The Effects of Multiple Flame Exposures on Thermal Shrinkage and Thermal Protective Performance of Fabrics used in Firefighter Clothing

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Abstract. In firefighting situations, firefighters will encounter multiple flame exposures during go through the fireground several times. In this study, the effects of multiple flame exposures on thermal shrinkage and thermal protective performance of three fabrics used in firefighting clothing were investigated. The fabric surface morphology after flame exposure was obtained by a handy scanner, and further processed in ArcGis software. The thermal shrinkage of fabrics was characterized by ten shrinkage parameters and then quantified by using principal component analysis. The results showed that flame exposure frequency had influence on the thermal shrinkage of fabrics. As compared to several short-duration exposures, a long-duration continuous exposure resulted greater thermal shrinkage. The correlation analysis showed that there was no significant correlation between thermal shrinkage of the fabric and its thermal protective performance. The findings in this study indicated that the effects of multiple flame exposures on thermal shrinkage and thermal protective performance of firefighters clothing should be considered during clothing design and performance prediction.

1. Introduction

Reported by NFPA (National Fire Protection Association) [1], an estimated 58,250 firefighter injuries occurred in the line of duty in 2018, of which 39 percent occurred on the fireground. During the firefighting operations, the extreme heat environmental factors such as convection, radiation, conduction and steam on the fireground pose a fatal threat to the health and life of firefighters. Thermal protective clothing is serviced as an important equipment for industrial workers such as firefighters working in high-temperature hazardous environments, which can reduce thermal injuries by blocking the heat transfer from environment to human skin. Therefore, the performance of thermal protective clothing is crucial, whether before or after the exposure. As specified in the standard NFPA 1971 [2], the structural integrity of the clothing and the performance must be guaranteed, such as mechanical property, thermal insulation, and thermal protective performance.

However, most of the materials currently used in the outer shell of thermal protective clothing will shrink under the exposure of flash fire [3]. As has been proven in the previous literature [4], the clothing made of aramid fiber greatly shrank when its temperature reached 400°C in the flame exposure. And the temperature of a flame-resistant fabric was as high as 600°C under the laboratory flame exposure with 80kW/m² heat flux[5]. Thermal shrinkage will not only change the physical
properties of fabrics such as thickness [6] and mechanical strength [7–9], but also cause change in the shape of the clothing, which in turn will change the air gap under the clothing [10]. And the changes in the air gap will directly affect the heat transfer to the human skin, which in turn affects the overall thermal protective performance of the clothing [5,10,11].

The influences of thermal shrinkage on thermal protective performance were experimentally and numerically investigated in the previous literature. The thermal response in flash fire of the flame-resistant materials with different thermal stability were compared by Morse et al. [4]. And the results showed that the better the thermal stability of the fabric, the better the thermal protective performance. A new cylindrical device was developed by crown et al. to capture the effects of thermal shrinkage, and the TPP (thermal protective performance) test by using this cylindrical device showed that the fabric that shrunk had reduced thermal protective performance [12]. Ghazy [13] introduced a numerical model to demonstrate the crucial role of thermal shrinkage on the reduction of clothing protective performance. Therefore, it is necessary to quantify the thermal shrinkage of fabrics in order to accurately evaluate the thermal protective performance of clothing.

In terms of the characteristic of thermal shrinkage, it appears to be random and irregular, which makes it difficult to be quantitively characterized. In the standards of NFPA 1971 [2] and NFPA 2112 [14], thermal shrinkage resistance test is required to check changes in the lengths of latitude and longitude, which is defined as thermal shrinkage rate, by exposing the outer shell to 5 minutes of heat in a 260degC oven. However, this standard method is not suitable for the flash fire exposure, as the temperature of the flash fire is higher than 260 °C and the exposure duration is less than 5 seconds.

That means the thermal shrinkage rate measured by this method could not reflect the thermal shrinkage exposed to flash fire. In full-scale manikin test[15], the clothing shrinkage was characterized by measuring the change of clothing dimension in the key body parts. Li et al. [16] introduced an improved method in which the round markers were sealed on the garment before exposure. And after exposure, the dimension changes in various directions were calculated to characterize thermal shrinkage of garment. In fact, all the methods mentioned before focus on two-dimensional shape change, which is not enough to characterize three-dimensional shrinkage. With the developing of three-dimensional scanning technology and image-processing technology, Wang et al. [17] proposed more detailed parameters, namely garment surface area change and volume and thickness change of the air gaps, to characterize thermal shrinkage of the garment. In the fabric level, Li et al. [18] developed an innovative method to evaluate the 3D deformation of fabrics by using the ArcGis software, which was generally used in the geological area, and the heights and slope angles of the tags and crests was analyzed for the characterization of thermal shrinkage of fabrics.

Considering the actual fire scenes, firefighters must enter burning structures multiple times to search and rescue victims. It means thermal protective clothing will suffer multiple flame exposures and thus the influence of multiple flame exposures on the thermal shrinkage and thermal protective performance should be evaluated to determine whether the garment can be worn again in next firefighting emergency. However, most of the previous studies focused on single continuous exposure, the effect of multiple successive exposures on thermal shrinkage and thermal protection were seldom considered. In Lu et al.’s study[19], the tensile strength of fabrics after multiple radiation exposures were predicted. For the multiple flash fire exposures, the thermal protection retention of clothing was evaluated by Wang et al.[3]. This study mainly focused on giving an integrated quantitative value for the evaluation of thermal shrinkage of fabrics after multiple flame exposures, as well as the corresponding change of thermal protection.

In this study, the commonly used flame-resistant fabrics were exposed to multiple flash fire in bench-scale test. With 3D scanning and post-processing technology, ten parameters were extracted to characterize the thermal shrinkage of the fabrics. Further, the thermal shrinkage was synthetically evaluated using principal component analysis. In addition, the effect of thermal shrinkage due to repeated flash fire exposures on the protection provided by the fabrics was investigated. The research findings will provide guidance for the design and optimization of thermal protective clothing, and provide a theoretical basis for end users to evaluate whether the clothing can continue to be used.
2. Methodology

2.1. Materials
To prevent the dropping down of the samples from the support frame of testing device (TPP tester) into the fire, three fabrics were selected for their relatively lower shrinkage (Shrinkage rate is less than 5%) under flash fire exposure. And the shrinkage ratio was calculated based on the following Equation [18]:

\[
\text{Thermal shrinkage rate} = (1 - \frac{\text{Projection area of the burned fabrics}}{\text{Surface area before being burned}}) \times 100\%
\]

The fabrics were typically used as outer shell in firefighters’ protective clothing. And the detailed information is shown in Table 1. Kevlar/polybenzimidazole (PBI) and PI have intrinsic and permanent flame retardancy, while FR cotton is made of cotton with flame retardant finishing.

Table 1. Description of the test samples.

| Sample Code | Fabric       | Weave | Area density (g/m²) | Thickness (mm) | Color |
|-------------|--------------|-------|---------------------|----------------|-------|
| F1          | FR cotton    | twill | 350                 | 0.69           |       |
| F2          | Kevlar®/PBI  | plain | 195                 | 0.55           |       |
| F3          | PI           | twill | 211                 | 0.60           |       |

FR cotton: flame resistant cotton; Kevlar/PBI: Kevlar/polybenzimidazole; PI: polyimide.

2.2. Experimental protocol

2.2.1 Flame exposure of fabrics. The fabric samples were exposed to 84kW/m² heat flux with a mixture of 50% convective and 50% radiant heat flux. This was conducted on a TPP tester (CSI-206, Custom Scientific Instrument Corporation, USA), which can produce precise heat flux as prescribed in ISO 13506. Generally, a copper sensor was mounted on the inner surface of the specimen to measure its temperature rise exposed to heat source. In this study, the copper sensor was not used to simulate the natural wearing condition of clothing without gravity. According to the standards ISO 13506 and ASTM F 1930 for single layer thermal protective clothing testing, 3 seconds and 4 seconds were selected as the individual exposure duration in the repeated flash fire exposure, respectively. Each fabric sample was exposure to flame three times. On the other hand, the case of continuous flash fire exposure was conducted, in which 9 seconds and 12 seconds were set as the exposure durations. Three replicates were exposed for each case. All flame exposures and the subsequent TPP (Thermal protective performance) tests were summarized in Fig. 1.

![Figure 1](image1.png)

Figure 1. Experimental procedures for two different modes of flash fire exposure: (a) repeated flash fire exposures; (b) continuous flash fire exposure.

2.2.2 Thermal protective performance (TPP) Test. Thermal protective performance of the fabrics was evaluated by the TPP tester based on NFPA 1971. In generally, the copper calorimeter was placed contact with the sample or with a 6.4 mm distance to simulate the air gap between the clothing and human skin. In order to match the test condition of the flame exposure, the TPP test was conducted...
with 6.4 mm air gap spacer between the fabric and the testing copper sensor. In such condition, only the narrow area of the fabric edge was restricted by the sensor, and the heated area of the fabric was not affected by the pressure of the sensor, which was similar to the case of not using the sensor in the thermal shrinkage test of the fabrics. The time required to reach a second-degree skin burn was obtained using the Stoll curve of skin burn and the TPP value was determined by multiplying by 2.

2.2.3 Three-dimensional scanning and image-processing. A handy laser scanner (Handyscan 3D, Creaform, Canada) was used to measure the fabric surface morphology after the heat exposure. The 3D point cloud data obtained by the scanner was further processed in the Geomagic software to be optimized. As little information about thermal shrinkage could be obtained from in Geomagic, and the morphology of the shrunk fabric is similar to the sags and crests in geology, ArcGis (ESRI, US) software which is usually used in geological studies was used to analyze the images of the shrunk fabrics to quantify the thermal shrinkage of the fabrics [18].

2.3. Quantification and calculation of fabric thermal shrinkage

2.3.1 Characterization parameters of thermal shrinkage. Table 2 summarizes the characterization parameters of thermal shrinkage and the calculation method. Ten characterization parameters of thermal shrinkage fabrics, which can be divided into four types: altitude, slope, curvature and volume, were extracted by ArcGis software.

Table 2. Shrinkage characterization parameters

| Type (code)       | Parameters (code)                  | Definition                                                                 | Method used in ArcGis          |
|-------------------|-----------------------------------|----------------------------------------------------------------------------|-------------------------------|
| Altitude (A)      | Maximum height ($A_1$)            | /                                                                          | Altitude image                |
|                   | Average height ($A_2$)            | /                                                                          |                               |
|                   | Coefficient of variation of height ($A_3$) | Ratio of standard deviation to average                                    |                               |
| Slope (S)         | Maximum slope ($S_1$)             | /                                                                          | Slope image                   |
|                   | Average slope ($S_2$)             | /                                                                          |                               |
| Curvature (C)     | Section curvature ($C_1$)         | Vertical curvature                                                        | Curvature image               |
|                   | Plane curvature ($C_2$)           | Horizontal curvature                                                      |                               |
| Volume (V)        | Shrinkage ratio of surface area ($V_1$) | Ratio of reduced projected area after combustion to projected area before combustion | “3D analyst-Functional surface-Surface volume” tool |
|                   | Surface roughness ratio ($V_2$)   | Ratio of surface area to projected area                                   |                               |
|                   | Projected volume ($V_3$)          | /                                                                          |                               |

2.3.2 Principal component analysis (PCA). The ten characterization parameters of thermal shrinkage obtained in ArcGis were all imported into IBM SPSS Statistics 22.0. The result of KMO and Bartlett’s test showed that the KMO was 0.793, which indicated that the data was suitable for factor analysis. The P value of Bartlett’s Test of Sphericity was less than 0.01, that is, there was a significant correlation between variables. Then according to the table of total variance explained, four components with 86.859% of cumulative variance were used. Communality refers to the degree to which the original information contained in the variable can be extracted by the common factor extracted. It is generally accepted that the communalty is greater than 0.4. And the component communality of the characterization parameter all reached above 0.7, which verified the validity and accuracy of the principal component analysis.

Through factor analysis, the factor loading of each characterization parameter on the four principal components was obtained. For each principal component, divide the factor loading by the arithmetic square root of the characterization parameter to calculate the principal component eigenvector. Based
on the component score coefficient matrix consisted by the eigenvector, the score values for four principle components were calculated, which defined as $X_1$, $X_2$, $X_3$ and $X_4$, respectively. And the calculation formulas are as follows:

$$X_1 = A_1 \times 0.324 + A_2 \times 0.384 + A_3 \times 0.128 + S_1 \times 0.346 + S_2 \times 0.386 + C_1 \times 0.306 + C_2 \times 0.250 - V_1 \times 0.135 + V_2 \times 0.374 + V_3 \times 0.385$$  \hspace{1cm} (1)

$$X_2 = A_1 \times 0.092 - A_2 \times 0.109 + A_3 \times 0.610 + S_1 \times 0.165 + S_2 \times 0.030 + C_1 \times 0.377 - C_2 \times 0.162 + V_1 \times 0.629 - V_2 \times 0.070 - V_3 \times 0.101$$  \hspace{1cm} (2)

$$X_3 = A_1 \times 0.308 + A_2 \times 0.274 - A_3 \times 0.636 + S_1 \times 0.277 - S_2 \times 0.044 + C_1 \times 0.229 - C_2 \times 0.164 - V_1 \times 0.388 - V_2 \times 0.219 + V_3 \times 0.264$$  \hspace{1cm} (3)

$$X_4 = A_1 \times 0.160 - A_2 \times 0.091 - A_3 \times 0.060 - S_1 \times 0.075 - S_2 \times 0.032 - C_1 \times 0.027 + C_2 \times 0.932 + V_1 \times 0.278 - V_2 \times 0.096 - V_3 \times 0.048$$  \hspace{1cm} (4)

Then the integrated score value of thermal shrinkage ($X$) is calculated using the variance contribution rate (The values for component 1 to 4 were 5.754, 1.345, 0.926, 0.660, respectively), which is expressed as follows:

$$X = (X_1 \times 5.754 + X_2 \times 1.345 + X_3 \times 0.926 + X_4 \times 0.660) / A$$

where $A = 5.754 + 1.345 + 0.926 + 0.660$.

In the following text, the integrated score value of thermal shrinkage ($X$) is used as an indicator of the magnitude of thermal shrinkage. If it is negative, it means the magnitude of thermal shrinkage is below the average level. And the higher the $X$ is, the greater the magnitude of thermal shrinkage is, and vice versa.

3. Results and discussion

3.1. Effect of exposure frequency on thermal shrinkage

The effect of exposure frequency with individual exposure duration of 3s on thermal shrinkage is shown in Figure 2. The integrated score of thermal shrinkage showed different change trends for the three fabrics. For the fabric F1, the thermal shrinkage score showed significantly increase after each exposure frequency ($p < 0.050$). For the fabric F2, the thermal shrinkage score increased firstly after second exposure frequency, and then decreased after third exposure frequency. For the fabric F3, the increase of exposure frequency decreased the thermal shrinkage score. The impact of exposure frequency with individual exposure duration of 4s on thermal shrinkage is demonstrated in Figure 3. The fabric F1 showed similar change trend with that in the individual exposure duration of 3s. That is the thermal shrinkage significantly increased with the increase of exposure frequency ($p < 0.050$), but showing different increments. The main increase in thermal shrinkage in the 3s group occurred between second and third exposure frequency, while it occurred between first and second exposure frequency in the 4s group. For the fabric F2, the thermal shrinkage score decreased firstly and then increased, which was completely opposite to that of 3s exposure duration. And for both individual exposure durations of 3s and 4s, the thermal shrinkage score kept similar value between first and second exposure frequencies, whereas it showed a relative higher difference after the third exposure. For the fabric F3, the thermal shrinkage score dropped firstly, and then increased. It could be observed that in the individual exposure duration of 4s, it showed similar change trend between the fabrics F2 and F3.
The fabric F1 is flame-retardant finishing fabric. The change in thermal shrinkage increment could be due to the volatilization of the flame retardant. For the flame-retardant finishing fabric, the flame retardant played a role at the beginning of the heat exposure. As the duration of heat exposure increased, the flame retardant was gradually exhausted, causing the flame retardancy of the fabric to decline and shrink easily. The difference in thermal shrinkage increment after different exposure frequencies for the fabric F1 in the 3s and 4s individual durations could be attributed to the combination effects of the difference in the individual exposure duration, the volatilization of flame retardant, and the limit of thermal shrinkage. The inherently flame-retardant fabrics F2 and F3 showed excellent thermal stability in the appearance in the multiple flash fire exposures. The thermal shrinkage scores of these two fabrics slightly reduced with the increase of exposure frequency. And a possible explanation for this could be the fabrics became flatter after carbonization.

3.2. Comparison between repeated exposures and continuous exposure

The fabric F2 was selected for a long-duration continuous exposure due to its excellent thermal dimensional stability shown in the pre-test. Two groups of exposure were compared, while in each group, keeping the same cumulative exposure duration for repeated exposures and continuous exposure. Fig. 4 demonstrates the thermal shrinkage scores after repeated exposures and continuous exposure. It was observed that the thermal shrinkage score after continuous exposure was more than that after repeated exposures. It means the continuous exposure caused more severe shrinkage to the fabric. In a study by Lu et al. [19], a similar finding was obtained after multiple radiation exposures, that is a single long exposure caused more serious damage to the fabrics, compared to several short exposures. A possible explanation for this might be that for the repeated exposures, enough time was...
provided after each exposure for the fabric to release the heat stored during the last exposure, while for the continuous exposure, it was a cumulation of temperature and heat in a long-duration exposure, which resulted in more serious thermal damage to the fabric. The results presented in the present study indicated that thermal protective clothing used in flame exposure, the thermal shrinkage of clothing can be weakened by diving a single long exposure into several short exposures.

**Figure 4.** Thermal shrinkage scores for repeated exposures and continuous exposure.

### 3.3. Changes in thermal protective performance due to thermal shrinkage

Figure 5 shows TPP values of fabrics after different frequencies of exposure with the individual exposure duration of 3s. For the fabric F1, it shows a relatively large change, with 22% decrease in TPP after second exposure, and then 6% increase after third exposure. As demonstrated in a previous study, the fabric F1 (FR cotton) exhibited significant decrease in the thickness and mass, which might be the reason for the large decrease in the TPP value after second exposure. For the fabrics F2 and F3, the TPP value slightly changed after repeated exposures. It slightly decreased (2-4%) from the first exposure to second exposure, and basically kept stable (0-0.6%) from the second exposure to third exposure. It might be due to the good thermal dimensional stability of the F2 and F3.

Similarly, Figure 6 presents TPP values of fabrics after different frequencies of exposure with the individual exposure duration of 4s. For the fabric F1, the TPP value was shown the same change trend with the case of 3s individual exposure. It exhibited 12% decrease in TPP value after second exposure, and 12% decrease after third exposure. The TPP values decreased from the first exposure to the second exposure for both F2 and F3. For the third exposure, the TPP of the fabric F3 further decreased, while the TPP of the fabric F2 increased.

**Figure 5.** TPP values after different frequencies of exposure (3s per exposure)
It has been shown that the thermal shrinkage of fabrics would decrease the thermal protective performance in the study of Crown et al. [12]. In order to further investigate the effects of thermal shrinkage on thermal protective performance, correlation analysis was performed between the thermal shrinkage score and the TPP value. There was no significant correlation between the thermal shrinkage score and the TPP value (p>0.05). For the individual exposure duration of 3s, the correlation coefficients between thermal shrinkage score and TPP value was zero, indicating that there was no linear relationship between them. For the individual exposure duration of 4s, there was a weak negative correlation between thermal shrinkage score and TPP value, with a correlation coefficient of -0.129. It means the greater the thermal shrinkage, the worse the thermal protective performance. The insignificant correlation between thermal shrinkage and TPP were demonstrated in the present study. This might be due to that the change of fabric basic properties after repeated flame exposures is the main factor affecting its thermal protective performance, such as the increased thickness caused by carbonization. This revealed that more factors about the fabric thermophysical properties should be considered, such as fabric thickness and density.

4. Conclusion
The effects of multiple flame exposures on thermal shrinkage of flame-retardant fabrics and thermal protective performance were investigated in this study. The thermal shrinkage of fabrics was characterized and by using the principal component analysis. It showed that the thermal shrinkage score of fabrics under different flame exposure frequencies showed different change trends for the fabrics FR cotton, Kevlar®/PBI and PI. For the fabric FR cotton (flame-retardant finishing), exposure frequency showed significant effect on the thermal shrinkage. As exposure frequency increased, the thermal shrinkage score of FR cotton significantly increased. For the fabrics Kevlar®/PBI and PI (intrinsic flame-retardant), the flame exposure frequency had no significant effect on thermal shrinkage. For the fabric Kevlar®/PBI, a long-duration continuous exposure resulted greater thermal shrinkage, as compared to several short-duration exposures. The correlation analysis showed that there was no significant correlation between thermal shrinkage of the fabric and its thermal protective performance. The findings of this study provided a theoretical reference for the performance evaluation of thermal protective clothing that is repeatedly exposed to flame.

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