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Determination of the thermal protective performance of clothing during bench-scale fire test and flame engulfment test: Evidence from a new index

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Abstract

The protective performance of heat- and flame-resistant materials can be studied using a bench-scale test or a full-scale instrumented manikin test. However, there are some limitations of these evaluation methods. The existing bench-scale test could not be applied entirely to assess the thermal protective performance of fabrics if the exposure duration is fixed, while the existing manikin test only provides limited information about the local difference in thermal insulation. This study developed a new index of maximum attenuation factor to second-degree burn injury (maximum attenuation factor) as an improved quantitative method of the thermal protective performance, and then investigated the use of maximum attenuation factor during the bench-scale test as well as the manikin test. It demonstrated that the calculations of maximum attenuation factor were highly repeatable. In both the bench-scale and the manikin test, strong correlations were found between the results derived from the proposed method and the measurements from the existing test method. The results between the bench-scale test and the manikin test can also be compared as a united index.

Keywords

Protective clothing, thermal protective performance, flame manikin, maximum attenuation factor, skin burn injury

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Introduction

It is reported that tens of thousands of firefighter injuries occur in the line of duty every year as firefighters are the first responders to suppress unwanted fires and rescue victims. The role of protective clothing and other personal protective equipment made of heat- and flame-resistant textiles is fundamental for the firefighter's safety. In order to develop advanced protective ensembles and equipment for emergency responders, test methods for evaluating the ability of personal protective systems are required by research institutions and companies.

Several kinds of test methods have been developed to determine the thermal risks with textile materials. The use of any particular standard test method is based on the end use of the textile material and the country where the material is to be used. Test method that quantifies the thermal protective performance of fabrics exposed to a simulated flashover condition is specified in ISO 17492:2003.[1] This test method is widely known as the TPP test, which is used to determine the performance characteristics of the fabrics or fabric combinations in providing protection against second-degree burn injury upon exposure to a flash fire. Besides the bench-scale test, the performance characteristics of a flame-resistant clothing ensemble can be studied using a full-scale instrumented manikin, and the details of this test method are defined in ASTM F1930-13.[2] With the introduction of the TPP test and manikin test, the protective performance of flame-resistant clothing has been extensively investigated. The efficiency of the thermal protective fabric is affected by its physical properties such as thickness, density, weight, air permeability, thermal conductivity, and structures.[3,4] Other factors related to the whole garment such as the accessories, design features, and the fit of the garment may also affect the overall performance.[5,6] Previous studies, including the bench-scale tests[7] and flame manikin tests,[8,9] showed that air gaps played an important role in thermal protection.

Although the protective properties of materials can be evaluated using either bench-scale tests or instrumented manikin tests, the evaluation methodology of the test approaches is different. In the manikin test, the instrumented manikin will be exposed to simulated fire for a fixed period of time.[2] This fixed exposure duration is varied based on the layers of the protective clothing and also the test requirements. Heat sensors fitted to the surface of the manikin are used to measure the transferred heat flux variation with time. The measured heat flux of each sensor is then applied to calculate predicted second-degree and third-degree body burn injuries and their corresponding body areas based on a skin model. Existing bench-scale test, on the other hand, exposes a fabric and collect test data until a second-degree burn criterion is exceeded, rather than for some fixed duration.[10] Using the bench-scale test, fabrics are then rated on the basis of the total energy of exposure required to reach this second-degree burn criterion. Schoppee et al.[11] have tried to expose fabrics to the thermal source for a fixed duration indicative of the length of exposure in a manikin test. It was found that second-degree burn damage might occur to skin behind some kinds of fabrics while for others no burn injuries were predicted. In this situation, the pass/fail criterion is solely used to rate their protective capacities, but it is hard to distinguish their protective properties if all the tested fabrics get the equal grade of pass or fail. In other words, thermal insulative properties of the samples could not be entirely rated by the limited data obtained from the present bench-scale test in the case of the fixed exposure duration test. This would be the reason that a rating method based on the time to exceed the second-degree burn criterion is preferred for most of the bench-scale studies.[3,12] However, when exposed to heat and flame, the length of exposure time of firefighters is variable according to the specifics of the heat exposure and other conditions of operation. Similar to the manikin test, an evaluation method with fixed exposure duration is also required in the bench-scale test for it to be practical.

Utilizing a manikin to assess the overall performance of a firefighter turnout suit, it is available to find the locations and levels of burn injuries from a diagram of the manikin, and also get the results of predicted manikin area of burn injury. Apart from these shown discrete indicators of first-, second-, and third-degree burn injury or no burn injury, no more information could be used to differentiate the local differences in thermal protection. Regularly, the same degree burn injuries were predicted in different parts of the manikin, or several adjacent sensors, as shown in previous studies.[8,13] In this case, the weakness of the thermal protection within these parts is not that easy to be detected. That is to say, the existing flame manikin tests can just provide limited information about local differences in thermal insulation.[14] In addition to the above limitations in the existing bench-scale test and manikin test, another issue should be pointed out here. In the bench-scale test, a standard burn injury curve uses as an incipient second-degree burn threshold level based on experimental data from Stoll and Chianta,[15] while the Henriques'[16] burn integral is applied to calculate the levels of burn injuries in the manikin test. In some cases, differences would be found in the predicted burn injury results if the evaluation methods of the Stoll criteria and the Henriques burn integral are compared.[17] As a result, it poses an obstacle to compare the results from the bench-scale test and the manikin test since the evaluation methods used to predict the burn injuries are different.

This study proposed a new index to quantitatively assess the protection provided by clothing during the bench-scale fire test and the flame engulfment test. This new index can not only be used to evaluate the performance of fabrics with fixed exposure duration but also could be applied to the manikin test to provide differential information about the local thermal protection. The aims of this study were to investigate the validity of the new index and to compare the results with the measurements obtained by the existing bench-scale test and manikin test.

Evaluation methods

Materials and garments

A number of flame-resistant fabrics were selected in this study. The fabrics are commercially available and popularly found in the protective clothing field. Table 1 shows the

Table 1. Specifications of the fabric specimens.

Code	Fiber content	Structure	Weight (g/m^2)	Thickness (mm)	Air permeability $cm^3/(cm^2s)$
G1	98% Nomex® IIIA/2% CF	Twill	205	0.60	7.6
G2	98% Nomex® IIIA/2% CF	Twill	261	0.65	5.6
G3	100% m-aramid	Plain	158	0.51	39.4
G4	100% m-aramid	Twill	216	0.61	16.1
G5	98% PSA/2% CF	Plain	152	0.55	16.9
G6	98% PSA/2% CF	Twill	258	0.62	7.0
G7	100% FR cotton	Twill	325	0.73	9.6

CF: conductive fiber; PSA: polysulfonamide fiber; FR: flame resistant.

specifications of the selected fabrics. Garments used in the study were made of the materials presented below above, and all the testing garments were single-layer coveralls to the same size. The details of the garment style, and their configurations could be found in a previous study.[18]

Manikin tests

The flash fire manikin test of protective coveralls was performed on a newly developed flame manikin system, which corresponds to the technical requirements specified in ASTM F1930-13.[2] This manikin was built with the technical support of Measurement Technology Northwest, USA. The size of the manikin is on the basis of the average dimensions of a Chinese adult male with the height of 175 cm. The simulated flash fire exposure with average heat flux of 84 kW/m^2 is generated by six groups of propane gas burners distributed evenly around the manikin. A total of 135 individual calorimeter sensors are distributed over the body surface of the manikin to measure the incident heat flux. The exposure time was always 4 s for these single-layer coveralls. A large amount of thermal energy that stores during exposure may discharge to the skin after exposure and contribute to burn injuries.[4,19,20] Therefore, the total data acquisition time was set to 60 s, so that the thermal energy transferred through and from the test specimen during and after the exposure could be measured by thermal energy sensors. According to ASTM F1930, the predicted skin damage related to second-degree and third-degree burn was determined using a skin model. In this study, the head, hands, and feet were not included, as they were not covered with clothing during the flame exposure.

Bench-scale tests

A versatile laboratory test apparatus, widely known as TPP tester (Custom Scientific Instrument Corporation, USA), was modified and used in this study. The tester consists of two Meker burners and a bank of nine translucent quartz infrared lamps producing a nominal heat flux of 84 ± 2 kW/m^2, with 50% convection and 50% radiation upward to a fabric sample. An electronically triggered pneumatic water-cooled shutter is used to insulate the test specimen from heat sources for controlling accurate exposure time. A thermal sensor is positioned in direct contact with the back of the specimen to measure the temperature rise. The duration of exposure selected was 4 s, the same length of exposure time as in the manikin test. After heat exposure, samples were separated from the heat source by inserting the blocking shutter. Sensor data continued to be recorded after terminating the heat exposure until the total data acquisition time reached 60 s. By prolonging data collection time, thermal energy transfer caused by stored energy after exposure was taken into account as well. Computer software used in the tester was modified to accommodate a longer data collection time.

In order to investigate the validity of the proposed new index in this study, measurements for assessing the protective properties of fabrics derived from a standard test method should be compared. A newly developed bench-scale test method ASTM F2703-08[21] was used. Comparing with the conventional TPP test, the test method ASTM F2703 is designed to account for the effect of the thermal stored energy on the predicted skin burn injury. This standard test method defines the term "thermal performance estimate (TPE)" for the quantitative assessment of thermal protective properties of fabrics. The TPE value is expressed as the product of the exposure heat flux and the certification exposure time, at which the skin burn injury is just predicted after considering the stored energy effect. The Stoll criteria are applied as the second-degree burn threshold level in the test standard. The TPE rating acts similarly to the TPP rating, which means that better protection will be predicted with a higher TPE value. The TPE values of the test specimens were measured according to ASTM F2703.

Maximum attenuation factor to second-degree burn injury

In the light of ASTM F2703-08[21] for the bench-scale test, the response of the sensor requires to be compared with the Stoll criteria to predict the onset of the second-degree burn. The Stoll criteria established in this standard differ from the normal Stoll curve, and it is found to be the total amount of energy rather than the temperature rise of the sensor that must be absorbed by the skin to sustain second-degree burns for a given length of time. Therefore, the total transferred energy of the sensor needs to be converted. The temperature rise of the sensor under a particular heat exposure can be used to calculate the heat flux on the sensor,[22] and then, the total transferred energy can be derived by integrating the heat flux with time. The details of the equation for the calculation of the total transferred energy are described in ASTM F2703. Figure 1 shows an example of the sensor response and the Stoll criteria under ASTM F2703. In order to examine the relations between the sensor response and the Stoll criteria, the ratio between them at each time step was introduced in this study, and a new index named maximum attenuation factor (MAF) to second-degree burn injury was proposed, which was calculated as the maximum ratio of the sensor response to the Stoll criteria throughout the test

$$\mathrm{MAF} = \max\left[\frac{Q(t)}{S(t)}\right] \tag{1}$$

where $Q(t)$ stands for the total transferred energy at time t (kJ/m^2) and $S(t)$ stands for the value observed in the Stoll criteria at the same time point t (kJ/m^2). If the value in MAF is

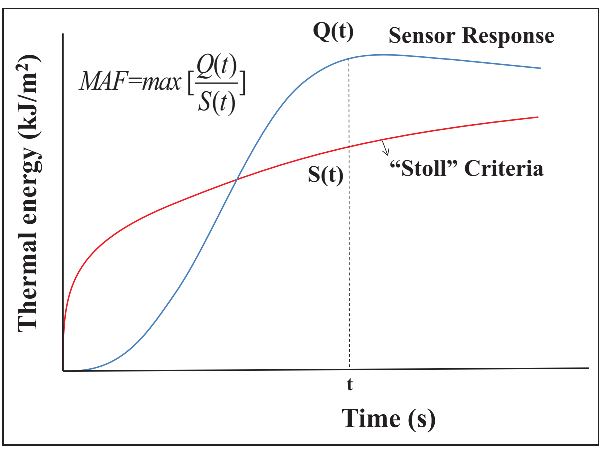

Figure 1. Schematic representation of the sensor response and the Stoll criteria under ASTM F2703 and the determination of the MAF.

attained to be less than 1.0, the total transferred energy is below the amount of energy absorbed by the skin to cause the second-degree burn injury throughout the test. If the MAF is found to be more than 1.0, the total transferred energy is expected to exceed the burn injury performance curve of Stoll criteria at some time point, indicating the occurrence of the second-degree burn injury.

The index of MAF was first introduced in the bench-scale test, and then it was extended to the flame manikin test. In order to obtain the MAF value, the Stoll criteria should be taken as the skin burn perdition guide curve in the manikin test as well. In fact, this study was not the first attempt to apply the Stoll criteria to an instrumented mannequin test. Like ASTM F2178-12,[23] the Stoll criteria are considered as the second-degree burn threshold level for the assessment of the protective performance of the face product mounted on a standard mannequin head. In the manikin test, the MAF of each single sensor could be determined by using equation (1). The overall maximum attenuation factor (OMAF) of a garment in the manikin test was obtained from the area weighted average of the index over the entire covered surface

$$\mathrm{OMAF} = \sum_{i=1}^{n} \left\{ \max\left[\frac{Q_i(t)}{S(t)}\right] \right\} \cdot \frac{A_i}{A} \tag{2}$$

where $Q_i(t)$ stands for total transferred energy of sensor i at time t (kJ/m^2), A_i stands for the area attributed to sensor i (m^2), A stands for the total operating area of the manikin (m^2), and n stands for the number of sensors.

Results and discussion

MAF assessment in the bench-scale test

The repeatability of the method for the determination of the MAF was first verified in this study. Table 2 shows the standard deviation and coefficient of variation of the MAF in the bench-scale test. Three test replications were conducted using the same test material. The standard deviations are in the range of 0.6%– 3.6% when compared to the means of each test specimen, indicating that the proposed method has a high repeatability. This repeatability value is higher than the repeatability value listed in the bench-scale test standard (coefficient of variation ranges from 5.6% to 16.9%), where the performance is rated by the TPE value.[21] The observation that the coefficient of variation varies from specimen to specimen shows that the type of composite tested affects the overall test repeatability.

Table 2. MAF to second-degree burn injury, SD, and CV of the MAF in the bench-scale test.

Fabric code	G1	G2	G3	G4	G5	G6	G7
MAF	1.71	1.41[a]	1.57	1.62	1.95	1.51	1.35[a]
SD	0.01	0.05	0.01	0.01	0.03	0.04	0.03
CV = SD/MAF $\times$ 100%	0.8	3.6	0.6	0.6	1.5	2.7	2.5

MAF: maximum attenuation factor; SD: standard deviation; CV: coefficient of variation.
The superscript a in a column means that no significant difference in the MAF is observed between G2 and G7, $p < 0.05$.

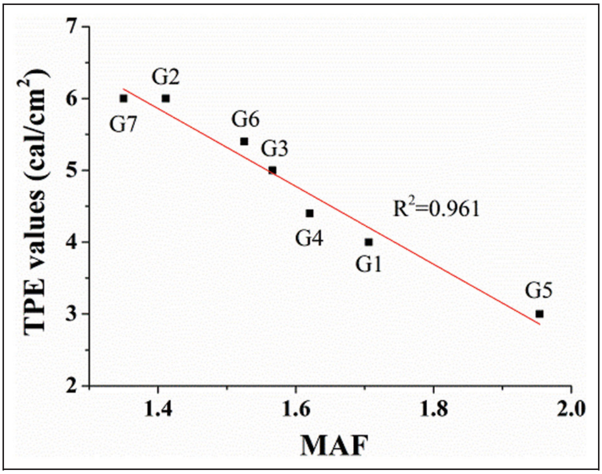

Figure 2. Relationship between the MAF and TPE values in the bench-scale test.

To further compare the values in MAF and the results derived from the standard test method, the correlation between the MAF and the TPE value is analyzed, as presented in Figure 2. The two indices display a strongly negative linear relationship with $R^2 = 0.961$. The fabric with a higher MAF value is found to have a smaller value in the TPE rating, which indicates the decrement in the predicted thermal protection of the fabric. Since the MAF is determined as the maximum quotient between the total transferred energy of the sensor and the reading value in the Stoll criteria at precisely the same time point, the total transferred energy will be much above the demanded amount of energy to generate skin burns if a higher value in the MAF is observed. The predicted degrees of skin burns are correlated with the total transferred energy to the sensor,[14] and inferior protection will be predicted if the total transferred energy is great.[24,25] It can be inferred that the test sample will be predicted to provide better thermal protection with a smaller MAF value, whereas it has greater capability to produce more serious burn injuries if a larger value is found in the MAF.

The TPE values range from 3.0 to 6.0 cal/cm^2 over the entire turnout composites; therefore, the certification exposure time should stay between 1.5 and 3 s. Utilizing 4 s exposure, second-degree burn injuries will be certainly predicted behind these fabrics. The same results are obtained by the proposed method as all the tested fabrics have MAF values greater than 1.0. As can be seen in Table 2, MAF values are significantly different among the tested fabrics with the same exposure time of 4 s, but the only exception is observed between G2 and G7 ($p < 0.05$). Interestingly, the TPE ratings of G2 and G7 are also found to be the same as shown in Figure 2, which means no significant difference existed in the prediction of the thermal protection between the two fabrics. The samples of G2 and G7 that have higher fabric weight are observed to show smaller MAF values, whereas the sample of G5 generates the greatest MAF value with the lowest fabric weight. However, the MAF of fabric G3, which has lighter fabric weight, is smaller than that observed in G1 and G4, and similarly this finding consists with the result found in the TPE evaluation. The detailed comparisons between the MAF and the TPE values demonstrate that performance assessed by the proposed method agrees well with the outcomes derived from the standard test, but the

Table 3. OMAF to second-degree burn injury, SD, and CV in the manikin test.

Fabric code	G1	G2	G3	G4	G5	G6	G7
OMAF	1.30	0.90	1.21	1.35	1.57	0.99	0.66
SD	0.05	0.01	0.03	0.01	0.02	0.03	0.02
CV = SD/OMAF × 100%	4.0	0.6	2.7	0.7	1.2	3.3	2.3

OMAF: overall maximum attenuation factor; SD: standard deviation; CV: coefficient of variation.
The OMAF is significantly different among the garments ($p < 0.05$).

proposed new method could be further used to distinguish the thermal protective properties of fabrics even though the test procedure is set with a fixed exposure duration.

MAF assessment in the manikin test

Similarly, the repeatability statistics of the proposed method for assessing the OMAF in the manikin test are listed in Table 3. These statistics were derived from three test replications. For all the types of garments, the coefficient of variation never exceeds 4%, which indicates that the method is repeatable to be analyzed in the manikin test. The coefficient of variation of the skin burn percentages found in an earlier publication ranged from 5.4% to 37.1%;[13] moreover, another recent research work that suggested the energy transmission factor as the indicator to assess the protective performance of clothing found that the repeatability value of the this factor was between 1.0% and 3.9%.[14] It can be concluded that the repeatability of the method for the determination of OMAF is higher than the repeatability of the existing evaluation method used in the manikin test or at least at the same level as the repeatability obtained by other newly developed evaluation method. Also, the statistics described in Table 3 show that variation within the test does depend on the materials of garments.

The total percentage of burn injury can be obtained from the existing manikin evaluation method. The relationship between the total percentage of burn injury and the OMAF is presented in Figure 3. The total percentage of burn injury examined here includes the percentage of second- and third-degree burns. A strongly positive linear relationship with $R^2 = 0.905$ is predicted between the two indices. The overall trend demonstrates that the predicted OMAF in the manikin test goes up with the increase in the total percentage of burn injury. That is to say, the predicted protective performance indicated by the OMAF is reduced as the OMAF value goes higher. Therefore, garment G5 that has the highest OMAF value shows the lowest rank in the predicted thermal protection, whereas garment G7 is predicted to provide the best thermal protection with the smallest OMAF value. A significant difference in the OMAF is observed between test garments ($p < 0.05$, Table 3). However, in terms of the total percentage of burn injury, it is not significantly different among the outcomes for garments G1, G3, and G4 ($p < 0.05$). Checking the OMAF values for garments G1, G3, and G4, it is found that the difference within these three garments is around 10%. This is acceptable since the burn injury evaluation method used in the existing flame manikin test is different from that used as the basis for the determination of the OMAF.

In order to examine the local thermal insulation of the clothing, the MAF values for garment G3 and the corresponding burn injury damage results are compared in Figure 4. The weakness of the burn injury risk evaluation (Figure 4, left) is clearly seen as the local thermal

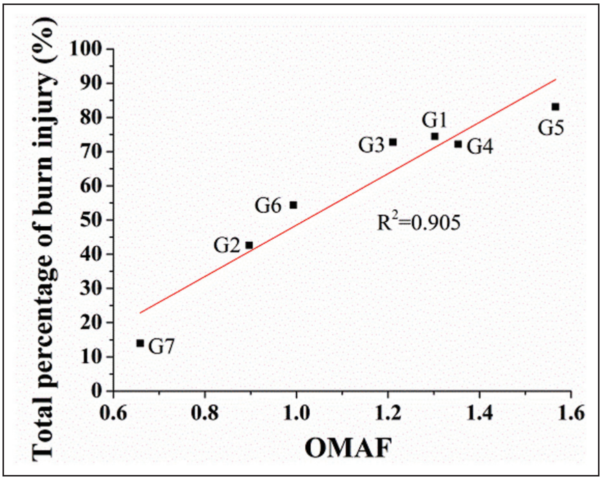

Figure 3. Relationship between values in the OMAF and the total percentage of burn injury in the manikin test.

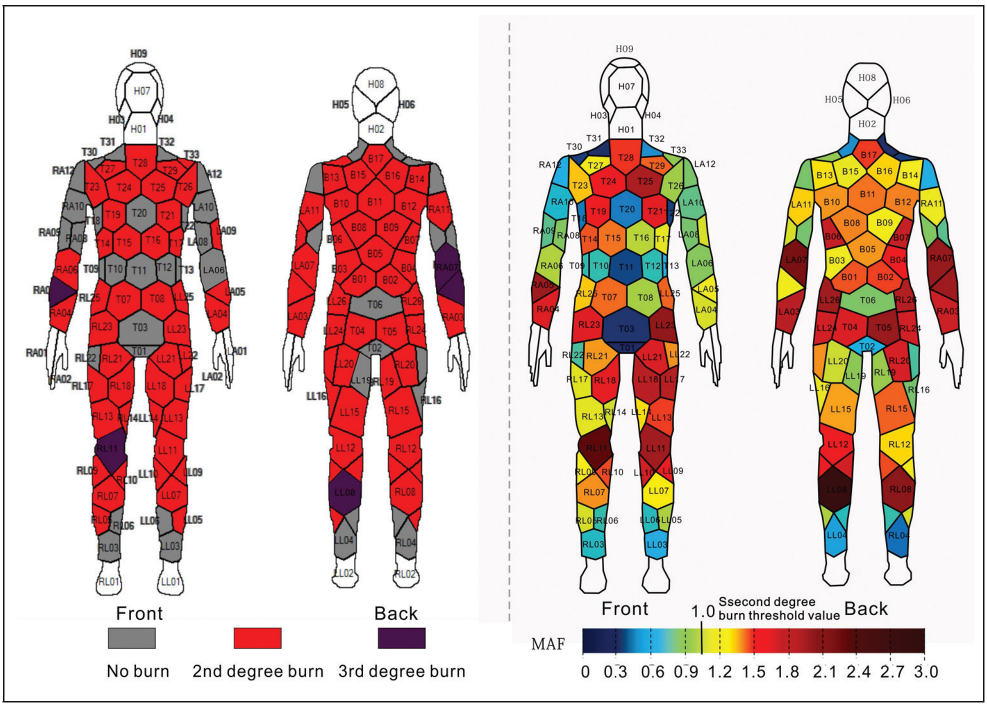

Figure 4. Burn injury predictions by the existing evaluation method (left) and the distribution of the MAF over the manikin surface (garment G3, sample 1).

protection is only distinguished by the discrete indicators of no burn, second-, and third-degree burns. The predicted second-degree burn contributes 95% of the total burn injury, indicating that the overwhelming majority of regions on the burned body get the same rating in the assessment process. In the region of the left front thigh, it is hard to detect the weak spots in thermal insulation as all the sensors reached the second-degree burn level. On the other hand, with the introduction of the MAF method (Figure 4, right), the root of the thigh and the knee regions of the left leg are easily found to be frail due to the observed higher MAF values. In contrast to the burn injury risk evaluation, the calculated MAF is a continuous value and it provides distinguishing rates between several sensors with the same burn injury result. Recently, as more attention has been drawn to explore the relationship between the local thermal protection and the air gap distribution[26,27] or the local thermal shrinkage of the protective clothing,[8,18] the proposed MAF method in this study would provide a practical way in these analyses. As can be seen in Figure 4, the locations of the sensors that reach second-degree burn can be easily determined only if the MAF value is found to be more than 1.0. Comparing to the results of the burn injury prediction, the second-degree burn areas detected by the MAF method agree well with that observed by the burn injury risk method; moreover, the third-degree burn areas displayed in the left side of Figure 4 are found to have higher MAF values ranged from 2.0 to 2.8 for the selected test sample. When analyzing the MAF by segments, it is clear that the lower MAF value is observed in the abdomen and the upper arm regions. On the other hand, the higher MAF value is located in the lower arm, the buttock, and the leg regions.

The bar charts of the MAF distribution in classes of 0.3 for all the garments are displayed in Figure 5. The distribution of the MAF is different among the garments and the mode that the MAF value repeated most often is varied based on the type of test garment. For garment G7 that has the lowest OMAF value (0.66, Table 3), the mode of the MAF ranges from 0.6 to 0.9. For garment G5 that has the highest OMAF value (1.57), the MAF reaches its mode when the MAF is between 1.5 and 1.8. Although for garments G1 and G3, the modes of the MAF are found to be in the same range of 1.2–1.5, garment G1 (1.30 in OMAF) has eight more sensors with the MAF value over 1.5 compared with that found in garment G3 (1.21 in OMAF). Checking the mode of the MAF and the OMAF value for the other garments, it is found that the mode of the MAF for garments G2 (0.9 in OMAF) and G4 (1.35 in OMAF) is in the same range as that for garments G7 and G1, respectively; in addition, the MAF mode for garment G6 (0.99 in OMAF) is between 0.9 and 1.2. It demonstrates that the mode of the MAF is close to its OMAF value; moreover, the grade of the overall performance based on the mode of MAF is very similar to the ranking of the overall performance indicated by the OMAF. It seems that the mode of MAF can be used as an indicator to assess the overall performance of the garment.

Also as presented in Figure 5, different types of garments show that the maximum MAF value observed in this study is around 2.9. Garment G5 has several sensors with the MAF between 2.4 and 3.0. This garment also has the highest OMAF value and the highest number of sensors with the MAF value over 2.4 (11 sensors). Garment G4 has a higher OMAF value than that of garment G1 and then garment G3; also it is found that the quantities of the sensors reaching the MAF value over 2.4 are 8, 3, and 1, respectively. Garments G2 and G6 with relatively lower OMAF values show that the MAF values of the sensors never exceed 2.4. The number of the sensors with the MAF value over 1.8 is found to be 4 and 5 for garments G2 and G6, respectively. Garment G7 has no sensor with the MAF value over 2.1 and also this type of garment is detected to have the lowest OMAF value. Thus, the grade of the maximum MAF is also very analogous to the ranking of the OMAF. Similarly to the mode of

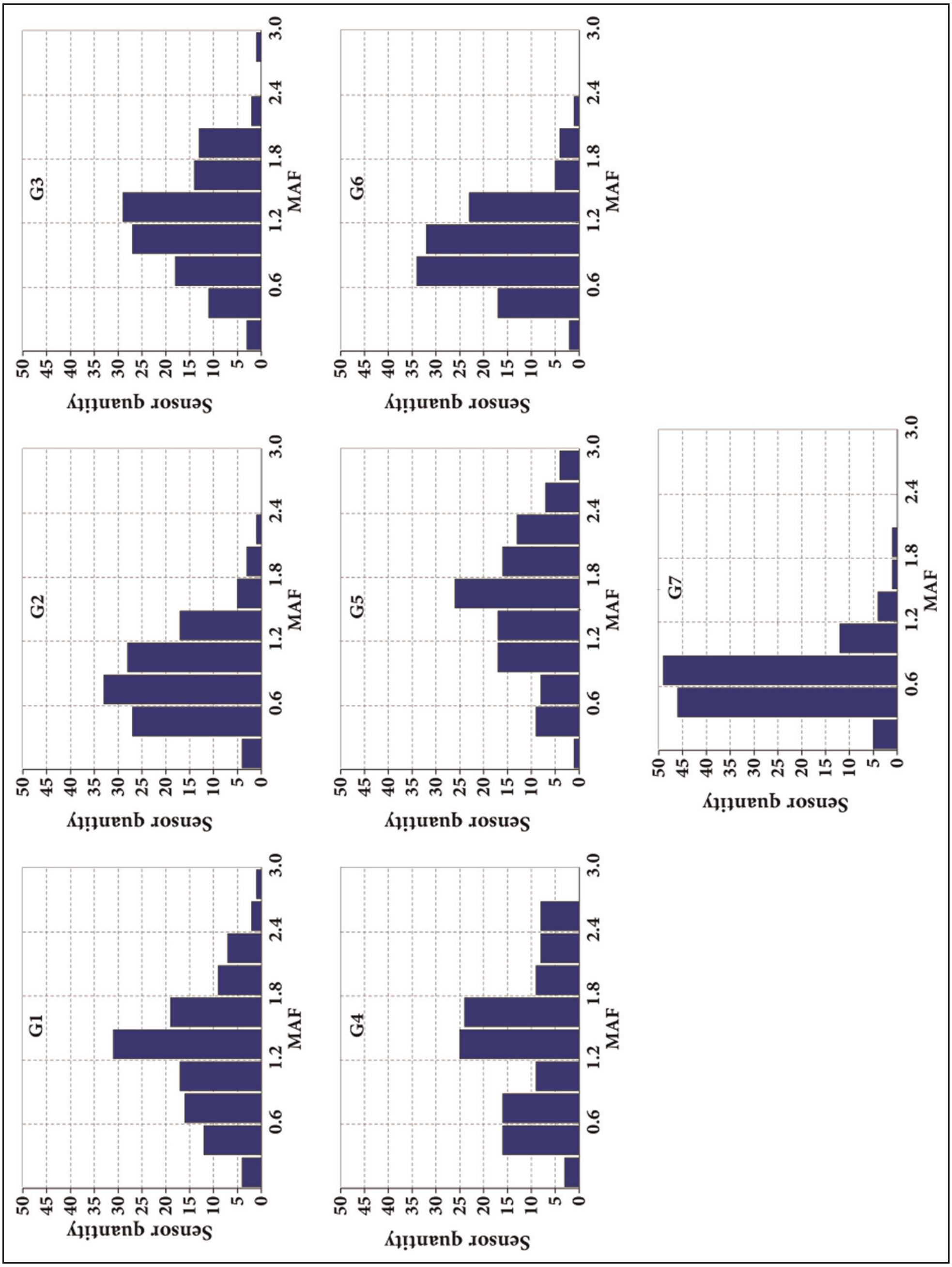

Figure 5. Bar charts of the MAF distribution for all the garments.

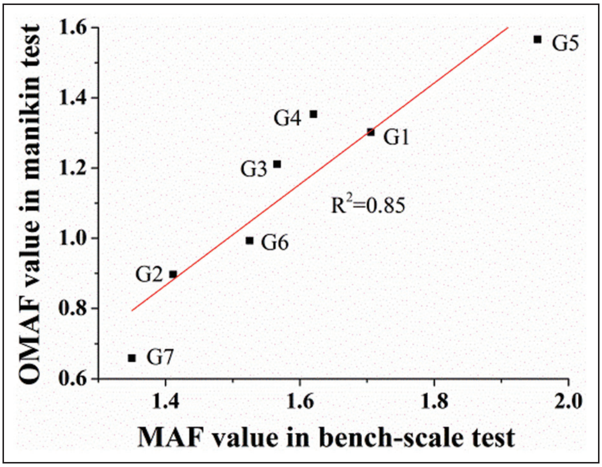

Figure 6. Relationship between the MAF in the bench-scale test and the OMAF in the manikin test.

the MAF, the peak MAF of clothing can be used as another indicator for the determination of the overall protective performance.

Correlation of bench-scale test with manikin test

Figure 6 shows the relationship between the results of the MAF in the bench-scale test and the OMAF in the manikin test. The performance between the fabric and the overall garment could be compared because the test procedure as well as the evaluation index is unified in the bench-scale test and the manikin test. A directly positive correlation exists between the results obtained by the two test methods ($R^2 = 0.85$). For most test samples, the fabric that predicts a higher MAF value during the bench-sale test is found to show a greater OMAF value during the manikin test. However, no significant difference is observed in the value of MAF when the results for fabrics G2 and G7 are compared (Table 2), while in the manikin test the garment made of G2 shows a significantly higher OMAF value. In addition, the MAF value found for fabric G1 is significantly higher than that for fabric G4, but the ranking of the OMAF is reversed during the manikin test. Compared with the bench-scale test, the manikin test is used to assess the overall performance of the garment assembly under a fire scenario and it accounts for many other factors except for the material.[9,27] It is clear that the MAF values obtained in the bench-scale test are much higher than the OMAF scores in the manikin test. The MAF value for G5 is 25% higher than its OMAF value; moreover, for sample G7 the difference is enlarged since the MAF value is twice as large as the value found in the OMAF. During the bench-scale test, the sensor is located at the back of the specimen with direct contact, which means no air gap existed between the sensor and the specimen. On the other hand, during the manikin test, there is a general air gap distribution between the clothing system and the manikin body due to the unique shape of human body and the drape of clothing systems.[28] The air gap acts as an efficient insulator and provides more thermal insulation against flash fire; as a result, the OMAF value obtained in the manikin test is expected to be lower than the corresponding MAF value in the bench-scale test.

Conclusion

A new method to assess the performance of protective clothing upon thermal exposure was proposed in this study. This method can be used during both the bench-scale test and the manikin test, and it overcomes many of the shortcomings in the current standard test methods.

Statistical analysis of the data obtained from this study shows that the proposed method has a high repeatability. In the bench-scale test, utilizing the proposed MAF to second-degree burn injury, the performance of the fabric can be rated even with fixed duration of exposure. It demonstrates that the MAF value is highly related to the TPE values obtained from the standard test method. In the manikin test, the difference in the local thermal insulation can be easily detected with the introduction of the MAF index. Also, it provides the information about the locations at which second-degree burn injury is predicted only if the MAF is over 1.0. The second-degree burn areas detected by the MAF method agree well with that found by the standard test method. The result obtained in this study shows that the OMAF of the garment correlates well with the total percentage of the burn injury. By using the MAF method, the results derived from the bench-scale test can be compared with the results from the manikin test as the test procedure and the evaluation index are unified in this study.

Declaration of conflicting interests

The authors declare that there is no conflict of interest.

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