body burn.

Although the test condition and design of the experimental garments were identical, they did show different magnitude of thermal shrinkage which would affect their thermal protective property. Thus, the fabric with better TPP did not necessarily rank better thermal protective property when made into garment if it shrank severely after heat exposure. In Lee's study [10], it was found that the bench scale test at zero air gap test conditions was capable of predicting burn injuries of the areas with zero or smaller air gaps of manikin test; whereas for the areas on the manikin with larger air gaps, bench scale test with spaced test conditions underestimated the manikin test results. Although the author did not give explanation for this difference, the research results in this paper might be able to account for it. As the testing samples were all Nomex-based military protective clothing, the original larger air gaps might decrease to less than 6.4 mm after exposure due to the severe shrinkage of Nomex fabrics observed in this research. Therefore, the burn injury in the manikin test was more severe than that in the bench scale test with unchanged 6.4 mm air gap size. Not only the bench scale test without thermal shrinkage considered would fail to indicate the results of manikin test, the heat transfer models of fire protective clothing without thermal shrinkage considered would overestimate the actual performance of the garment as well, which had been proved in a previous study [4]. To improve the precision of the modeling, the change of air gap size between the garment and manikin or other shrinkage parameters such as shrinkage time and rate could be involved into the models. In addition, the effect of thermal shrinkage was also reflected on the correlation between the fabric weight and thermal protective property. Abbott [17] found that for the fabrics with better thermal dimensional stability, there was good correlation between the fabric weight and heat transfer, while for the fabrics which were easy to shrink, the correlation was worse. In the bench scale test, TPP value had significant correlation with fabric weight. While in the manikin test, no significant correlation was observed between percent body burn and fabric weight. This was in accordance with the findings of Abbott because thermal shrinkage occurred in the flame manikin test.

Conclusion

Correlation between the bench scale test and flame manikin test results was investigated in this study. It showed that there was no significant correlation between the TPP value and percent body burn. Thermal shrinkage of the garments could reduce the air gap size and significantly affected the heat transfer after the exposure had ceased. The garment with larger thermal shrinkage generally developed larger percentage of burn injury. However, the effect of thermal shrinkage was not included in the bench scale test. This difference in the test setup was proved to be a key factor contributing to the weak correlation between the results of bench scale and flame manikin tests. Therefore, when only the TPP value is used to evaluate the thermal protective property of flame resistant fabrics, the fabric producers and end users will be misled. It is suggested that thermal dimensional stability of the fabrics should be taken into consideration when predicting or comparing the thermal protective property of a group of fabrics. The fabric thermal shrinkage can be simply characterized by an image processing method proposed by the work of Li [18]. Besides, developing a device that incorporates the thermal shrinkage effect of fabric similar to the work of Crown [11] is another way to make the bench scale test results more indicative of the manikin test results. And it should be noted that, the testing samples used in this study were only single layer fabrics or garments, whereas there are usually three or four layers for the firefighters' protective clothing. Further study should be conducted to investigate the correlation between bench scale and manikin test results when multilayer samples were employed.

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