

A prediction method to evaluate thermal performance of protective clothing based on the correlation analysis of the bench scale and flame manikin tests

Thermal
performance of
protective
clothing

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Chang Xu and Shifei Shen

*Department of Engineering Physics, Institute of Public Safety Research,
Tsinghua University, Beijing, China, and*

Ming Fu and Yayun Li

Hefei Institute for Public Safety Research, Tsinghua University, Hefei, China

Abstract

Purpose – Bench scale and flame manikin tests are two typical methods to evaluate thermal protective performance (TPP) of fire protective clothing. However, flame manikin test is limited to be widely used for its complication and high cost. The purpose of this paper is to develop a method to evaluate the thermal performance of protective clothing from the bench scale test results and garment parameters, which predicts the body burn injuries without conducting flame manikin tests.

Design/methodology/approach – Bench scale and flame manikin tests' data were collected from the previous research literature and then statistical analysis was performed to quantitatively investigate the correlations between the two test methods. Equations were established to predict the TPP values accounting for the effects of entrapped air gap and thermal shrinkage. Fitting analysis was conducted to analyze the relationship between the predicted TPP values and total burn injury. Finally, a method to predict total burn injury from the TPP values was proposed and validated.

Findings – The results showed that when the TPP value was predicted with the effects of air gap and thermal shrinkage considered, there was an approximate linear relationship between the predicted TPP values and total burn injury from the manikin test. Therefore, the prediction model of burn injury was developed based on the correlation analysis and verified with a generally good accuracy.

Originality/value – This paper presented a new prediction method to evaluate the thermal performance of protective clothing, which saved significant time and cost compared to the conventional methods. It can provide useful information for burn injury prediction of protective clothing.

Keywords Bench scale test, Flame manikin test, Protective clothing, Thermal protective performance, Air gap, Thermal shrinkage

Paper type Research paper

1. Introduction

Firefighter's protective clothing is used with the characteristics of flame retardant, thermal isolation and stability (Barker, 2005). Bench scale and flame manikin tests are two typical methods to evaluate thermal protective performance (TPP) (Lee *et al.*, 2010). The bench scale test can provide thermal performance of fabrics, and the flame manikin test simulates a real fire exposure environment to get body burn percent and distribution when the manikin dressed in the garment. Although the full-scale flame manikin tests accounting for the effects



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of the air gap, thermal shrinkage and design factors could provide more realistic thermal performance information of the fire protective clothing ensemble, it is limited to be used for its complication and high cost. While the bench scale test is more widely used as it is simpler, quicker and less costly.

There are some studies on the evaluation of the bench scale test to analyze the TPP of protective clothing (Shalev *et al.*, 1984; Torvi, 1998; Sawcyn, 2003; Song, 2007; Sawcyn *et al.*, 2009; Talukdar *et al.*, 2010; Mandal *et al.*, 2014; Udayraj *et al.*, 2017a, 2017b). It was shown that TPP was associated with the type and intensity of heat flux, fabric properties and air gap configuration (Shalev *et al.*, 1984; Udayraj *et al.*, 2017b; Mandal *et al.*, 2014). Fabrics with higher thickness and weight could provide more effective protection in flame and radiant exposure (Shalev *et al.*, 1984). Moreover, the air gap size between the fabric and sensor affected the modes of heat transfer (Sawcyn *et al.*, 2009). Energy mainly transferred through the air gaps by the conduction at a smaller size (< 3 mm), and transferred by the combined radiation and conduction as the gap size increased. The convection occurred when the gap size was more than 7.5 mm, and the predominant form of energy transfer was the combination of radiation and convection (Song, 2007). Meanwhile, some prediction models have been developed to predict the thermal performance, which can be classified into the mathematical models, artificial neural network models and fitting models. Mathematical models had relatively high accuracy, but they were limited in practical applications due to their complexities (Sawcyn *et al.*, 2009; Torvi, 1998; Sawcyn, 2003; Talukdar *et al.*, 2010; Udayraj *et al.*, 2017a). The accuracy of the artificial neural network models were in dependence on the training model and the number of test data (Udayraj *et al.*, 2017c). The fitting models revealed the statistical regression relationships between the heat flux, fabric properties and TPP value (Mandal *et al.*, 2014).

Flame manikin test has also been investigated to analyze the effects of test conditions on burn injury prediction (Dale *et al.*, 1992; Crown *et al.*, 1998; Kim *et al.*, 2002; Song, 2003, 2007; Chitrphiromsri, 2005; Mercer *et al.*, 2008; Ghazy, 2011; Li *et al.*, 2013; Tian *et al.*, 2016). Total burn injury was found to be related with the exposure conditions (heat flux and exposure time), fabric properties (thickness, weight and thermal conductivity), human status (static and running), human posture (upright and knee bending) and garment size and design. It was demonstrated that the unevenly distributed air gap between the garment and manikin surface had a significant effect on the heat transfer (Kim *et al.*, 2002). Moreover, for some kinds of fabric materials like Nomex, thermal shrinkage was found to be severe during the exposure, which decreased the air gap size and greatly affected the heat transfer (Song, 2007). The garment style, closure system and seam type, which can be collectively called as the design factors, also had influences on the thermal performance (Crown *et al.*, 1998). A few numerical models (Song, 2003; Chitrphiromsri, 2005; Mercer *et al.*, 2008; Ghazy, 2011; Tian *et al.*, 2016) have been developed to simulate the heat transfer in protective clothing during flash fire. The effects of the air gap and thermophysical properties of fabrics were also quantitatively analyzed. However, the numerical models to predict total burn injury with a high accuracy in the three-dimensional scale were rather complicated.

The correlation between bench scale and flame manikin tests has been discussed (Pawar, 1995; Crown *et al.*, 2002; Lee *et al.*, 2002; Mah *et al.*, 2010; Wang *et al.*, 2015, 2016). Bench scale and manikin tests both provide effective criteria of thermal performance, with differences in several respects including the orientation of material in the flame, sensor for sample configuration and exposure duration (Pawar, 1995). It was observed that the sensor temperature in areas without air gaps and with small air gaps on the manikin had a good correlation with that of the bench scale test (Pawar, 1995; Lee *et al.*, 2002). Thermal shrinkage was found to be severe in the areas with a large air gap on the manikin, which significantly decreased the gap size and greatly affected the heat transfer (Wang *et al.*, 2016). However, bench scale test described in the NFPA 1771 (2013) and ISO 17492 (2003) can not capture the

shrinkage effect, the air gap size between the fabric and sensor is constant throughout the test process. [Crown *et al.*, \(2002\)](#) measured the TPP values by a new cylindrical bench scale device which could capture the shrinkage effect. During the measurement, the fabric specimens can shrink close to the sensor and may even contact the sensor. The tested TPP results was observed to correlate better with the total burn injury values than that of the conventional planar bench scale test results, suggesting that shrinkage effect should be taken into account when comparing the relationship between the bench scale and flame manikin test. Furthermore, the differences in air gaps due to the garment style and fit significantly affected the burn degree prediction for the manikin test ([Mah *et al.*, 2010](#)). The thermal shrinkage and the garment design, which were not available to be considered in the bench scale test, have great influence on the comparison of two test methods, especially with a large gap size. It is of great value to investigate the quantitatively correlation of the two test methods, which is helpful to predict thermal performance of protective clothing from the simpler bench scale test. However, the previous studies limited on analyzing the relationship by TPP values tested in the fixed air gap condition ([Wang *et al.*, 2015](#)), the effects of the uneven distribution air gap and thermal shrinkage were not included in the correlation analysis model.

This paper aims to develop a prediction method to evaluate thermal performance of protective clothing based on the quantitatively correlation analysis of the bench scale and flame manikin tests. The research findings can provide an insight into the correlation of bench scale and manikin tests and give some guidance to the test methods of protective clothing.

2. Methodology

The flow chart for developing a prediction method to evaluate thermal performance of protective clothing was shown in [Figure 1](#). The data of thermal performance for the fabric and garment samples made of Nomex IIIA material were collected from the previous research literature. Details of fabric samples in the bench scale test were shown in [Table I](#). The data in the flame manikin test were listed in [Table II](#). [Section 2.1, 2.2](#) briefly introduced the experimental setup and [section 2.3](#) described the statistical analysis method.

2.1 Bench scale test

Bench scale tests in the referenced literature ([Li *et al.*, 2015](#); [Wang *et al.*, 2015](#)) were performed in accordance with NFPA 1971 (2013). Schematic of the TPP test apparatus was shown in [Figure 2](#). It consisted of two Meker burners and a bank of nine quartz tubes, to provide a combined flame and radiant heat source. A copper calorimeter test sensor was used in place of human skin to monitor temperature, and a metal spacer was applied to set a specified air gap between the fabric and test sensor. The fire source was set as 84 kW/m^2 , with 50 percent radiative and 50 percent convective heat flux. The TPP value was calculated as the time to

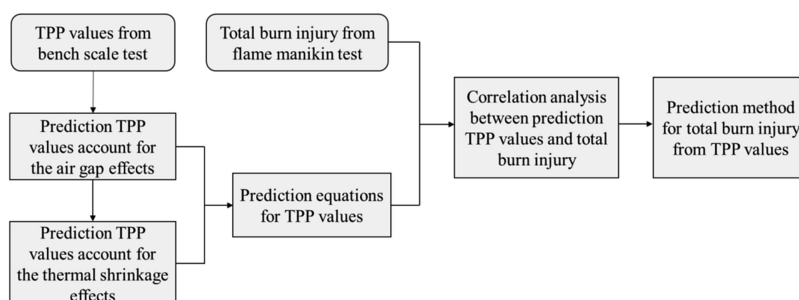


Figure 1.
Flow chart for
developing a prediction
method to evaluate
thermal performance of
protective clothing

Table I.
Details of fabric
samples in the bench
scale test

References	Gap size (mm)	Thickness (mm)	Weight (g/m ²)	TPP (kJ/m ²)
Li <i>et al.</i> (2015)	0	0.55	150	380
	3	0.55	150	475
	6	0.55	150	545
	9	0.55	150	610
	12	0.55	150	630
	15	0.55	150	608
	18	0.55	150	670
	21	0.55	150	675
	24	0.55	150	670
	0	0.63	210	400
	3	0.63	210	595
	6	0.63	210	645
Wang <i>et al.</i> (2015)	9	0.63	210	655
	12	0.63	210	680
	15	0.63	210	725
	18	0.63	210	730
	21	0.63	210	740
	24	0.63	210	760
	0	0.33	166	336
	0	0.42	198	382.2
	0	0.52	250	445.2
	6.4	0.33	166	541.8
	6.4	0.42	198	609
	6.4	0.52	250	680.4

Table II.
Specification of
garment samples in the
flame manikin test

References	Garment code	Size	Thickness (mm)	Weight (g/m ²)	Averaged air gap size (mm)		Averaged shrinkage rate(%)	Total burn injury (%)
					Before exposure	After exposure		
Song (2003)	G1	42	0.8	203	11.56	4.62	60.03	60.67
Li <i>et al.</i> (2013)	G2	34	0.63	210	9.49	6.07	36.05	68.00
	G3	36	0.63	210	11.68	7.39	36.75	56.10
	G4	38	0.63	210	13.89	7.91	43.05	56.50
	G5	36	0.55	150	11.68	6.53	44.10	80.07
	G6	36	0.58	175	11.68	7.10	39.20	79.73
Wang <i>et al.</i> (2015)	G7	42	0.33	166	25.00	14.86	40.58	59.30
	G8	42	0.52	250	24.42	17.94	27.50	42.60
Wang (2016)	X1	42	0.42	198	24.42	11.66	52.25	70.50
	X2	42	0.53	200	25.20	5.99	76.24	63.74
	X3	42	0.59	250	24.00	4.79	80.03	55.32

reach second degree burn multiplied by the heat flux intensity. The higher TPP value contributed to the better TPP and vice versa.

2.2 Flame manikin test

Flame manikin test in the referenced literature (Song, 2003; Li *et al.*, 2013; Wang *et al.*, 2015; Wang, 2015) were conducted in accordance with ASTM F1930 (2012) and ISO 13506 (2008). The flame manikin was designed to the 50th percentile male dimensions, and more than 120