ISSN: 2277-9655
Scientific Journal Impact Factor: 3.449
(ISRA), Impact Factor: 2.114

IJESRT

INTERNATIONAL JOURNAL OF ENGINEERING SCIENCES & RESEARCH TECHNOLOGY

# THE TESTING EQUIPMENT OF THE FLAME RETARDANT FABRICS: REVIEW

**Dr. Akram H M Ali**

Laboratory of High Performance Fibers & Products, Department of Textiles Engineering, College of Engineering & Industries Technology, Sudan University of Science and Technology, Khartoum, Sudan.

## ABSTRACT

Fire-Retardant clothes and fabrics are a vital necessity to provide amount of thermal protection to prevent injuries which occur as a result of exposure to fire. In relatively recent year, concern for individual working in high risk environments, especially those with the potential of being exposed to thermal source, Fire fighters' protective clothing provides a limited amount of thermal protection from environmental exposures produced by fires. This amount of thermal protection depends on various parameters which are design, materials, construction, and fitting of the protective garments. The present review is an attempt to sum up the recent developments taking place in the modification of testing equipment to measure the fabric performance against thermal hazards. The performance of these thermal protective clothing can be evaluated using a variety of standard tests which are also described.

**KEYWORDS:** Firefighting, flame retardant fabric, testing apparatus, heat flux, thermal hazard.

## INTRODUCTION

Every year people are injured by fire as a result of industrial accidents. For this reason, workers in many industries and the fire service wear thermal protective garments made of specialized fabrics. Thermal insulators may be defined as those materials or combination of materials, with air or evacuated spaces, which will retard the transfer of heat with reasonable effectiveness. Heat flux passing through a participating medium may generally be represented by several mechanisms: free and forced convection, conduction and radiation. The performance of these garments must be tested by some standardized means in order to assess their thermal protective value.

Firefighting protective clothing is usually used for all different activities of the fire fighters. But apart from heat protection function the clothes should also offer protection against swear weather conditions, different mechanical impacts and also should have wear comfort. For example firefighting turnout coats are designed to provide protection for long term exposures to moderate heat fluxes and short term exposure to high heat fluxes which can also occur during the ore of their work.

The common testing methods to check the flammability of textile materials used today in both industry and laboratory are the Limiting Oxygen Index (LOI) Method, Fabric Vertical Flammability Testing Method, Thermogravimetric (TG) Analysis Technique Cone Calorimetry and Micro-Scale Combustion Calorimetry.

To test the thermal stability of the fiber material characterization scholars thermogravimetric method (TG), differential thermal analysis method (DTA), differential scanning calorimetry method (DSC), thermo-mechanical analysis (TMA) and dynamic mechanical thermal method (DMA) systematic thermal analytical methods. However, these methods have various limitations. LOI is a valuable quantitative method to determine a material's ability to ignite, but it is not able to provide other critical information peak heat release rate. Vertical flammability test is not a quantitative method and therefore it is difficult to use this method for evaluating small differences in flame retardant fabric samples. TG only provides information related to a textile material's decomposition, not its combustion in oxygen. The most important parameter in evaluating the fire hazard of a material is the maximum speed at which its fire can generate heat, i.e., the PHRR. None of those analytical techniques are able to measure this parameter. Cone calorimetry is commonly used to evaluate the heat release rate of plastics, but it encounters experimental difficulties for textiles [22].

ISSN: 2277-9655
Scientific Journal Impact Factor: 3.449
(ISRA), Impact Factor: 2.114

## HISTORICAL BACKGROUND

In 2006 Cavanagh and investigated the flame spread rates, heat fluxes and resulting skin burn injuries of different fabric materials (100% cotton and 50% cotton/50% polyester blend) in normal and low-gravity environment [1]. In 2007 Zhu and investigated heat transfer around and within a cylinder enclosed with protective fabrics subjected to a combined convective and radiant heat flux. They have shown that the results of this work should also be valid for other high temperature resistant materials and energy transfer in vertical cylinder enclosure, such as filtering and separation industry [2]. In 2004 Mostafa studied the temperature dependence of the thermal properties of some basalt group samples, collected from different regions in the eastern desert of Egypt. And they concluded that these samples could be considered as thermal insulating materials. And they had supported their idea using TGA. Similarly, XRF and XRD confirmed that these rock samples have a crystalline phase [3].In 2004 Havenith described the methods for physiological load, heat protection, ergonomic design, and loss of performance, rain/moisture protection and conspicuity/visibility of the clothing for evaluation of protective clothing in general and for further development of standards on firefighters clothing [4].

In 2009, Yang have evaluated and analyzed the performance of flame retardant textiles They applied MCC to evaluate the flammability of different textile fabrics including cotton, rayon, cellulose acetate, silk, nylon, polyester, polypropylene, acrylic fibers, Nomex and Kevlar and concluded that MCC is an effective new analytical technique for measuring textile flammability and has great potentials in the research and development of new flame retardants for textiles [5]. In 2009, Tuutle and compared different standards of safety garments for conspicuity of first responders in both daytime and nighttime conditions [6]. In 2009 Sawcyn have presented the improved model of heat transfer in air spaces between test specimens and sensors. This model was able to calculate the temperature increase in the test sensor due to both convection and radiation heat transfer from the test specimen to the test sensor [7].

In 2007 Song discussed the role of air gaps existing in protective garments in providing thermal insulation when exposed to flash fire conditions. The results of flash fire manikin tests demonstrated that the burn predictions occur in smaller air gap areas (locations). Under the lab simulated flash fire conditions, our numerical model predicts that the optimum air gap size is around 7–8 mm for a particular type of one layer protective garment [8]. In 2009 Zhu developed a testing device integrated with a skin simulant sensor and a newly developed skin model for measuring thermal protective properties of flame resistant clothing fabrics, which simulated the cylindrical geometry and heat transport feature of the human body, in particular human limbs [9].

Recently in 2011, Park have assessed the effect of firefighting PPE and simulated strenuous firefighting activity on mobility, balance, and gait [10]. In 2010 Coca and tried to determine the effects of fire fighter protective ensembles on mobility and performance by measuring static and dynamic range of motion and job-related tasks [11]. In 2004 Barker carried out the numerical study of transient heat and moisture transport in firefighter protective clothing under high intensity thermal exposure. This model can be used to predict thermal response and thermal protective performance of the fabric. At different locations on the human body, the maximum durations of flash fire exposure before getting second and third degree burns can also be predicted for various amounts of the free liquid water in the fabric [12].

In 2004 Song and coworkers developed a numerical model to predict skin burn injury resulting from heat transfer through a protective garment worn by an instrumented manikin exposed to laboratory-controlled flash fire exposures [13]. In 2008 Gašperin presented a model-based system for protective garment assessment based on an estimation of the skin injuries during exposure to a flash fire. Their solution relied on a detailed thermal model of the temperature sensors, which serves for a reconstruction of the incident heat flux. The results were supported by extensive experimental runs on over 100 different garments [14]. They also suggested the importance of variable properties of the skin from the subject [15].

In 2009 Zhu have presented the numerical model of the heat transfer within heat-resistant fabric layer considering thermal degradation under fire condition. The numerical model can provide accurate prediction of experimental tests. The model was designed, as much as possible, to accommodate the variable high temperature environment, such as in the oil, gas, petrochemical and fire-fighting industry [16].

In 2008 Cuiand constructed network with a single hidden layer includes nine input nodes, eleven hidden nodes and one output node. And they claimed that the adaptive BP neural network to predict thermal

ISSN: 2277-9655
Scientific Journal Impact Factor: 3.449
(ISRA), Impact Factor: 2.114

protective performance of fabrics is accurate and effective [17]. In 2009 Bhattacharjee presented an approach to calculate the total heat transfer through woven fabrics based on the theories of heat transfer has been discussed [18]. In 2006 Fanglong formulated a new testing apparatus with a skin simulant sensor to assess the potential for skin burn injuries and to evaluate the thermal performance of heat resistant fabrics and then compared the results obtained by using Pennes equation [19]. In 2008 Dai and developed a mathematical model for predicting the temperature and thermal damage suffered by skin due to radiation heating [20]. In 2010 YanJiang have developed an integrated simulator for thermal performance assessment of protective clothing claiming that the study is perhaps the first attempt for full-scale simulation of the burn injury originating from fire events, and it still has many opportunities for improvement with respects to the prediction accuracies [21].

## TEST METHOD

There are a series of advanced and improved thermal protective fabrics or clothing test methods and standards, to test insulation performance for the fabric or to develop and a new test method to establish a more complete assessment of the flame retardant properties. The first standard defining firefighter protective clothing design was developed in the late 1940s. At this point, several organizations including the National Fire Protection Association (NFPA) began implementing performance tests to gauge the performance of thermal protective fabrics [23]. The NFPA continues to monitor the design of modern firefighter protective clothing through the periodically updated NFPA 1971: Standard on Protective Ensembles for Structural Fire Fighting and Proximity Firefighting [24]. This document describes in detail the required design and performance criteria for firefighter protective clothing garments including material specifications, standardized testing procedures, and minimum scoring.

### 3.1 The Thermal Protective Performance (TPP)

When testing a thermal protective fabric under high heat flux conditions, various aspects of the performance of the garment should be evaluated, such as the ability to resist charring, degrading and shrinking during exposures to extreme temperatures. The ability to reduce the transmission of energy to the skin and the corresponding reduction in the extent of an injury can also be tested. In order to test these various aspects of the fabric performance, standardized tests have been developed. Two thermal protective performance (TPP) test methods has received wide application by different associations and standards organizations [25]. One method is ASTM D4108-87, which uses a single laboratory gas burner as the heat source. The other procedure is a more versatile method that combines two gas burners and quartz heaters to provide different mixtures of radiant and convective heat. Typical TPP experimental arrangements use a methane gas flame in combination with a bank of quartz tubes to provide a convective and radiant heat source.

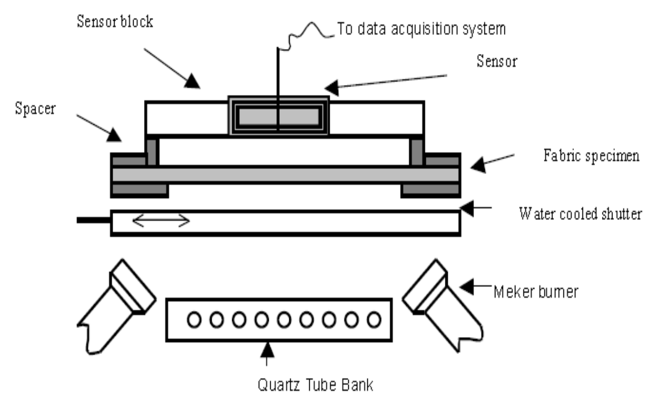


*Figure 1. Schematic Diagram of TPP Tester*

The TPP test is a convenient, precise and a relatively inexpensive means of comparing the thermal protective performance of fabrics. However, TPP tests are limited to a certain heat exposures, and to the configuration of test fabric. They cannot provide any information about the spatial effects which may be important in predicting the protective performance of clothing worn on the human body. They either cannot provide any information on the effects of garment design and construction, nor the role of seams, closures, pockets or vents to thermal protective performance by clothing in actual wear [26]. TPP value calculated as follows:

$$RPP = FT \quad (\text{cal/cm}^2) \tag{1}$$

where F is radiant heat flow 0.5cal / (cm2 • s) or 2.0cal / (of cm2 • s); T time (s) needed to cause second-degree burns.

ISSN: 2277-9655
Scientific Journal Impact Factor: 3.449
(ISRA), Impact Factor: 2.114

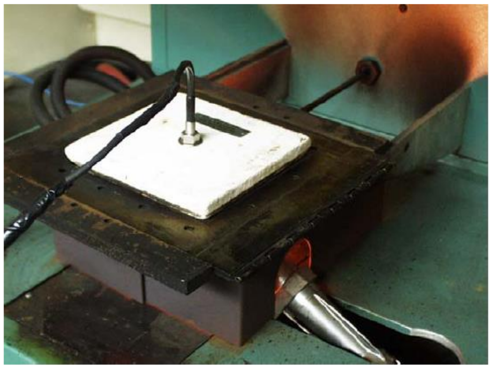

*Figure 2. Close up View of TPP Tester in NCSU*

**3.2 Thermal Radiation Protective Performance (RPP) Test**

The test is the specimen placed vertically before particular radiation heat source within a predetermined distance from the heat source to the 0.5 or 2.0 CA1 / (cm2 • s) (i.e. 21, or 84kW/m2) the heat flux on the sample subjected to heat radiation measuring sample brass behind calorimetry the resulting human skin second degree burns to the time required, and calculate the total calories of this time to obtain RPP (radiation protective performance ) value at exposure conditions brass calorimeter [27]. RPP value indicates that the heat radiation performance of the heat protective clothing, i.e. the better the insulation performance; conversely, the worse the thermal insulation properties.Causing human skin second degree burns of the time needed by the tachograph drawn calorimeter temperature with thermal radiation time curve with second degree burns standard curve intersects obtained. Sample of RPP value calculated as follows:

$$RPP = FT \quad (\text{cal/cm}^2) \tag{2}$$

where F is radiant heat flow 0.5cal / (cm2 • s) or 2.0cal / (of cm2 • s); T time (s) needed to cause second-degree burns.Because thermal radiation is one form of causing thermal damage to the main heat transfer, therefore, the method may be from one aspect the testing and evaluation of the better thermal protective clothing thermal protective performance. From RPP, the TPP test principle can be seen, the two test methods are assumed that the heat source-heat transferred to the surface of the fabric is a flat one dimensional skin simulator is a copper heat flow meter with different properties of human skin, and the heat source to provide the heat transfer mode is not comprehensive enough and tend to the steady-state heat source exposed under a very short time. Therefore, it cannot be a true simulation of the actual usage and expected to burn the extent not provide quantitative estimates. In addition, the TPP test could not be evaluated in the continuous thermal protective performance of heat transfer to cause additional damage fabric.

From test principle of RPP and TPP, the two test methods are assumed that the heat source-heat transferred to the surface of the fabric is a flat one dimensional skin simulator is a copper heat flow meter with different properties of human skin, and the heat source to provide the heat transfer mode is not comprehensive enough and tend to the steady-state heat source exposed under a very short time, and therefore, both cannot be true simulation of the actual usage, and be expected to burn the extent not provide quantitative estimates [28]. In addition, the TPP test could not be evaluated in the continuous thermal protective performance of heat transfer to cause additional damage fabric.

**3.3 Heat Flux Test Method**

This test method is similar to the test principle of the RPP and TPP test method a vertical fabric sample is exposed to the radiant heat source, the radiant heat of the heat source is constant, the thermal radiation within a predetermined distance from the heat source of the sample is within the predetermined time by trial the kind of heat flux may reflect sample heat radiation performance. The size of the heat flux through the sample (s) may the temperature level of the sample on the back of said, the higher the temperature, represented by the greater the heat flux of the sample, the poorer the sample anti-thermal radiation properties; Conversely, a sample heat-resistant radiation performance better. The biggest shortcoming of the test method is to ignore the thermometer measurement inertia error [29].

***3.4.1 Manikin***

All of the RPP, the TPP test methods and heat flux testing method, are based on a small piece of fabric samples for testing. It is difficult to completely reactive fire insulation overall thermal protective performance apparel and defects, so some companies and research institutes to develop combustion dummies model testing device.

Firstly, the DuPont Company with the U.S. Army in the 1970s jointly developed by Thermo-man ® test system, it was subsequently appeared Pyro-Man system of the United States of North Carolina State University and the University of Alberta (Alberta), Canada's "fire people" test System [30]. Substantially, the same as the principle of these types of test systems

ISSN: 2277-9655
Scientific Journal Impact Factor: 3.449
(ISRA), Impact Factor: 2.114

mentioned, are based on the body size of the model, and subjected to laboratory simulated controllable rapid combustion test conditions, including the thermal distribution through the mannequins, the thermal sensor properties, the measurement and calculation conduction through the measured clothing to the body heat, and the temperature of the surface of each part, in order to find firefighting suite and to evaluate the thermal protective performance of the clothing on the human body model, as well as human skin appear second degree and third-degree burns, the manikin test method was used to evaluate the clothing thermal protective and the heat effect on the human body [31], as shown in Figure 3.

A

B

*A: Front View of Fully Dressed Manikin*

*B: Side View of Fully Dressed Manikin*

*Fig 3. Fully View of Manikin*

The experimental device using the Thermo-man ® forecast (excluding hands and feet), displays different parts of the human body burns and burn area of inversion burns, skin burns can also create a three-dimensional human evolution over time, burn analog image, and thus the scene of the fire escape time "to evaluate prediction [32].

Relative to the RPP, TPP and heat flux measurement methods, the combustion of the dummy model test method can better simulate the actual flame burns of the human body and can be used to test the entire retardant protective clothing. And the simulated flame conditions can provide the actual degree of protection for the body. Although the burning dummy method can simulate different conditions and, closer to or into the actual situation, but the dummy stationary in the combustion chamber, the flame sprayed from all directions dummies, and the state of human motion in real fire is not completely consistent. In addition, the higher cost of burning dummy tests, the operation is more complex, and the test repeatability is more convenient.

G. Song developed test manikin using a size of 40 regular male, made from a flame resistant polyester resin reinforced with fiberglass [33]. There are sockets for 122 heat sensors, which are uniformly distributed on the surface. Leads from each sensor are taken to the data acquisition unit through a guarded, heat shielded cable. The manikin is suspended from the ceiling of the burn chamber on an adjustable fixture. A Computer System was used to control the National Instruments data acquisition system, acquire data from the sensor system and to calculate and display the results of the numerical model used to estimate skin damage

In addition, the United States of North Carolina State University, Hummel, Barker [34] and others newly developed model fire test system. Substantially identical to the system with the combustion the manikin test method test principle, using the model of manpower, impose laboratory simulated a controllable flame exposure conditions, the distribution of the thermal sensor by the staff on the model, measurement and calculation is conducted through the measured thermal protective gloves to heat and temperature of manpower to various parts of the surface, and thus predict the manpower of second degree burns and third-degree burns, and burns in the distribution of manpower skin, they have tested and compared the protective properties of different materials and structures of the gloves.

### *3.4.2 Full Scale Testing*

A comprehensive method of testing protective clothing is to outfit a mannequin with a fire protective garment and expose the mannequin to a laboratory fire estimated to simulate an industrial accident as seen in figure 4 [35]. The nominal heat flux of these simulated conditions is approximately 80kW/m2. A discussion of whether this heat flux magnitude is appropriate appears in Torvi [36]. By means of various test sensors placed on the mannequin's skin, the time required to receive second and third-degree burns for human skin

ISSN: 2277-9655
Scientific Journal Impact Factor: 3.449
(ISRA), Impact Factor: 2.114

in the same location as the sensor can be predicted. The major advantage of these full scale tests is that the behavior of the whole garment during a high heat flux exposure can be investigated.

Since some thermal protective fabrics experience extreme shrinkage during exposure areas such as the lower arms and legs may become exposed to the fire. This type of behavior is more easily witnessed during a full scale test. However, there is a large cost, in terms of time and money, associated with conducting this type of test. Consequently, there are limited facilities in existence to conduct full scale thermal protective garment testing.

*Figure 4. Full Scale Testing*

### *3.4.3 Bench Top Tests*

In these tests, convective and radiative heat sources simulate an industrial accident using a heat flux of approximately 80kW/m2. A test sensor is placed behind the fabric to measure the heat flux transferred through the fabric in order to estimate the time required to produce second degree burns in human skin located in the same position as the test sensor. Realistically, the clothing a person wears is not always in direct contact with their skin. This phenomenon is reflected in various tests by either the presence or absence of a finite air gap between the test sensor and the protective fabric. The location of the sensor, either directly in contact with the fabric or with a finite air gap between the sensor and the fabric, will have a large impact on the heat transfer between the fabric and sensor, and hence the predicted skin burns damage.

Previously, Torvi developed a finite element model of the heat transfer in thermal protective fabrics under high heat flux conditions [37]. The purpose of the model was to predict the thermal response of a thermal protective fabric as it is exposed to a high heat flux. The model was also used to estimate the energy transfer between the fabric and the bench top test sensor. As will be shown, the model performed extremely well for smaller air gap values. However, the accuracy of the model decreased as the width of the air gap increased.

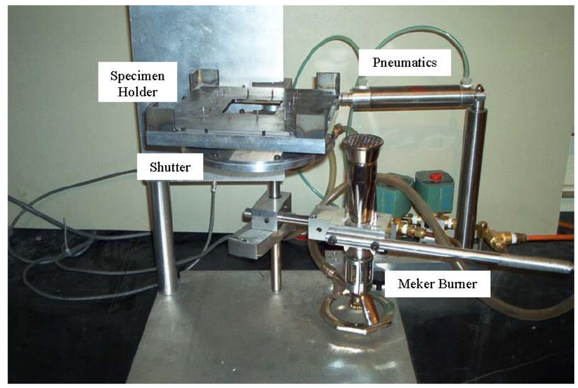


*Figure 5. Photograph of the Bench Top Testing Apparatus*

A more accessible, affordable, and easy method of evaluating thermal protective fabrics is the bench top test. The bench top test allows a small sample of the thermal protective fabric to be tested instead of an entire garment. Also, the need for multiple burners and test sensors is eliminated. One of the first bench top tests was developed by Behnke [38]. This test was used to evaluate fabrics under high heat flux exposures for short durations. Today, similar tests are used that are based on this earlier platform.

In Figure.5 a photograph of the bench top testing apparatus is shown. The apparatus consists of a fabric specimen holder, a Burner Maker, a water-cooled pneumatically-actuated computer-controlled shutter, and a copper calorimeter test sensor (not shown). In 2010, Yang have applied Micro-scale Combustion Calorimetry to evaluate the flammability of different textile fabrics and concluded that MCC is an effective new analytical technique for measuring textile flammability and has great potentials in the research and development of new flame retardants for textiles [39]. The schematic of MCC is shown in Figure. 6.

ISSN: 2277-9655
Scientific Journal Impact Factor: 3.449
(ISRA), Impact Factor: 2.114

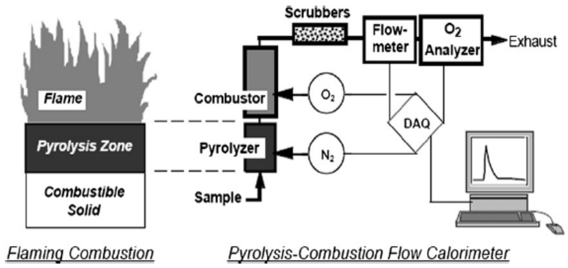


*Figure. 6. A schematic Diagram of Micro-scale Combustion Calorimetry (MCC) [39].*

The heat and moisture transmission through clothing materials or material combinations can be measured by using sweating cylinder in order to find out the best combination of textile materials, which simulate clothing system. Measured thermal comfort properties of material combinations evaluated with a sweating cylinder can provide valuable information for the textile and clothing industry by manufacturing/designing new textiles and clothing systems, shown in Figure.7 [40].

*Figure. 7. A sweating cylinder for measuring heat and moisture transmission through clothing materials*

Thermal protective clothing is primarily designed to provide protection from thermal hazards which include exposure to high temperature radiant sources, flame impingement, hot liquids and gases, molten substances, hot solids and surfaces. Three general categories are used to identify common thermal environmental conditions. These are routine, hazardous, and emergency [41–43]. A great amount of research has been performed on emergency conditions [44–49]. Barker, Shalev and Lee [44-47] have reported extensively on the use of the TPP (NFPA 1971) test to understand the thermal response of single layered fabrics in high heat exposures.

In 2007 Fanglong and proposed a new apparatus to measure heat transmission through protective fabrics using the thermal-electric analog method, which is concerned with the hot plate heat flux determination as shown in Figure. 7.

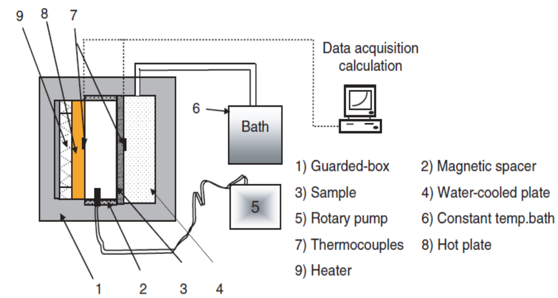


*Fig. 8. A novel experimental apparatus called thermal simulating box is designed to evaluate the heat transmission of protective fabrics subject to radiation/convection heat flux representative of typical high temperature occupational environments [57].*

Recently Song and performed a laboratory simulation to study the thermal protective performance of fabric systems under low level thermal hazards, as shown in Fig. 9. The results obtained have shown the difference in measured protection level under low radiant heat from different approaches and demonstrated that the stored thermal energy released from the clothing system significantly lowers the measured thermal protective performance [58].

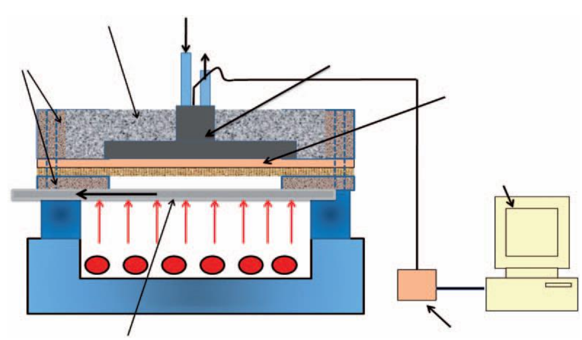

*Figure. 9. A test apparatus used to perform the laboratory simulation of low level radiant thermal hazards [71].*

ISSN: 2277-9655
Scientific Journal Impact Factor: 3.449
(ISRA), Impact Factor: 2.114

## CONCLUSION

- During last few years, there is a huge development in the field of firefighting testing apparatus. The testing methods have been revolutionized throughout the last few years and day by day they are improving a lot. With the expansion of scientific routes and upgrading of the technologies in this field the hazards associated to flames can be diminished considerably.
- Despite the existence of the standardized bench top tests for evaluating fabrics for thermal protective clothing for flash fire and other high heat flux exposure there are still many questions about the thermal response of these then fibrous materials under high heat flux condition. While others have developed analytical and numerical methods of these materials, these models are difficult to use and have not been overly successful predicting fibers
- Protective cloth can be evaluated using test which simulate possible accidents. The evaluation of the protective qualities can be done by a variety of method such as predicting the skin burns that person wearing various fabrics or garment in such accidents will receive
- Additionally, a lot of progression has been observed in the maturity of materials used as moisture barrier and as thermal liner.
- A point should be made here about the dynamics of constructing protective clothing. Tests concerning the effectiveness of fibers or fabrics are only relative guidelines as to how one fabric may perform compared to another. Such tests should be considered as starting points. Many things may affect test results including moisture, thickness, airspace, etc. The insulation value of a fabric or garment changes dramatically when the body bends, twists, sweats, and does work. The use of and results of the manikin test in bum evaluations is a case in point. Even so, the test is a static one and disagreement exists on the procedures and validity of testing.
- With the expansion of scientific routes and upgrading of the technologies in this field the hazards associated to flames can be diminished considerably. In this review efforts have been made to have a look of the research activities taking place in the field during very last few years.

## References

[1] J. M. Cavanagh, D. A. Torvi, K. S. Gabriel and G. A. Ruff, Test Method for Evaluating Fabric Flammability and Predicted Skin Burn Injury in Microgravity, Bremen Microgravity science and technology, (2006) 14

[2] F. Zhu, W. Zhang and G. Song, Heat Transfer in a Cylinder Sheathed by Flame-Resistant Fabrics Exposed to Convective and Radiant Heat Flux, Fire Safety Journal, 43 (2008) 401.

[3] M. S. Mostafa, N. Afify, A. Gaber and E. F. Abu Zaid, Investigation of Thermal Properties of Some Basalt Samples in Egypt, Journal Of Thermal Analysis And Calorimetry, 75 (2004) 179.

[4] G. Havenith and R. Heus, A Test Battery Related to Ergonomics of Protective Clothing, Applied Ergonomics, 33 (2004) 3.

[5] C. Q. Yang, Q. He, R. E. Lyon and Y. Hu, Investigation of the Flammability of Different Textile Fabrics using Micro-Scale Combustion Calorimetry, Polymer Degradation And Stability, 95 (2010) 108.

[6] S. J. Tuttle, J. R. Sayer and M. L. Buonarosa, The Conspicuity Of First-Responder Safety Garments, Journal of Safety Research, 40 (2009) 191.

[7] C. M. J. Sawcyn and D. A. Torvi, Improving Heat Transfer Models of Air Gaps in Bench Top Tests of Thermal Protective Fabrics, Textile Research Journal, 79 ( 2009) 632.

[8] G. Song, Clothing Air Gap Layers and Thermal Protective Performance in Single Layer Garment Journal of Industrial Textiles, 36 (2007)193.

[9] F. Zhu, X. P. Cheng and W. Zhang, Estimation of Thermal Performance of Flame Resistant Clothing Fabrics Sheathing a Cylinder with New Skin Model, Textile Research Journal, 79 (2009) 205.

[10] K. Park, K. S. Rosengren, G. P. Horn, D. L. Smith and E. T. H. Wecksler, Assessing Gait Changes in Firefighters due to Fatigue and Protective Clothing, Safety Science, 49 (2011) 719.

[11] A. Coca, W. J. William, R. J. Roberge, J. B. Powell, Effects of Fire Fighter Protective Ensembles on Mobility and Performance, Applied Ergonomics, 41 (2010) 636.

[12] R. L. Barker, G. Song, H. Hamouda, D. B. Thompson, A. V. Kuznetsov and A. S. Deaton, Modeling of Thermal Protection Outfits for Fire Exposures, National Textile Center Annual Report, (2004) F01-NS50.

[13] G. Song, R. L. Barker, H. Hamouda, A. V. Kuznetsov, P. Chitrphiromsri and R. V. Grimes, Modeling the Thermal Protective Performance of Heat Resistant Garments in Flash Fire, Textile Research Journal, 74 (2004) 1033.

[14] M. Gasperin, D. Juri ci c, B. Musizza, I. Mekjavi, A model-based approach to the evaluation of flame-protective garments, ISA Transactions 47 (2008) 198–210.

[15] D. A. Torvi, Heat Transfer in Thin Fibrous Materials under High Heat Flux Conditions, Ph.D. thesis. University of Alberta, Edmonton, 1997

[16] F. L. Zhu and W. Y. Zhang, Modeling Heat Transfer for Heat-resistant Fabrics Considering Pyrolysis Effect under an External Heat Flux, Journal of Fire Sciences, 27 (2009) 81.

[17] Z. Cui and W. Zhang, Adaptive Neural Network System for Prediction of Thermal Protective Performance of Fabrics, Proceedings of 3rd International Conference on Intelligent System and Knowledge Engineering, (2008) 837.

[18] D. Bhattacharjee and V. K. Kothari, Heat transfer through woven textiles, International Journal of Heat and Mass Transfer, 52 (2009) 2155.

[19] F. Zhu, W, Zhang, and G. Song, Thermal Performance Assessment of Heat Resistant Fabrics Based on a New Thermal Wave Model of Skin Heat Transfer. International Journal of Occupational Safety and Ergonomics, 12 (2006) 43.

[20] W. Dai, H. Wang, P. M. Jordan, R. E. Mickens and A. Bejan, A Mathematical Model for Skin Burn Injury Induced by Radiation Heating, International Journal Of Heat And Mass Transfer, 51 (2008) 5497.

[21] Y. YanJiang, E. Yanai, K.Nishimura, H. Zhang and N. Abe, An Integrated Numerical Simulator For Thermal Performance Assessments Of Firefighters Protective Clothing, Fire Safety Journal, 45 (2010) 314.

[22] C. Q. Yang, Q. He, R. E. Lyon and Y. Hu, Investigation of the Flammability of Different Textile Fabrics using Micro-Scale Combustion Calorimetry, Polymer Degradation and Stability, 95 (2010) 108-115

[23] P. Hasenmeier, The History of Firefighter Personal Protective Equipment, Fire Engineering, 2008. 4(1).

[24] NFPA. NFPA 1971:Standard on Protective Ensembles for Structural Fire Fighting and Proximity Fire Fighting. National Fire Protection Association, 2006.

[25] Behnke, W.P., Thermal Protective Performance for clothing, Fire Technology, 1977,. 13, (1): p. 6-12.

[26] ASTM F1939-08. Standard Test Method for Radiant Heat Resistance of Flame Resistant Clothing Materials with Continuous Heating

[27] ASTM F2702-08. Standard Test Method for Radiant Heat Performance of Flame Resistant Clothing Materials with Burn Injury Prediction

[28] A. M. Stoll, M. A. Chianta, Heat Transfer Through Fabrics as Related to Thermal Injury. Transactions of the New York Academy of Sciences, 1971. 33(7): p. 649-70.

[29] ASTM C177 - 10 Standard Test Method for Steady-State Heat Flux Measurements and Thermal Transmission Properties by Means of the Guarded-Hot-Plate Apparatus.

[30] ASTM E2683 - 09 Standard Test Method for Measuring Heat Flux Using Flush-Mounted Insert Temperature-Gradient Gages.

[31] G, Sun., H. S. Yoo, N. Pan, Radiant Protective and Transport Properties of Fabrics Used by Wildland Firefighter, Textile Research Journal, 2000, 70 (7): 567-573., 2000. 70(7): p. 567-573.

[32] NFPA 2112: Standard on Flame-Resistant Garments for Protection of Industrial Personnel Against Flash Fire.

[33] G. Song, Modeling Thermal Protection Outfits For Fire Exposures. A PhD thesis submitted to the Graduate Faculty of North Carolina State University in partial fulfillment, 2002. UMI: 3107792.

[34] A. Hummel, R. Barker, K. Lyons, A. S. Deaton and J. M. Aslanis, Development of Instrumented Manikin Hands for Characterizing the Thermal Protective Performance of Gloves in Flash Fire Exposures. Fire Technology, 2010. 47(3): p. 615-629.

[35] American Society for Testing and Materials, "ASTM F 1930 Standard Test Method for Evaluation of Flame Resistant Clothing for Protection Against Flash Fire Simulations Using an Instrumented Manikin, West Conshohocken, PA, . 2000.

[36] D. A. Torvi, Heat Transfer In Thin Fibrous Materials Under High Heat Flux Conditions.PhD Thesis, University of Alberta, Edmonton, 1997.

[37] W.P. Behnke, Predicting Flash Fire Protection of Clothing from laboratoy tests using second degree burn to rate terformance. Fire and Materials, 1984. 8: p. 57-63.

[38] Y. Wang, Z. Yijing, L. Jun, Z. M. Meng , Evaluating the Moisture Transfer Property of the Multi-layered Fabric System in Firefighter Turnout Clothing, Fibres & Textiles in Eastern Europe, 2011. 19(6): p. 101-105.

[39] F. Salaun and E. Devaux, Development of Phase Change Materials in Part I: Clothing: Formulation of Microencapsulated Phase Change, Textile Research Journal, 10 (2009) 195.

ISSN: 2277-9655
Scientific Journal Impact Factor: 3.449
(ISRA), Impact Factor: 2.114


[40] X. Wan and J. Fan, A New Method for Measuring the Thermal Regulatory Properties of Phase Change Material (PCM) Fabrics, Measurement Science And Technology, 20 (2009) 025110.

[32] C. Q. Yang, Q. He, R. E. Lyon and Y. Hu, Investigation of the Flammability of Different Textile Fabrics using Micro-Scale Combustion Calorimetry, Polymer Degradation And Stability, 95 (2010) 108.

[41] J. A. Foster and G. V. Roberts, Measurements of the Firefighter Environment-Summary Report, Fire Engineers Journal, 55 (1995) 30.

[42] N. J. Abbott and S. Schulman, Protection from fire: Nonflammable Fabrics and Coatings, Journal of Coated Fabrics, 6 (1976) 48.

[43] B. N. Hoschke, Standards and Specifications for Firefighters Clothing, Fire Safety Journal, 4 (1981) 125.

[44] Y. M. Lee and R. L. Barker, Thermal Protective Performance of Heat-Resistance Fabrics in Various High Intensity Heat Exposures, Textile Research Journal, 57 (1987) 123.

[45] G. Sun, H. S. Yoo, X. S. Zhang and N. Pan, Radiant Protective and Transport Properties of Fabrics used by Wildland Firefighters, Textile Research Journal, 70 (2000) 567.

[46] I. Shalev and R. L. Barker, A Comparison of Laboratory Methods for Evaluating Thermal Protective Performance in Convective/Radiant Exposures, Textile Research Journal, 54 (1984) 648.

[47] I. Shalev I and R. L. Barker, Analysis of Heat Transfer Characteristics of Fabrics in an Open Flame Exposure, Textile Research Journal, 53 (1983) 475.

[48] E. M. Crown, M. Y. Ackerman, J. D. Dale and Y. Tan, Design and Evaluation of Thermal Protective Flightsuits Part 2: Instrumented Mannequin Evaluation, Cloth Textile Research Journal, 16 (1998) 79.

[49] G. Song, R. L. Barker, H. Hamouda, A. V. Kuznetsov, P. Chitrphiromsri and R. V. Grimes, Modeling the Thermal Protective Performance of Heat Resistant Garment in Flash Fire Exposures, Textile Research Journal, 74 (2004) 1033.

[50] Z. Fanglong and Z. Weiyuan, Measuring the Thermal Conductive Property of Protective Fabrics to Radiant Heat Exposure, Journal of Industrial Textiles, 37 (2007) 175.

[51] D. Celcar, H. Meinander and J. Gersak, A Study of the Influence of Different Clothing Materials on Heat and Moisture Transmission Through Clothing Materials, Evaluated using a Sweating Cylinder, International Journal of Clothing Science and Technology, 20 (2008) 119.


## Author Bibliography

**Dr. Akram Hassan Mohammed Ali**

The author did his B.Sc. degree in Textile Engineering at Sudan University of Science and Technology (SUST), Khartoum, Sudan in 2004. M.Sc. Degree in Refrigeration and Air Conditioning at Sudan Academy of Science, Khartoum, Sudan in 2007, and PhD degree in Textile Engineering Donghua University, Shanghai, People republic of china in 2014. He published many articles in the textile engineering field, high performance fiber, technical textiles and composite. His research interests include material, and composite. Dr. Akram Hassan Mohammed Ali is working at the Department of textile engineering- Sudan university of science and technology-Sudan.