ARTICLE

Computational Frameworks for Engineering Firefighter Protective Gear

Sallam Kashif[1,*]

[1] University of Education, Faisalabad, Pakistan

Abstract

A computational model of thermal conduction in firefighter protective apparel is employed to illustrate the influence of key textile attributes under various scenarios. The impact of fabric characteristics during brief, high-intensity heat exposures is contrasted with their behavior during extended, low-intensity heat exposures. Furthermore, the significance of these properties on the cooling rate of garments after exposure is examined. The findings highlight the effectiveness of computational models in designing protective gear and enhance comprehension of the level of safety provided to firefighters by their equipment.

Keywords: Engineering Firefighter, textile attributes, fabric characteristics, heat exposures

Citation
Sallam Kashif (2022). Computational Frameworks for Engineering Firefighter Protective Gear . Mari Papel Y Corrugado, 2022(1), 1–6.

1 Introduction

Firefighting is an extremely hazardous profession that demands extensive physical and mental endurance, alongside specialized gear to protect firefighters from the high temperatures and unpredictable conditions encountered during operations [1, 2]. Among these, the protective clothing worn by firefighters plays a crucial role in safeguarding them against various thermal hazards such as direct flame, radiant heat, and steam [3]. Designing such protective gear, however, involves intricate trade-offs between ensuring adequate thermal insulation and minimizing weight and bulk, which can impede a firefighter's mobility and comfort [4].

Traditionally, the evaluation of these protective garments has relied on physical testing methods that expose fabric samples to simulated fire conditions [5]. While these empirical tests are valuable for understanding how fabrics behave under specific scenarios, they can be time-consuming, costly, and limited in scope. For example, conventional testing might not encompass all the potential conditions a firefighter might face, such as prolonged exposure to lower levels of radiant heat or sudden bursts of high heat flux [1, 2, 6].

To address these limitations, numerical modeling has emerged as a powerful tool in the design and optimization of thermal protective clothing. Numerical models allow researchers to simulate a wider array of thermal exposures and predict how different fabric properties—such as thermal conductivity, heat capacity, and thickness—affect the overall performance of protective garments [7]. This enables designers to explore various material combinations and garment configurations before physical prototypes are made, thus accelerating the development process and reducing costs. In this paper, Torvi and Dale present a numerical model to evaluate the performance of firefighter protective clothing under different thermal exposures. Their work aims to provide deeper insights into the roles that fabric properties play during varying exposure conditions, highlighting the importance of tailoring garment designs to specific fire scenarios [8].

Submitted: 07 January 2022
Accepted: 19 April 2022
Published: 30 June 2022

Vol. 2022, **No.** 1, 2022.

***Corresponding author:**
✉ Sallam Kashif
sallam@gmail.com

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† The author read and approved the final version of paper.

2 Model Description

The numerical model developed in this study is designed to simulate the heat transfer processes occurring in a typical firefighter's protective clothing system, which generally consists of three layers: the outer shell, moisture barrier, and thermal liner. Each of these layers has distinct thermal properties that contribute differently to the overall protective performance of the garment [9].

The outer shell is primarily responsible for resisting external flame and radiant heat. It has high thermal resistance to prevent heat penetration but must also be lightweight to maintain mobility. The moisture barrier serves to keep water and steam out, while the thermal liner offers insulation to protect the skin from heat transfer through the outer layers [10].

In the model, the fabric system is exposed to two different thermal scenarios: a short-duration, high-intensity heat flux and a long-duration, low-intensity heat flux. These scenarios mimic conditions a firefighter might experience, such as flashover in a room fire or prolonged exposure to radiant heat from burning materials. The heat transfer through the fabric system is modeled using a differential equation that takes into account conduction, convection, and radiation. This equation is solved using the finite element method, a numerical technique that divides the fabric into small elements and calculates the temperature changes in each element over time [11].

This model not only captures the temperature distribution across the different layers but also evaluates how varying the properties of each layer—such as thermal conductivity, specific heat, and thickness—impacts the overall heat transfer. The ability to manipulate these variables in the model enables a thorough analysis of how individual fabric properties influence the protective performance under different thermal conditions.

3 Fabric-Air Gap-Sensor/Human Skin System

To evaluate the model's accuracy, the authors use an experimental setup that mimics the conditions of a standard bench test for thermal protective fabrics, such as the ASTM D4108 [12]. This setup consists of a fabric specimen placed above a copper calorimeter sensor, with an air gap between the two. The air gap is crucial as it introduces an additional layer of thermal resistance that can affect the rate of heat transfer through the fabric. The setup simulates heat transfer from a flame to the fabric, then through the fabric and air gap, and finally to the test sensor, which acts as a proxy for human skin.

The heat transfer mechanisms considered in the model include conduction (heat transfer through solid materials), convection (heat transfer between a surface and fluid like air), and radiation (heat transfer through electromagnetic waves). The model is used to predict how the fabric temperature changes over time and how long it takes for heat to penetrate through the fabric layers and cause a burn injury [13].

The air gap between the fabric and skin is of particular interest because it can significantly influence the thermal resistance of the clothing system. Small changes in the air gap size can alter the rate of heat transfer, affecting the time it takes for the heat to reach a critical level that can cause skin burns [14]. By including this air gap in the model, the authors aim to replicate the complex interactions that occur in real-life scenarios, where the fit and movement of the clothing can create varying air gaps between the fabric and skin.

The heat transfer model developed in this study is based on the fundamental principles of thermal conduction, convection, and radiation. It is expressed as a differential equation that represents the rate of temperature change within the fabric layers over time. The model takes into account the density, specific heat, and thermal conductivity of each layer, as well as the net heat flux from external sources such as flames and hot surfaces.

The differential equation is solved using the finite element method, which divides the fabric system into small, discrete elements. Each element is analyzed independently, and the results are then integrated to provide a comprehensive view of the temperature distribution across the entire fabric system. The finite element method is particularly well-suited for this type of analysis because it can accommodate complex geometries and varying material properties, making it ideal for simulating the layered structure of firefighter protective clothing.

In addition to predicting fabric temperatures, the model is used to estimate the time required for the heat to penetrate through the fabric layers and reach a temperature that would cause second- or third-degree burns to human skin. This burn prediction is based on established criteria, such as the Stoll criterion, which defines the threshold temperature and exposure time required to cause skin damage.

4 Results and Discussion

The results from the numerical model presented in this study provide a comprehensive understanding of how variations in fabric properties influence the thermal performance of firefighters' protective clothing under different heat exposure conditions. These findings shed light on the critical role that thermal conductivity, specific heat, and fabric thickness play in determining the effectiveness of protective gear in preventing burn injuries. In this section, we delve into the detailed outcomes of the simulations and discuss their implications for the design of protective clothing, the limitations of the current model, and potential directions for further research and refinement.

4.1 Influence of Thermal Conductivity

Thermal conductivity is a key parameter that determines the rate at which heat is conducted through a material. The results of the study reveal that higher thermal conductivity leads to faster heat transfer through the fabric layers, which can reduce the time required for heat to reach the skin, thereby increasing the risk of burn injuries. For example, when the fabric is exposed to a high-intensity heat flux for a short duration, as simulated in the model, fabrics with higher thermal conductivity allow heat to penetrate more rapidly, causing a steep rise in temperature at the inner surface of the fabric.

This behavior is particularly critical in situations where firefighters are exposed to sudden bursts of high heat, such as flashovers in a confined space. In these scenarios, the time to reach critical skin temperatures (e.g., temperatures associated with second- or third-degree burns) can be significantly reduced for fabrics with higher thermal conductivity. As such, selecting materials with lower thermal conductivity for outer shell fabrics can be beneficial in delaying heat transfer to the inner layers, thereby providing additional time for firefighters to escape or reposition themselves.

However, the study also indicates that the effect of thermal conductivity varies depending on the type of exposure. During prolonged exposure to a lower heat flux, the influence of thermal conductivity becomes less pronounced. In these cases, other factors, such as specific heat and thickness, play a more significant role in determining the protective performance of the garment. This finding suggests that material selection should be tailored to the specific exposure conditions firefighters are likely to face, with a focus on minimizing thermal conductivity for high-intensity, short-duration exposures.

4.2 Impact of Specific Heat on Thermal Protection

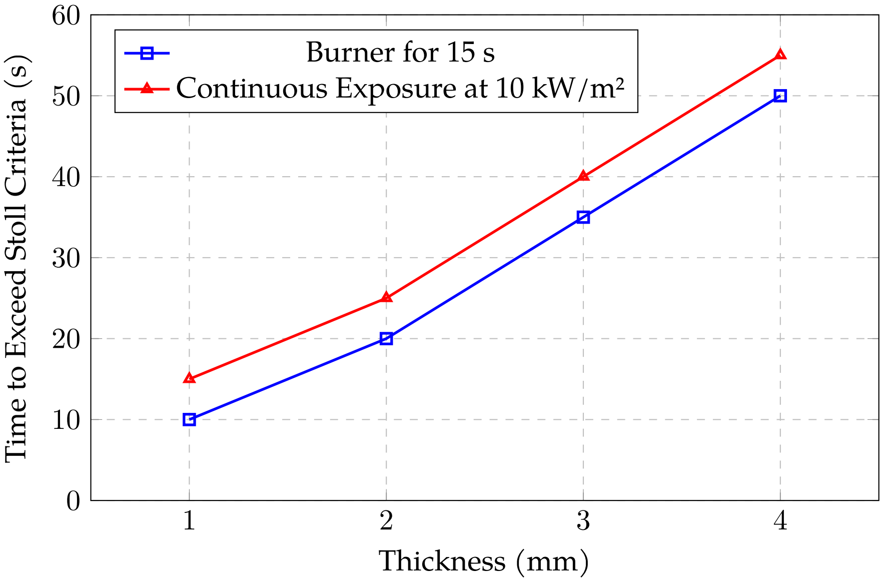
Specific heat, which defines the amount of energy required to raise the temperature of a unit mass of material, has a profound effect on the thermal performance of protective clothing. The numerical model shows that fabrics with higher specific heat are capable of absorbing more energy before their temperature rises significantly. As a result, materials with a high specific heat can slow down the rate of temperature increase, providing a buffer period before heat penetrates to the inner layers and reaches the skin.

This characteristic is particularly advantageous during short-duration, high-intensity exposures. For such conditions, the ability of the fabric to absorb and temporarily store energy can prevent a rapid temperature rise on the inside surface of the fabric, thereby delaying the onset of skin burns. Consequently, fabrics with a high specific heat are preferable in scenarios involving intense but brief exposures to heat.

On the other hand, the results indicate that for long-duration exposures, a high specific heat can become a disadvantage. While the fabric initially absorbs a large amount of energy, it also releases this energy slowly over time, which can lead to sustained heat transfer to the skin even after the external heat source has been removed. This prolonged heat release can potentially cause burns at a later stage, even if the initial exposure was not severe enough to cause immediate damage. Hence, in situations where firefighters are expected to be exposed to heat over extended periods, fabrics with a lower specific heat may be more effective in preventing delayed burn injuries.

4.3 Role of Fabric Thickness

Fabric thickness is another critical factor that influences the thermal insulation properties of protective clothing. The results from the numerical model show that increasing fabric thickness generally enhances the thermal resistance of the clothing, which helps in reducing the rate of heat transfer through the fabric. This effect is particularly pronounced for short-duration exposures to high-intensity heat fluxes. Thicker fabrics create a larger thermal barrier, which results in lower temperatures on the inner surface of the fabric, thereby delaying the time required for the heat to penetrate to the skin.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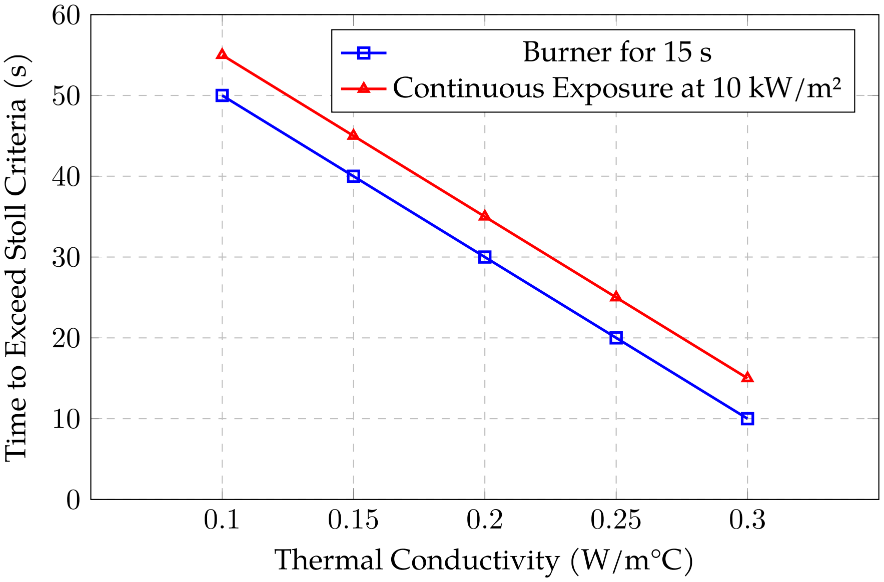
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However, the study also highlights a diminishing return effect as fabric thickness increases beyond a certain point. While thicker fabrics do provide better insulation, the additional benefits become marginal at higher thicknesses. Furthermore, increasing fabric thickness can lead to other practical drawbacks, such as reduced mobility, increased weight, and higher heat stress on the wearer due to decreased breathability. Therefore, a balanced approach is required when considering fabric thickness, ensuring that it is sufficient to provide thermal protection without compromising other functional aspects of the protective clothing.

4.4 Comparison of Different Exposure Conditions

The numerical model evaluates two distinct types of thermal exposures: a short-duration, high-intensity heat flux and a long-duration, low-intensity heat flux. The results indicate that the effectiveness of different fabric properties varies significantly depending on the exposure scenario. For short-duration, high-intensity exposures, low thermal conductivity and high specific heat are crucial in providing the best protection, as they slow down heat transfer and absorb more energy without a rapid temperature increase.

In contrast, for long-duration, low-intensity exposures, maintaining a moderate level of thermal conductivity and lower specific heat can be beneficial to prevent the fabric from storing excessive energy that might lead to sustained heat transfer to the skin. This variation in the behavior of different fabric properties under diverse exposure conditions underscores the need for a more nuanced approach to fabric selection, where the expected exposure conditions dictate the choice of materials and fabric configurations.

4.5 Limitations and Future Directions

While the results of the numerical model provide valuable insights into the thermal behavior of firefighter protective clothing, the study acknowledges several limitations that must be addressed in future research. One limitation is that the current model does not account for the effects of moisture transfer within the fabric layers. Moisture plays a significant role in thermal protection, as the presence of water in the fabric can alter heat transfer rates and potentially lead to steam burns. Incorporating moisture transfer into the model would provide a more realistic representation of the fabric's behavior under actual firefighting conditions.

Additionally, the model assumes constant thermal properties for the fabric layers, which may not accurately reflect the changes in these properties at high temperatures. Future research should focus on integrating variable thermal properties into the model to capture the complex interactions between heat and fabric materials at elevated temperatures. Moreover, physiological effects such as sweating and increased blood flow to the skin, which can influence heat transfer and the onset of skin burns, should also be included in more sophisticated models.

Overall, the results from this numerical study demonstrate the critical role of fabric properties in determining the thermal performance of firefighter protective clothing. By providing a deeper understanding of these interactions, the model serves as a valuable tool for optimizing protective clothing designs and guiding material selection based on specific exposure conditions.

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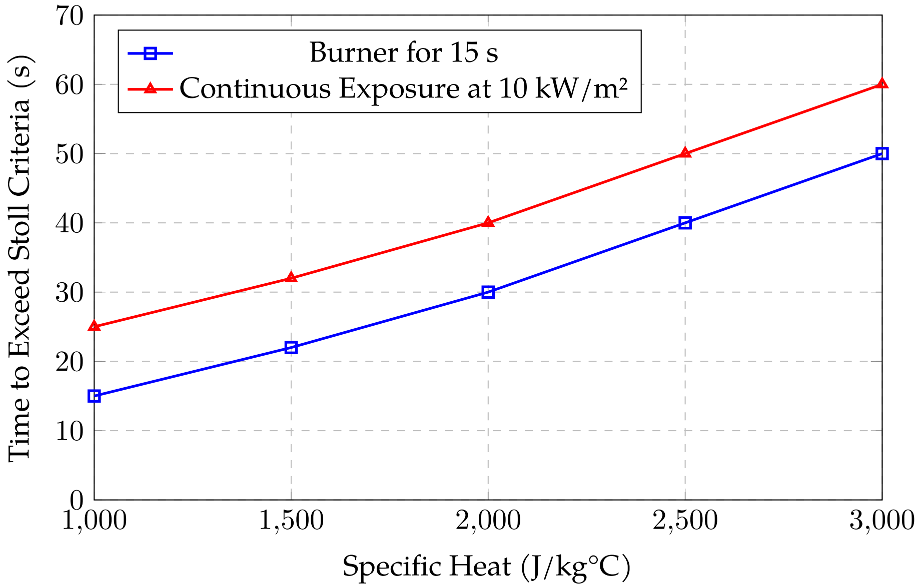

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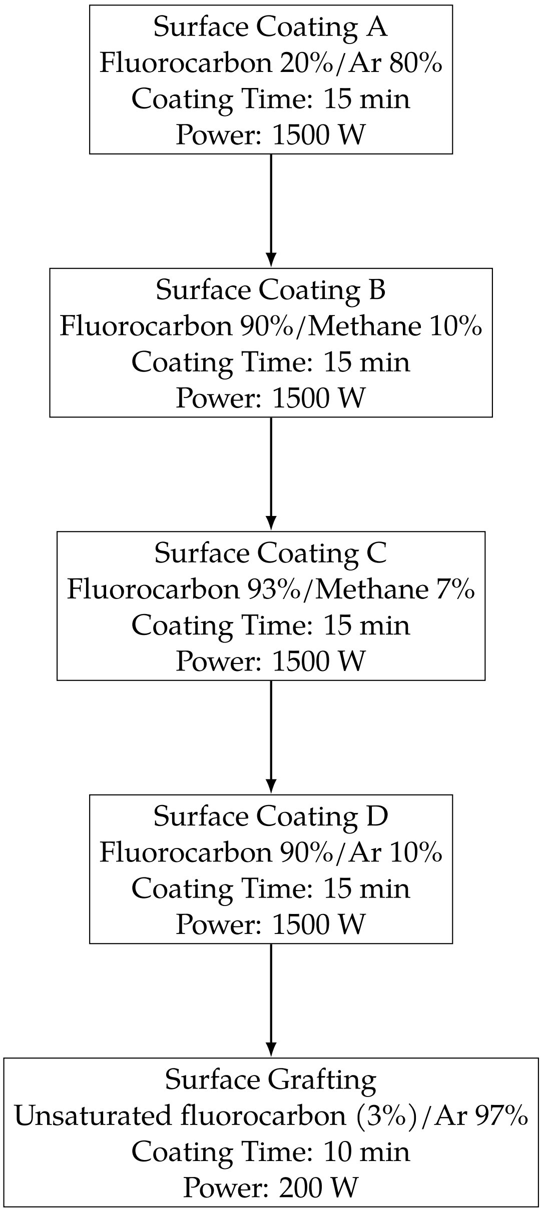

Figure 1. Representation of Surface Coatings and their Parameters