Fire Technology, 46, 833–841, 2010

DOI: 10.1007/s10694-010-0139-z

A Heat Transfer Model for Firefighters' Protective Clothing, Continued Developments in Protective Clothing Modeling

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Received: 23 October 2009/**Accepted:** 8 January 2010

Abstract. In the year 2000, a paper entitled "A Heat Transfer Model for Firefighters' Protective Clothing" was published in Volume 36, No. 1, of *Fire Technology,* and it received the 2001 Harry C. Bigglestone Award for Excellence in Written Communication of Fire Protection Concepts from The Fire Protection Research Foundation. Since the publication of this paper, there has been additional development of the heat transfer model. The radiant heat transfer element has been refined, and the model can now address predictions of heat transfer through wet protective clothing materials. Additionally, there has been an extension of the thermal properties database for fabric materials used to manufacture firefighters' protective clothing. These improvements have significantly expanded the capabilities of the model and provide users with a more robust tool for economically predicting thermal protective clothing performance.

Keywords: Heat transfer, Computer modeling, Fire, Firefighter safety, Protective clothing, Thermal insulation, Turnout coats

1. Introduction

The paper "A Heat Transfer Model for Firefighters' Protective Clothing," was an element of a much larger effort that had been underway at the National Institute

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of Standards and Technology, NIST, for several years. The study that generated the heat transfer model followed an earlier effort at NIST that also focused on the protection of firefighters, and it received the 1989, Harry C. Bigglestone Award. This earlier paper by Krasny, Rocket, and Huang was entitled, "Protecting Fire Fighters Exposed in Room Fires: Comparison of Results of Bench Scale Test for Thermal Protection and Conditions During Room Flashover" [1]. The paper by Krasny et al., reported on a study that compared Thermal Protective Performance (TPP) test results from the National Fire Protection Association, NFPA 1971, Standard for Protective Clothing for Structural Fire Fighting, with test results from a series of large-scale room fire tests, conducted by NIST [2]. This and earlier work by NIST and others laid the foundation for the studies that produced the protective clothing heat transfer model.

2. Development of Analytical Test Methods

The first tasks in this program were focused on the development of measurement methods that could be used for detailed evaluations of heat flow through firefighters' protective clothing assemblies. Up to this point in time, heat flow measurements for thermal protective clothing were generally made with a single measurement on the inside surface of a clothing assembly. This provided a measure of total heat flow through a garment system, but it did not provide any data on heat flow through the multiple layers of a thermal protective garment assembly. Therefore, a different approach was needed for determining the thermal performance of the various layers of materials used in the construction of firefighters' protective clothing.

The first measurement method reported from this study addressed the thermal performance of firefighters' protective clothing when exposed to thermal radiation [3]. In this measurement method (Figure 1) a test specimen is heated by a gas-fired radiant panel that provides a heat flux to replicate exposures experienced during firefighting. These thermal exposures can be varied from a low level that is equivalent to an average solar flux during a mid-summers day (approximately 1 kW/m^2) to a high end radiant heat flux that represents a firefighting environment during the onset of room flashover (approximately 50 kW/m^2). The resulting paper from this work describes the test apparatus and test protocol that allows a researcher to measure the thermal performance of protective clothing systems using thermocouples mounted throughout the thickness of a protective clothing assembly. This measurement technique places thermocouples on the surface of the outer shell fabric, at locations between fabric and moisture barrier layers inside the protective clothing system, and at the thermal liner surface where the firefighter's clothing or skin would in contact with the garment. When data sets from these measurements are plotted, the temperature curves provide a detailed picture of how a protective clothing system performs when exposed to a given thermal flux environment. This test apparatus may also be used for investigating the effects of moisture inside protective clothing systems. Moisture can be applied to selected layers of the garment assembly, and then the test garment assembly is exposed to a heat flux.

Figure 1. Radiant panel test apparatus.

Thermal performance of the wet garment assembly is determined by observing temperature changes as the water evaporates and the resulting water vapor passes through the garment. In addition, the test apparatus and measurement methods allow for specimens to be studied for a time period ranging from several seconds to more than 30 min.

In April of 2000, NIST reported on the development of an apparatus (Figure 2) that measured the thermal performance of wet and dry protective clothing systems when exposed to thermal conductive conditions when the fabric assembly is experiencing compression [4]. The dynamic compression test apparatus was developed based on conditions that produced burn injuries to the knees of firefighters. This apparatus has been used to measure the thermal performance of firefighters' protective clothing in either wet or dry firefighting environments. The measurement apparatus design is based on studies conducted by the New York City Fire Department (FDNY) that show the contact surface area of the human knee is approximately 3710 mm^2 (5.75 $in.^2$) for a male firefighter with a body mass of about 79 kg (174 lbs). In addition, the FDNY data showed that a fully equipped firefighter operating a charged 44.5 mm (1¾ in.) hoseline had a mean average knee compression (force per unit area) of 133 kPa (19.3 $lbf/in.^2$). The test apparatus and operating procedures take into account these human data. This test apparatus uses a timer controlled pneumatic piston to compress a thermal sensor against the protective clothing test specimen. In addition, small diameter thermocouples can be placed between the protective clothing layers in order to measure performance conditions throughout the thickness of the garment assembly. Test results from this apparatus discriminate between various levels of thermal performance for protective knee pad systems and other elements of a thermal protective garment that may become compressed.

The next step, following development of the above mentioned apparatus for measuring the thermal performance of firefighters' protective clothing, was the

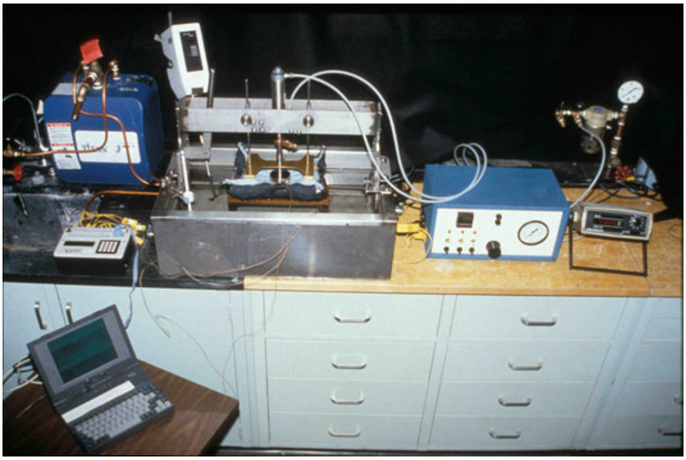

Figure 2. Compression test apparatus.

construction of a physics based model for predicting the thermal performance of protective clothing assemblies. The measurement tools and thermal test methods could be used to quantify the performance of physics based computer models for heat transfer through protective clothing garment assemblies.

3. Development of the Heat Transfer Model

A physics based analytical computer model was developed to provide detailed information on heat transfer through firefighter protective clothing assemblies. Initially, the performance of the model was tested by comparing temperature predictions to temperature measurements of dry, uncompressed, protective clothing from the radiant panel laboratory test apparatus. Efforts to predict the thermal performance of protective clothing assemblies during wet and/or compressed conditions would occur during a later stage of model development.

In order to compute heat transfer via thermal radiation, convection, and conduction the model required material properties and empirically derived constants for the fabrics being studied. Air gaps between garment assembly layers and boundary conditions were taken into account. Values for the thermo-optical properties of the fabrics used in this original work represented the weakest elements of the model and resulted in the largest portion of model prediction errors. Future work which developed estimates of thermal-optical properties specifically for a set of protective clothing fabric materials helped to improve model predictions.

When the work concluded which lead to publishing the 2001 Bigglestone Award paper the model was restricted to dry fabrics and to temperatures and heat flux levels which are low enough that no thermal degradation of the fabric occurs. The paper focused on the formulation of the first stage in a heat transfer model suitable for predicting temperatures and heat flux in firefighter protective clothing.

Therefore, this initial effort was fairly limited in scope. The predictive model made it possible to only study thermal performance of a protective garment during only a small fraction of the environmental conditions that may be experienced during firefighting. It was clear that additional development was needed to broaden the usefulness of the predictive model. Additional work was required in the development of predictions for moisture effects in multi-layered garments systems. Also, it was recognized that a variable-property human skin model would be needed for estimating the potential for the risk of burn injury.

4. Expanding the Thermal Properties Database

The initial modeling work done for the original paper used generic thermal properties data for fabric materials, and it used new estimates of thermal conductivity that were created by NIST the same year as the heat transfer model [5]. This provided a reasonable starting point for the effort; however, more detailed thermal property data was needed to improve the accuracy of the model. Therefore, an effort was carried out to develop a basic set of the necessary data for the fabrics considered. Results from this work were reported in 2005 by NIST, in NISTIR 7282, which is entitled, "Estimates of Thermal Properties for Fire Fighters' Protective Clothing Materials" [6]. In this work, nine materials typically used in the fabrication of fire fighters' protective clothing and one cotton fabric were tested to develop estimates of thermal conductivity, specific heat, and the thermo-optical properties of transmittance, reflectance, and absorptance. These fire fighters' protective clothing materials included outer shell fabrics, moisture barriers, thermal-liner batting, and reflective trim. All measurements were made using commercially manufactured test apparatus and standard test procedures. The materials were tested at a mean room temperature of 20°C (68°F) and across a range of skin tissue temperatures, 48°C (118°F), 55°C (131°F), and 72°C (162°F), known to produce burn injuries in humans. Results measured in this study compared favorably with the thermal properties of several other common materials. Thermal conductivity and specific heat data for the thermal protective clothing materials have been formed into least square equation tables that may be easily referenced for use. Data for the thermo-optical properties are presented in graphical format since each property is strongly dependent on the wavelength of the incident radiation.

The data presented by that report provides a complete set of thermal property values for the selected protective clothing materials. These data, plus the reported density for each material, may be incorporated into computer models for predicting the thermal performance of fire fighters' protective clothing systems. The data presented in the report do not address the thermal performance of fire fighter protective clothing systems that have undergone thermal degradation. Additional work will be required to insure that protective clothing predictive models have valid thermal properties data for clothing that is wet, aged or used, dirty, or thermally degraded. Also, to support general application of predictive modeling, the thermal properties data base must be extended to include all the materials used to manufacture fire fighters' protective clothing.

5. Continuation of Model Development

The primary application of this heat transfer model is to further our understanding of how, and how well, firefighter protective clothing protects human skin from thermal injury when exposed to high intensity thermal radiation. The initial work, which followed the original study, was carried out by Prasad et al. and was described in a report published, in 2002 [7]. In this study, a detailed mathematical model was constructed to study transient heat and moisture transfer through multi-layered fabric assemblies with or without air gaps. The model accounted for changes in thermodynamic and transport properties of the fabric due to the presence of moisture. The governing equations used for transient heat and mass (moisture) transfer through firefighters' protective clothing when subjected to a radiant heat flux were derived from first principles. These equations account for the conductive, convective, and radiative heat transfer through a multi-layered fabric assembly, as well as solving for convection, diffusion, evaporation, condensation, absorption and desorption of moisture through the porous cloth. The effect of moisture on thermodynamic and transport properties was also accounted for in the governing equations.

Numerical simulations were performed to study heat and mass transfer through wet thermal liners (used in firefighters' protective clothing) when subjected to a radiant heat flux from a gas fired radiant panel. Results of the model predictions were found to compare well with the experimental measurements. Peak temperatures predicted by the model were within 10% accuracy when compared to the experimental measurements. The numerical solutions were further analyzed to provide a detailed physical understanding of the governing processes. Results showed that moisture in the cloth tends to vaporize upon heating and part of it diffuses and then condenses on different parts of the fabric, depending on local temperature. Moisture content and distribution along the thickness of the fabric assembly was found to have a profound effect on the computed and measured temperature. It was observed that the temperature of the fabric layers and the total heat flux to the skin is significantly influenced by the amount of moisture and the distribution of moisture in the protective clothing. It was also concluded that moisture can have a significant effect on the observed temperature and heat flux at the human skin surface and can enhance or reduce burn injury (under different conditions) experienced by a firefighter. Finally, simulations were performed for a wet turnout coat assembly to demonstrate the flexibility of the model for designing firefighters' protective clothing.

Following this effort, a software tool called PCPS (Protective Clothing Performance Simulator) was developed for predicting the thermal performance of fire fighter clothing, in protecting the skin from burn injury that results from exposure to high intensity thermal radiation. The software can be obtained by contacting any of the authors, and the work was documented in the NISTIR 6901 report entitled, "Thermal Performance of Fire Fighters Protective Clothing, 2. Protective Clothing Performance Simulator—User's Manual" [8]. The PCPS software allows the user to easily set up a numerical experiment using an interactive Graphical User Interface. The interface allows the user to study transient heat and mass transfer through the multi-layered fabric/skin assemblies with or without air gaps. Fabric layer characteristics, air gap thickness, moisture levels, compression, boundary conditions and other advanced features can be prescribed through the graphical user interface. The results of a simulation can be interactively visualized using a set of pre-defined (x y) plot and animations, included in the software.

Also in January of 2003, a project was completed that used the PCPS to simulate an NFPA 1971, Thermal Protective Performance (TPP) test [2]. Results from this study were reported in NISTIR 6993, "Thermal Performance of Fire Fighters' Protective Clothing. 3. Simulating a TPP Test for Single-Layered Fabrics" [9]. In this work, a series of simulations was performed to predict the response of a single layer of fabric to the high intensity, short duration, convective and radiant heat fluxes that may arise during fire exposures. Figure 3 shows a comparison of numerical simulations performed using the PCPS software and experimental data obtained from a TPP test performed on Nomex III A fabric. The solid navy blue line shows the simulated value of the temperature rise (y axis) plotted as a function of time (x axis) where the thermal exposure is comprised of 50% convective and 50% radiative heat transfer mechanism. The dashed green line and dashed

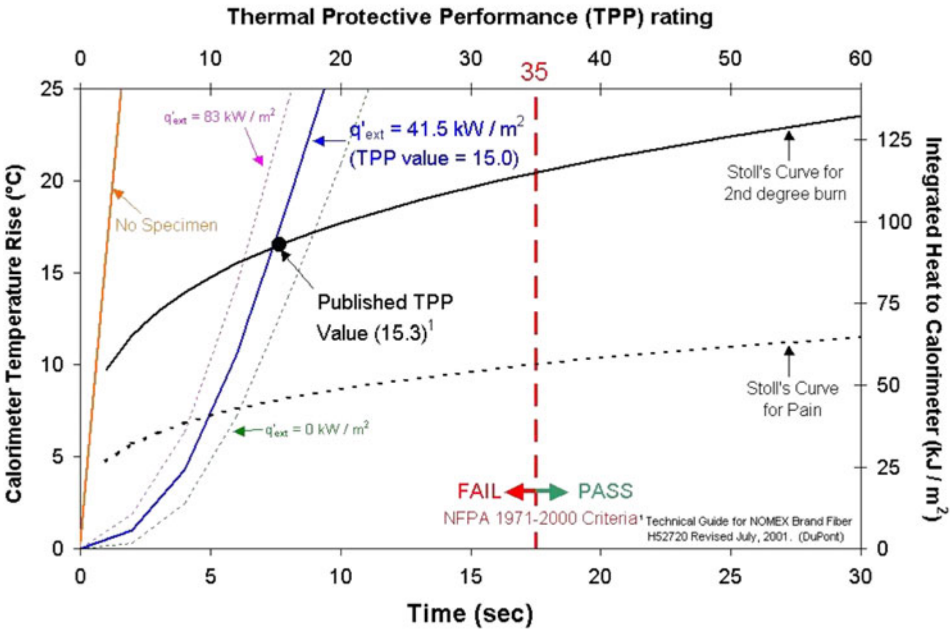

Figure 3. The simulated temperature response for Nomex IIIA fabric plotted as a function of time during a TPP test. Solid lines (navy blue) denote model simulations and discrete points (filled circle) denote experimental measurements. The TPP criteria curve for onset of second-degree burn (solid black line) is also presented. Stoll's curve for onset of pain is indicated by the dashed black line.

purple line show the simulated temperature rise for 0% and 100% radiative thermal exposure, respectively. Stoll's curve for onset of pain (dashed black line) and onset of 2nd degree burn (solid black line) is also indicated. Published experimental data [10] from the TPP test conducted on Nomex III A fabric (indicated by a solid circle) was 15.3, which compares favorably with the predicted TPP value of 15.0. Computer model predictions for different thermal protective clothing fabrics tested as part of this study were within 6% of the experimental results and were within the range of uncertainty for the experimental measurements.

6. Conclusions

As can be seen from the above, work has continued on the development of the heat transfer model for firefighters' protective clothing. It is also clear that additional work is needed to refine the model's performance. It is interesting to note that research and development related to this effort was impaired by the attack on the World Trade Center, on September 11, 2001. Primary researchers who had been developing measurement techniques and the heat transfer model began working with the National Construction Safety Team, and their focus changed to the investigation of events associated with the World Trade Center attack and collapse of the buildings. However, attempts were made during the period following 2001 to continue developmental work on the model. Currently, the heat transfer model for firefighters' protective clothing is a usable tool that can be applied to predicting the thermal performance of protective clothing systems, but it can also be seen that refinements are still needed which will improve the accuracy of the model and will bring the software up to date with current operating systems. Additionally, work needs to continue on the development and extension of a catalog of physical properties data required by the predictive model.

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