RELATIONSHIP BETWEEN TOTAL HEAT LOSS AND THERMAL PROTECTIVE PERFORMANCE OF FIREFIGHTER PROTECTIVE CLOTHING AND CONSEQUENT INFLUENCE ON BURN INJURY PREDICTION VIA FLAME-ENGULFMENT MANIKIN TEST

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Firefighter protective clothing (FPC) provides barrier protection from hazardous materials. Two of the important performance factors tested for FPC are total heat loss (THL) and thermal protective performance (TPP). The present study evaluated the relationship between THL and TPP, and tested its subsequent influence on burn injury prediction via the flame-engulfment manikin test, using three FPC samples from the United States, Europe, and South Korea. The study results showed an inverse relationship between THL and TPP ($r=-.949$, $p<.001$). Predicted total area of second and third degree burn injury was 7.2±1.6, 19.7±4.1, and 5.0±1.0% for the United States, European, and South Korean FPC, respectively, which was significantly explained by both THL and TPP ($F=34.630$, $p=0.001$, $R^2=.920$). The flame manikin test results showed that affected burn injury areas are not uniform over the body, but more frequent on the head and limbs.

INTRODUCTION

Firefighting is one of the most dangerous jobs, and requires specialized equipment and strategies to safely and effectively respond to fire emergencies. It is essential for this profession to wear firefighter protective clothing (FPC) to provide barrier protection from the dermal contact of hazardous materials such as heat, flame, and combusted products. Therefore, FPC is tested for various aspects of its protective performance both in textile and clothing levels via standardized bench scale and manikin tests, respectively.

Two of the commonly considered performance criteria for the selection of FPC in the United States are the rating of total heat loss (THL) and thermal protective performance (TPP). Both are bench scale test derived values from a sample textile of FPC. THL shows the capability of a textile to lose heat through the combination of evaporative and dry heat exchange related to user comfort, whereas TPP shows the capability of a textile to resist thermal exposure from the combination of radiant and convective heat related to user protection.

While several textile and clothing factors affect THL and TPP variably, there is a general understanding that an inverse relationship (or tradeoff) exists between the two performance factors, making it somewhat difficult to find an optimal performance level that may largely depend on the nature of emergency scenes (e.g. wildland vs. structural FPC). Further, there is an inherent limitation in these tests. The protective performance factors evaluated at the textile level may not be directly applicable to actual FPC wearing conditions. Other known clothing and human factors (e.g. insulating air layer, metabolic heat production, uneven distribution of skin temperature/depth, etc.) may affect the wearing conditions.

There is little data available regarding how different combinations of THL and TPP composites affect the overall thermal protective performance of FPC. Therefore, the aim of this study was to evaluate the relationship between bench scale test derived values of THL and TPP, and consequent effects on the prediction of burn injury by utilizing the flame-engulfment manikin test which simulates more realistic thermal exposure scenarios firefighters may encounter during field operations. For these purposes, we have tested three representative sets of FPC certified and widely used in the United States, Europe, and South Korea.

METHODS

Firefighter Protective Clothing

Three representative FPCs for structural firefighters, certified and widely used in the United States, Europe, and South Korea were procured for this study. Composite samples for THL and TPP tests were directly obtained from FPC jackets to ensure the samples are tested in the same way FPCs are configured. A complete set of each FPC for a flame-engulfment manikin test consisted of jacket, pants, balaclava, helmet, gloves, and boots from its own combination, together with a set of underwear (100% cotton, t-shirt and briefs).

Bench Scale Test for THL and TPP

THL of each FPC composite was determined on a sweating guarded hotplate according to ASTM F1868: Part C (2014) with the fabric specimen directly obtained from each set of FPC. Following the standard procedure, THL values (W/m^2) were calculated based on the measured intrinsic thermal resistance and apparent intrinsic evaporative resistance. TPP of each FPC composite was determined on a thermal protective performance tester according to ISO 17492 (2003) with a fabric specimen directly obtained from each set of FPC. Following the standard procedure, TPP was tested under a total incident heat flux of 85 kW/m^2 (with 50/50 convective and radiant heat flux) on a sample. TPP values (Cal/cm^2), the amount of heat energy per surface area passing through the sample, and consequently the time (seconds) that would cause the second degree burn injuries at the given TPP, were calculated. All THL and TPP tests were triplicated for each set of FPC.

Flame-engulfment Manikin Test

The flame manikin test of each complete set of FPC was carried out on a flash fire manikin instrumented with 131 thermocouple sensors throughout 10 body zones (head, chest, abdomen, upper back, lower back, left and right arms, left and right legs, and feet). The simulated flash fire exposure was carried out by 12 propane gas burners positioned at the lower and upper levels of, and surrounding, the manikin. The exposure time was 8 seconds and the test was triplicated on a completely new set of FPC. According to ASTM F1930 (2015), the predicted area of second and third degree burn injuries (%) was calculated using a prediction skin model.

Data Analysis

Pearson's correlation coefficient between THL and TPP was determined by pooling all individual test results. A multiple regression analysis was carried out to determine whether the area of burn injuries assessed via the flame-engulfment test can be predicted based on THL and TPP values. A significant level was set at $p<.05$ and all analyses were carried out using a statistical software package (SPSS v.19).

RESULTS & DISCUSSION

THL and TPP test results are summarized in Table 1. According to NFPA 1971 (2013), the average THL shall not be less than 205 W/m^2 and TPP shall not be less than 35 Cal/cm^2 for structural FPC. Therefore, all samples met the THL criteria, but the European sample did not pass the TPP criteria. However, it should be noted that European FPC is certified according to a European standard (UNE-EN 367, 1994) by which the sample used meets its own FPC performance criteria.

As expected, there was a significant inverse relationship between THL and TPP ($r=-.949$, $p<.001$), confirming a tradeoff between the two performance factors in line with the previous findings (Xin & Li, 2016). Therefore, with given limitations of the bench scale tests, it may be deduced that FPC, with a higher breathability, has reduced protection against exposure to fire (in other words, time to reach a second degree burn injury is faster). On the other hand, FPC, with a higher TPP, likely increases metabolic heat stress and decreases comfort due to diminished heat exchange.

Table 1. Summary of total heat loss and thermal protective performance results

Sample	Total Heat Loss			Thermal Protective Performance	
	Thermal resistance ($K \cdot m^2/W$)	Evaporative resistance ($kPa \cdot m^2/W$)	THL (W/m^2)	TPP (cal/cm^2)	Heat-transfer burn time (s)
United States	0.1338	0.0148	252.6	44.8	24.8
Europe	0.1368	0.0134	267.8	31.9	18.2
South Korea	0.1819	0.0138	251.5	50.4	27.3

Table 2. Summary of flame-engulfment manikin test results

Sample	Pain area (%)	1st-deg. burn injury area (%)	2nd-deg. burn injury area (%)	3rd-deg. burn injury area (%)	Predicted total area of burn injury (2nd + 3rd deg.; %)
United States	19.6±0.8	1.3±1.7	4.2±1.7	2.9±0.5	7.2±1.6
Europe	24.7±4.9	5.9±0.9	13.1±3.4	6.7±1.6	19.7±4.1
South Korea	21.9±1.7	1.9±0.9	3.7±1.7	1.3±1.7	5.0±1.0

The results for the flame-engulfment manikin tests are summarized in Table 2 and individual test results showing the affected body area and classification of burn injuries are shown in Figure 1. Although not being considered for certification purposes, NFPA 2122 (2012) provides that the manikin test shall have a body burn rating of not more than 50%. Based on this performance specification, all samples met the criteria with a predicted total surface area of second and third degree burn injury. Regression analysis showed that THL and TPP statistically significantly predict the area of burn injuries ($F=34.630$, $p=0.001$, $R^2=.920$) with unstandardized coefficients of .514 and -.350 for THL and TPP, respectively. These results also support the inverse relationship between the two performance factors.

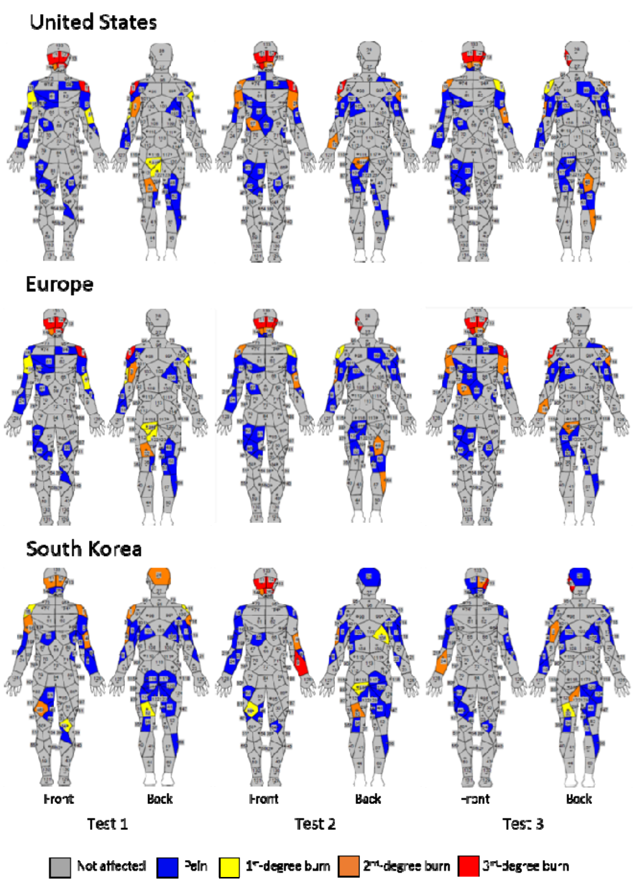

Figure 1. Predicted burn injury on the total area of the manikin covered by firefighter protective clothing

However, a more detailed look into the manikin test regarding the distribution of the burn injury areas provides important findings to consider besides the bench scale based TPP performance. The head (e.g. face) and limbs (e.g. upper arms and legs) are the most commonly burned areas, while the torso, hands, and feet are less burned areas. This implies a need to select and focus on body areas for more protection against fire exposure, while using more breathable and lighter materials on less affected areas may provide better comfort and less physical burdens. However, it is important to emphasize that there are other factors, such as clothing design (e.g. seams, openings) and accessary materials (e.g. pockets, reflective realms), affecting the overall quality of THL and TPP and thereby the prediction of burn injuries through the flame manikin test.

Limitations of this study include that only three samples have been tested and, therefore, a general inference of the present results in terms of the influence of THL and TPP relationship to burn injury prediction should be taken carefully. Also, different designs of FPC helmets do not fit tightly to the manikin’s head in the same way worn by firefighters. Future studies need to better simulate burn injuries on the head area as it has been reported one of the commonly injured areas in firefighters (Kahn et al, 2012).

In conclusion, the present study demonstrated that bench scale THL and TPP are competing performance factors by which the prediction of burn injuries can be affected significantly. The flame manikin test showed that affected burn injury areas are not uniform over the body, but more frequent on the head and limbs.

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