CHARACTERIZING THE TENSILE STRENGTH OF OUTER LAYER FABRICS USED IN FIREFIGHTERS' PROTECTIVE CLOTHING UNDER RADIANT HEAT EXPOSURE

By

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Abstract: More than sixty thousand firefighters' injuries have been reported by the National Fire Protection Association (NFPA) in U.S. in 2019. Inadequate protection of the uniform worn by the firefighters could be reason for most of the injuries. Firefighters repeatedly encounter various hazards especially thermal hazards during routine exercise, on-site firefighting, and emergency rescue. Degradation could occur on the bunker gear's fabric, which comes repeatedly in direct contact to thermal hazards when worn in the fire ground. It has also been found that performance of the fabric is extensively affected by the moisture accumulated in the fabric, which may come from the wearers' sweat. Proper evaluation and accurate prediction of the tensile strength of the high-performance fabrics used in both single and multi-layer clothing system could help maintain the overall integrity of the bunker gear and reduce firefighter injuries. This study focuses on evaluation of tensile strength of the fabrics when exposed to 10, 15, and 20 kW/m^2 radiant heat fluxes. Different levels of moisture were added to the test samples to simulate the wearers' sweating. In each fabric system, a total of sixty-four different samples were prepared for four different types of fabric, four levels of moisture and exposed to three different heat fluxes for five minutes. Results show that heat flux and moisture levels have significant impact on fabric tensile strength. Moisture had significant more effect on tensile strength in three-layered fabric system compared to the single layer fabric system depending upon the heat flux and fabric properties. This study leads to an understanding on the impact of fabric strength in the presence of fire and moisture; this understanding could lead towards development of new fabrics that could provide better protection for firefighters.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER I

INTRODUCTION

Firefighting is considered a dangerous occupation because of the environment in which firefighters work. Fire departments in the U.S. responded to 1.3 million fires in 2019, and there is always the risk of death and injury for on-duty firefighters (Ahrens & Evarts, 2020; Smith, 2008). Based on the survey "United States Firefighter Injuries in 2019", the National Fire Protection Association (NFPA) estimated that in 2019 over 60,000 firefighters' injuries occurred in the line of duty. Around 40% of these injuries happened at the fire-ground, areas where firefighting operations are carried out (Ahrens & Evarts, 2020; Campbell & Evarts, 2020). In total, forty-eight firefighters died while on duty in the U.S. in 2019 (Fahy et al., 2020). Improved protective clothing can minimize the risk of injuries to the firefighters (McLellan & Selkirk, 2006).

Thermal protective clothing is mainly designed to protect firefighters from thermal hazards like high temperature, radiant heat, hot liquids and surfaces, hot solids and gases, molten substances, etc. (Abbott & Schulman, 1976; Foster & Roberts, 1994; Lawson, 1997; Lawson & Jason, 1996; Rossi, 2003; Song et al., 2011). Researchers statistically determined the key properties of the fabrics affecting the protective performance (Mandal et al., 2019). It has been found that the thermal protective performance of the bunker gear is affected mostly by the thermal and evaporative resistance of the fabrics. The performance of the clothing is affected by fabric properties such as thickness, air permeability, clothing size, and garment ease, or the size of the air gap between wearers' bodies and clothing. These properties control heat and mass transfer through clothing systems that influence the thermal protective performance of gear (Mandal et al., 2018; Mandal et al., 2019; Mandal et al., 2014; S. Mandal & G Song, 2012; S. Mandal & G. Song, 2012; Mandal & Song, 2014; Mandal, Song, & Grover, 2021; Mandal, Song, Rossi, et al., 2021; Wang et al., 2018).

It has also been found that protective and comfort performances of the fabric are affected by the moisture accumulated inside the fabric (Barker et al., 2006; Ghazy & Bergstrom, 2011; Guan, Annaheim, et al., 2019; He et al., 2016; Keiser et al., 2008; Lawson et al., 2004; Lee & Barker, 1986; Veghte, 1987; Zhang et al., 2018; Zhiying et al., 2010). Moisture affects both the protective and comfort performance of thermal protective clothing. Altering the protection properties is not the only problem. Moisture in the fabric can turn to steam and cause steam burn. Moisture from sweat is accumulated in the two layers nearest the skin; for example, the underwear and inner layer. To understand the distribution of the moisture in the different layers it is very important to understand the occurrence of steam burn (Keiser et al., 2008).

Barker states that moisture negatively affects the protective performance of the fabric most severely when the amount of added moisture is lower (2006). Second degree burn time is lower at critical moisture level (15-20%). If the moisture level increases beyond a critical level, time for second degree burn increases. The lowest protective performance at the critical moisture level is due to the large difference in thermal conductivity between the bunker gear and water. On the other hand, the increase in protective performance with increased moisture beyond the critical level is due to the large difference in specific heat of the protective clothing system and water (Barker et al., 2006). When exposed to radiant heat, wetted samples provided more thermal protection than dry samples (Veghte, 1987). Depending on the heat intensity, heat transfer may be increased or decreased by the moisture in the clothing system. Under high heat flux flame exposure, internal moisture increases the heat transfer. This scenario is reversed for the low heat flux flame exposure. Under low heat flux exposure, the internal moisture has a tendency to decrease the heat transfer of a two layered wildland firefighters' clothing system where the inner layer was completely soaked (Lawson et al., 2004).

Moreover, the thermal protective fabrics are exposed to various thermal hazards (i.e., radiant heat, steam, hot fluids, etc.) during their lifetime. The outer layer of the fabric comes into direct exposure of these hazards every time bunker gear is worn to a fireground. These hazards might cause polymer chain scission of the fiber which may lead to a change in tensile strength. This changes the integrity of the clothing, which is rarely considered. However, the loss of protective performance due to the loss of tensile strength, which is caused by the polymer degradation of the fiber of the outer layer, might not be detected visually until the damage is extreme. The reduction of thermal protective performance due to the potential strength loss of the outer layer fabric not only has an economic cost, but also it is related to the safety of the firefighters. Therefore, it is very important to know how the outer layer is effected as it is exposed to various thermal hazards over time, and how this affects the thermal protective performance (Cui et al., 2015; Lu et al., 2018).

Many researchers studied the effects of repeated exposure to heat of personal protective gear (Cui et al., 2015; Deng et al., 2020; Lu et al., 2018). Studies included intensity of heat flux, time and frequency of exposure, among others. Lu et al. (2018) found that high heat exposure causes more loss of tensile strength compared to low heat exposure. These researchers also found that at the same heat level the duration of exposure time has an effect on the loss of tensile strength. The more exposure time, the more loss of strength (Lu et al., 2018). Cui et al. (2015) also studied fire protective gear which was subjected to low radiant heat exposure. The researchers found similar kinds of results - that the amount of heat intensity has significant effects on the mechanical performance of the fabrics. However, these researchers reported that the thermal protective performance did not change considerably compared to the mechanical properties (Cui et al., 2015). Aidani et al. (2011) did similar kinds of experiments with a moisture barrier. In this study effects of repeated heat exposure of a moisture barrier were evaluated at five different temperatures between 190 and 320 °C. The results showed significant changes of mechanical properties of the moisture barrier due to repeated thermal exposure (Aidani et al., 2011). Deng et al. (2020) evaluated the effects of flash fire on the mechanical properties of single layer thermal protective fabrics. Similar kinds of results were found; the heat flux significantly affected the mechanical properties of the thermal protective fabrics (Deng et al., 2020).

The strength loss of the outer layer due to repeated thermal exposure could disintegrate the clothing system. Due to the structural change of the clothing system, the protective performance of the overall clothing system would also be changed. This ultimately could contribute to the causes of injury to firefighters. As of now, only a small amount of research has been done to examine the change of strength of the fabrics used in bunker gear due to radiant heat exposure (Aidani et al., 2011; Arrieta et al., 2010; Cui et al., 2015; Davis et al., 2010; Day et al., 1988; Deng et al., 2020; Dolez et al., 2019; Horn et al., 2021; Houshyar et al., 2018; Lu et al., 2018). Nevertheless, no research was found which could determine strength loss of the outer layer after being exposed to heat when underlying fabric is in moist condition. Our research focus is to investigate the strength loss of the outer layer fabrics used in bunker gear under different heat exposures. Moisture exists in the inner layer due to fire fighters sweating, which also has an impact on the overall integrity of the apparel. Therefore, this research will focus on a comprehensive study about strength loss under different heat exposures in dry and wet conditions of fabric. A statistical modeling approach will be used to analyze various factors affecting the change of tensile strength when exposed to radiant heat in the presence of moisture.

- The primary purpose of this research is to identify how radiant heat intensity affects the tensile strength of the outer layer.
- The secondary purpose is to see how moisture affects the degradation process. Tests will be carried out at different moisture levels in the thermal liner and outer layer fabrics to simulate various levels of sweating in three-layered and single layered clothing system respectively.

CHAPTER II

REVIEW OF THE LITERATURE

The act of fighting the spread of and extinguishing unwanted fires in vehicles, buildings, wildlands, etc. is known as firefighting. There are typically two different types of firefighting; structural and wildland. When the fire involves structural components of various residential, commercial and industrial buildings it is known as a structural fire. On the other hand, non-structure fires occur in forests or other open spaces with minimal buildings and are known as a wildland fire. Structural firefighters mostly work with the structures of residential, commercial, or industrial buildings. Responsibilities of structural firefighters include entering a burning building, extinguishing the fire, rescuing victims, smoke ventilation and post-fire overhaul for searching any hidden fire after the incident.

Hazards from fire is one of the dangers that firefighters face. Firefighters must wear thermal protective gear, called bunker gear, when called out of their station house to protect them from fire and other hazards such as hot liquid, steam, etc. (Colburn et al., 2011). NFPA certified firefighter bunker gear consists of three layers; an outer shell, a moisture barrier, and a thermal liner. The outer layer protects the firefighters from direct flame while also ensuring abrasion and tear resistance. The moisture barrier works as a barrier between the wearers' body and exterior water. At the same time, the moisture barrier also provides breathability; allowing the sweating to move away from the body. The thermal liner which provides most of the thermal protection also makes the uniform comfortable to wear by sliding more easily against the body (*"Learning About Materials", (n.d.)*).

Even though high performance thermal protective gear is available to protect the firefighters from thermal hazards, the actual performance of the bunker gear depends on many factors such as the design of the gear and environmental factors such as moisture both of which have a significant effect on the performance of the bunker gear (Crown et al., 1998; Tan et al., 1998). In the following review the overall fire scenario of the U.S. including firefighter injuries and fire loss will be discussed. The mechanism of protection by the thermal protective gear will be discussed as well. Research related to the effect of moisture on protective performance will be reviewed. This review will focus on the importance of modeling for predicting the strength loss of the outer layer in presence of moisture in the inner layer after radiant heat exposure.

2.1 History of Thermal Protective Gear

Without modern technology, firefighters have had to deal with thermal hazards until the 17^{th} century. The key breakthrough in firefighting was achieved with the first fire engine in the 17^{th} century (Spirkina, 2013). As thermal protective gear at this time was not enough to protect from heat and flame, the firefighters had to work from the outside of any burning structure, and often the structures burnt to ground. The first helmet to protect the wearer from the fire was invented in the 1730s in New York. The current style of fire helmet was not invented until 1836. The term ‘bunker gear’ and ‘turn-out gear’ became famous later as personal protective clothing was developed (*"The History of Firefighter Personal Protective Equipment", (n.d.)*).

Standards for the thermal protective gear were established after World War II (Lee & Meyer, 2000). Different organizations began to test the performance and develop the standards for the bunker gear. The National Fire Protection Association was the pioneer in developing the standards for personal protective equipment specifically for firefighters. The first standard of NFPA for thermal protective gear was developed and adopted in 1975 as “NFPA 1971: Standard on Protective Clothing for Structural Fire Fighting” (National Fire Protection Association, 2007). The three-layered concept for the firefighter’s bunker gear was also developed after the Second World War. At this time, the flame-resistant outer shell would have been able to withstand 500 °F for five minutes (Lee & Meyer, 2000). The moisture barrier in the middle or second layer should prevent the fire hose water passing through the clothing system so as to prevent the wearer from being soaked. The thermal liner as the third/innermost layer was responsible for heat transfer management (*"The History of Firefighter Personal Protective Equipment", (n.d.)*; *"The History of Personal Protective Equipment" n.d.*; Lee & Meyer, 2000; Yates, 2012).

2.2 Fire Loss, Firefighter Injuries and Fatalities

In 2019, fire departments in the U.S. responded to around 1.3 million fires. Around 37% of total fire incidents occurred in or on structures (Ahrens & Evarts, 2020). Most of the fire losses included injuries, death and property damage caused by the structural fires, including 84% of the injuries, 80% of the death and 83% of the total property damaged. Approximately 17% of the fires were reported as vehicle fires. The remaining 45% of the fires mostly included wildland, brush or grass fires. The estimated number of fires were much less in 2019 compared to 1980. The number of fires were 48-66% lower in most of the categories (i.e., structural fire, vehicle fire, outside and other fire). Though the fire incidents were much lower, the injuries and death associated with these reported fires have not improved. For home fires, the overall civilian injury and death rate per 1000 fires are 34% and 15% higher respectively (Ahrens & Evarts, 2020). More than 60,000 firefighter injuries were estimated in 2019, which is approximately a 4 percent increase over 2018. About 39% of the reported injuries occurred in the fire ground in 2019. Most of the firefighters' injuries include strain, sprain and muscular pain, which was around 50% of the total injuries in 2019. The prime concern of this research was the burn injuries, which includes just under 3%, or approximately 1,775 incidents, of the total number of injuries in the U.S. in 2019 (Campbell & Evarts, 2020).

2.3 Thermal Protective Performance of Firefighter's Bunker Gear

The performance of the bunker gear under various conditions depends on the type of exposure, characteristics, and the structural features of the gear itself (Mandal et al., 2013). Bunker gear is designed to give the wearer protection from different hazards – radiant heat, flame, hot liquid, gases, steam, etc. The protection performance of most of the traditional thermal protective fabrics relies on the thermal performance of the fabrics (Ali & Yu, 2014). Bunker gear is meant to give protection to the wearer primarily from thermal hazards which include flame, radiant heat, hot surface and liquids, etc. (Song et al., 2011). To ensure wearers' safety, the improved protection performance of bunker gear against thermal exposure is a crucial need (Ali & Yu, 2014). There are basically two types of thermal hazards that the firefighters need to be aware during their job – fire and the heat stress (Lin et al., 2019).

The three categories to identify common thermal environment conditions are routine, hazardous and emergency (Song et al., 2011). Firefighters operating hoses or fighting from a distance is considered a routine condition. This condition is equivalent to being outdoor on hot summer day or standing beside an open fire pit. Air temperature up to 60 °C or 1.25 kW/m^2 heat flux intensity are considered routine conditions. Often times no special clothing is necessary for these conditions. A condition where firefighters are outside of a burning room or a small burning building is considered hazardous. Bunker gear is necessary in this condition to protect the firefighters from burn injuries and heat stress. Air temperature in this condition is between 60 °C to 300 °C which is about 1.25 kW/m^2 to 8.4 kW/m^2 heat intensity. Flashover within a building or an aircraft crash are types of emergency conditions. Special equipment along with proper breathing apparatus are required to work in these conditions (Hoschke, 1981). Emergency conditions are characterized by high intensity and short duration exposure. Heat intensity could be up to 105 kW/m^2, which is around 1000 °C. Considerable research has been conducted about emergency conditions (Lee & Barker, 1987; Shalev & Barker, 1983, 1984; Song et al., 2004; Sun et al., 2000; Yang et al., 2010; Zhiying et al., 2010).

In emergency conditions, the exposure level can vary from 20-160 kW/m^2. Up to 20 kW/m^2 of heat transfer rate is considered as low radiant heat exposure. Heat transfer rate of up to 40 kW/m^2 is considered as medium radiant heat, and above that is considered high radiant heat. This condition may be associated with several thermal problems and also life threatening injuries (heat stress, burn injuries, etc.) (Song et al., 2011).

2.4 The Effects of Absorbed Moisture on Thermal Protective Performance

Firefighter’s bunker gear can absorb moisture from the wearers sweating while they work. The moisture accumulated inside the bunker gear can affect the performance of the gear against thermal exposure (Barker et al., 2006). Moisture can also be accumulated from external sources like rain or dew, spray of water, etc. (Lawson et al., 2004). Researchers found that moisture absorbed in the fabric plays a crucial and complicated role in the performance of firefighters’ bunker gear as water transfers heat much faster than air (Lee & Barker, 1986; Zhiying et al., 2010). With the addition of moisture, the heat transfer property of the thermal protective gear changes significantly. Both the thermal conductivity and heat capacity increase with the presence of water (Keiser et al., 2008). The effect of the moisture absorbed in the fabric may vary depending on the amount of moisture absorption, location of moisture inside the bunker gear, and the duration of the heat application (Lawson et al., 2004).

Moisture in the fabric can turn to steam when exposed to thermal hazards, causing steam burn. Most of the moisture is accumulated in the two layers near the skin, for example, clothing worn under the bunker gear and the thermal liner. To understand the distribution of the moisture in different layers it is very important to understand the occurrence of steam burn (Keiser et al., 2008). Moisture negatively affects the protective performance of the fabric most severely when the amount of added moisture is lower. When the moisture level increases beyond a critical level (15% of fabric weight), second degree burn time increases (Barker et al., 2006). Difference in thermal conductivity and specific heat between the bunker gear and water at lower and higher moisture absorption respectively are the reasons for differences in protective performance. When exposed to radiant heat, a moistened sample provides more thermal protection than dry samples (Veghte, 1987). Depending on the various factors, heat transfer may be increased or decreased by the moisture in the clothing system. Under high heat flux of flame exposure, external moisture tended to decrease the heat transfer through the fabric and internal moisture tended to increase the heat transfer. This scenario is reversed for the low heat flux flame exposure (Lawson et al., 2004). Table 1 summarizes the effect of moisture on heat transfer.

Table 1

Summary of Literature: Moisture Effect on Heat Transfer

Authors	Fabric Layers	Moisture Application Level/Location	Test Method	Method	Result
(Barker et al., 2006)	Permeable moisture barrier with outer and inner layers. Impermeable moisture barrier with outer and inner layers	Dry, saturated and six different moisture percentage from 5%-70%.	Sprayed on the fabric layer.	ASTM F1939	Performance is lower at 15% moisture addition. As the amount of moisture increases the protection performance also increases.

Authors	Fabric Layers	Moisture Application	Test Method	Method	Result
(Zhang et al., 2018)	Three layered clothing; outer shell, moisture barrier and thermal liner.	Outer shell (Dry, Saturated, 30%, and 60%).	Added water by spraying for 30 and 60 % saturation. Immersed in water for 100% saturation.	NFPA 1971	Moisture on outer shell increases the protection performance.
(He et al., 2016)	Three layered clothing; outer shell, moisture barrier and thermal liner.	Thermal liner (5, 10, 20, 50 & 70 %).	Distilled water was spread on the thermal liner.	NFPA 1971	Thermal protection is least at 20% moisture, then again increases with the moisture addition.
(Guan, Psikuta, et al., 2019)	Single and multi-layered clothing systems.	Inner layer.	Moisture applied on the inner layer by a sweating torso manikin.	ASTM F1868	Perspired moisture reduces protective performance.

2.5 The Effects of Heat Exposure on Strength Loss of the Outer Layer

During the firefighting and rescue operations, firefighters are exposed to hazardous environments. These environments include, but are not limited to, flames and radiant heat. Thermal protective gear is used to protect firefighters from these hazards and ensure their safety. However, the strength of the outer layer of the thermal protective gear might deteriorate over time as it is exposed repeatedly to heat. This can lead to the loss of overall integrity of the thermal protective gear; hence, the performance of the garment might deteriorate. The consequences of this deterioration are high as the safety of the firefighters could be affected due to the loss of integrity of the thermal protective gear. Therefore, the continuous protective performance of the bunker gear should be carefully monitored (Cui et al., 2015; Deng et al., 2020).

Many researchers have studied the effects of heat exposure on thermal protective gear. The intensity of heat, the exposure time, the frequency of exposure, etc. effected the thermal decomposition of the outer layer of the thermal protective gear (Lu et al., 2018). Davis et al. (2010) experimented with the effect of ultraviolet (UV) light on polyaramid and polybenzimidazole (PBI) based outer layer fabrics used in thermal protective gear. They found that UV light significantly affected the mechanical performance of these fabrics (Davis et al., 2010). A similar experiment was done by Houshyar et al. (2018). They evaluated the deterioration of thermo-mechanical and performance properties of PBI and polyamide fabrics used in protective gear. They found similar results in that there was a 79% tensile strength loss of PBI/Kevlar fabric and 51% loss of tensile strength of polyamide fabric after frequent exposure to heat and UV light (Houshyar et al., 2018). Deng et al. (2019) evaluated the effect of flash fire on mechanical properties of a single layer thermal protective fabric. They found that flash fires effect the tensile and tearing strength significantly, approximately 40-60% strength loss was identified when compared to the unexposed samples (Deng et al., 2020). PBI and Kevlar fabrics were exposed to different heat levels between 190°C to 320°C by another research group (Arrieta et al., 2010). They found that the breaking force reduces by 50% when fabric is exposed at lower temperature for twelve days. Whereas, at higher temperature breaking strength reduces to 50% within an hour (Arrieta et al., 2010). Cui et al. (2015) exposed Aramid fiber at two different heat flux intensities 6.5 kW/m^2 and 9.7 kW/m^2 for a duration between 0 to 30 minutes. They found that the heat intensity had significant negative effects on the mechanical properties (i.e., tensile strength, tearing strength and elongation at break) (Cui et al., 2015). Lu et al. (2018) exposed thermal protective gear at 21 kW/m^2 radiant heat exposure and also found that tensile strength decreases after radiation (Lu et al., 2018). Table 2 summarizes the effect of heat exposure on tensile strength of the outer layer fabric.

Table 2

Summary of Literature: The Effects of Heat Exposure on Strength Loss of the Outer Layer

Author	Experiment	Finding
Davis et al. (2010)	Effect of ultraviolet (UV) light on polyaramid and polybenzimidazole (PBI) based outer layer fabrics.	UV light significantly affected the mechanical performance of these fabrics.
Houshyar et al. (2018)	Effect of heat and ultraviolet (UV) light on polyaramid and polybenzimidazole (PBI)/Kevlar fiber-based fabric.	About 79% strength loss of PBI/Kevlar fabric and 51% loss of tensile strength of polyamide fabric after frequent exposure to heat and UV light.
Deng et al. (2019)	Effect of flash fire on mechanical properties of a single layer thermal protective fabric.	Approximately 40-60 % strength loss was identified when compared to the unexposed samples.
Arrieta et al., (2010)	PBI and Kevlar fabrics were exposed to different heat levels between 190°C to 320°C.	Breaking force reduces by 50% when fabric is exposed at lower temperature for twelve days, whereas, at higher temperature breaking strength reduces to 50% within an hour.
Cui et al. (2015)	Exposed Aramid fiber at two different heat flux intensities 6.5 kW/m^2 and 9.7 kW/m^2 for a duration between 0 to 30 minutes.	Heat intensity had significant negative effects on the mechanical properties (i.e., tensile strength, tearing strength and elongation at break).
Lu et al. (2018)	Exposed thermal protective clothing at 21 kW/m^2 radiant heat exposure.	Tensile strength decreases significantly after radiation.

2.6 Knowledge Gap in the Existing Literature

From the above discussion we know that the heat exposure has significant effect on changing the mechanical properties of the outer layer of thermal protective fabric. In the earlier discussion, we have seen that the presence of moisture in the clothing system significantly affects the overall performance of the thermal protective gear system. As was stated earlier, moisture accumulates in the inner layer of the thermal protective gear due to sweating of the firefighters. As of now, there are only a few research studies that have been done to determine the change of tensile strength of the outer layer of bunker gear due to radiant heat exposure (Cui et al., 2015; Lu et al., 2018). Moreover, no research was found which examines the changes in strength of the outer layer after heat exposure when the inner layer is moist, simulating wearers' sweating. The strength loss of the outer layer fabric could negatively affect the health and safety of firefighters. Therefore, the strength loss of the outer layer in the presence of different levels of moisture content in the inner layer after exposure to heat should be determined. These results will help to understand the performance of thermal protective gear during its service period and suggest when gear should be retired.

CHAPTER III

METHODOLOGY

Firefighters wear bunker gear which consists of both single and multi-layered fabric systems in order to provide protection from the high heat encountered at a fireground. This research is to determine if there is a change of tensile strength of the high-performance fabrics, which are used in a single layer fabric system and also used as outer layers in multi-layered fabric system, after being exposed to radiant heat. Different amounts of moisture were added to the fabric system while exposing it to heat to simulate the wearer's sweating.

3.1 Materials

Four different types of high-performance fabrics which are typically used for firefighters' bunker gear were selected and labeled A, B, C and D. For the single layer fabric system these same four high-performance fabrics (A, B, C and D) were used. To compose the three-layered fabric system, a moisture barrier (fabric E) and thermal liner (fabric F) were used together with the four (A, B, C, and D) high-performance fabrics. Four different types of multilayered assemblies are as follows: AEF, BEF, CEF and DEF. Four different high-performance fabrics A, B, C and D together with an example of three-layered fabric systems is shown in Figure 1. The tensile strength of the selected fabrics in dry and wet conditions were measured by using a tensile strength tester before and after being exposed to radiant heat. The process of moisture application, heat exposure and tensile strength measurement are discussed below.

Figure 1

Fabric A, B, C, D and an Arrangement of Three-layered Fabric System

The properties of all four high-performance (A, B, C, and D) fabrics are listed in Table 3. Fabrics properties were measured according to the appropriate standards as noted in Table 3. The average value of three repetitions of each test measurement is tabulated in Table 3.

Table 3

Properties of the High-performance Fabrics Experimented

Sample	Fiber content	Weave Structure	Weight [a] (g/m^2)	Thickness [b] (mm)	EPI/PPI, Fabric Count [c] (EPI+PPI)	Yarn Count in Metric System (Warp/Weft) [d]	Absorbency [e]	Tensile Strength [f] (Warp Direction)
A	Meta-aramid	Twill	261	0.62	75/45 (120)	21 Nm/15 Nm	0	1135 N

Sample	Fiber content	Weave Structure	Weight [a] (g/m^2)	Thickness [b] (mm)	EPI/PPI, Fabric Count [c] (EPI+PPI)	Yarn Count in Metric System (Warp/Weft) [d]	Absorbency [e]	Tensile Strength [f] (Warp Direction)
B	Para-aramid/Meta-aramid	Ripstop	204	0.53	60/45 (105)	17 Nm/18 Nm	100	1309 N
C	Polybenzimidazole/ Para-aramid	Twill	196	0.51	45/45 (90)	15 Nm/14 Nm	100	1166 N
D	FR Cotton	Twill	269	0.71	90/50 (140)	28 Nm/21 Nm	0	470 N

[a] Measured according to ASTM D3776 (ASTM International, 2020); [b] Measured according to ASTM D1777 (ASTM International, 2019a); [c] Measured according to ASTM D3775 (ASTM International, 2017b); [d] Measured according to ASTM D1059 (ASTM International, 2017a); [e] Measured according to AATCC 22 (AATCC, 2017); [f] Measured according to ASTM D5034 (ASTM International, 2017c).

3.2 Cone Calorimeter

To simulate the radiant heat exposure that the firefighters face during daily fire activities, a cone calorimeter (Figure 2) was used. The cone calorimeter machine is able to provide heat release rate, ignition time, mass loss and other properties related to fire behavior from a relatively small size sample (10 cm by 10 cm) (Chakrabarty et al., 2016). Therefore, cone calorimeter is the most widely used instrument to study fire related behavior of materials (Yang & Zhang, 2019). The name of the cone calorimeter actually came from the conical shape of the radiant heater; with a 160 mm diameter at the bottom and 80 mm on top, the cone produces nearly uniform heat flux on the sample under study (ASTM International, 2017d). The radiant heat flux can be controlled by the cone-shaped heating element, which is made out of Inconel alloys (Babrauskas, 2016). These alloys are suitable for extreme heat environments due to their oxidation-corrosion resistance properties (*"Inconel® Applications & Properties", (n.d.)*). The specimen holder and the heater are placed horizontally, and there is a shutter plate in between separating the fabric from the heat. The plate is removed when the test begins, therefore the radiant heat reaches the surface of the sample. Fabric samples (10 cm by 10 cm) were prepared according to the standard (ASTM E1354) and placed 25 mm below the cone heater (Figure 3a & 3b) (ASTM International, 2017d). The samples were exposed to three different heat flux levels: 10 kW/m^2, 15 kW/m^2 and 20 kW/m^2 for five minutes. Five minutes exposure time was done to keep it uniform for all the fabrics at all three heat fluxes. At 20 kW/m^2 more than five minutes of exposure caused complete burn out of fabric D. Five minutes exposure was the highest exposure time without complete degradation of the fabrics; therefore, measuring the strength of the fabrics was possible. The ASTM E1354 standard test method was designed to evaluate fire-retardant materials. Using this test method, samples were conditioned in the textile lab for 24 hours before the heat exposure. After conditioning, samples were transferred to zip-top bags and exposed to radiant heat within three hours. The moisture was applied on the fabrics just before the heat exposure. The details of moisture application are explained in section 3.4. Once exposure was completed, samples were immediately transferred to the zip-top bags and again conditioned for 24 hours in textile lab before measuring the strength. The heat exposure time was five minutes for all the samples.

Figure 2

Cone Calorimeter

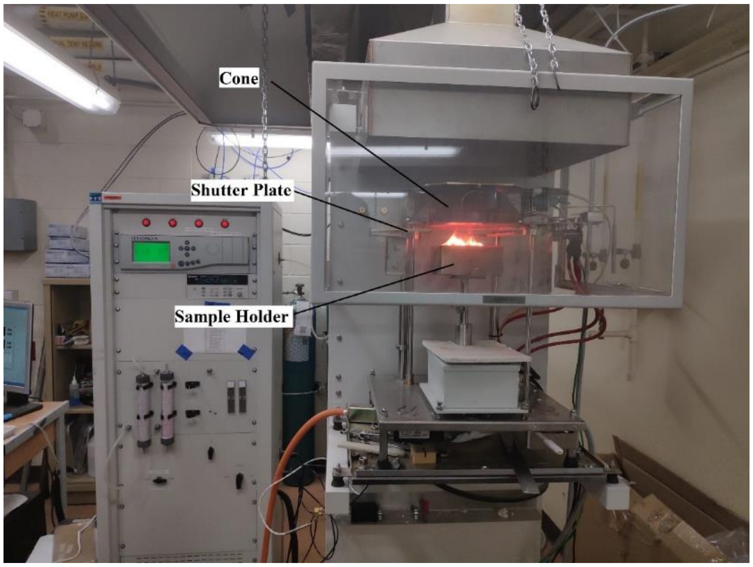


Figure 3a

Picture of a High-performance Fabric Before and After Radiant Heat Exposure

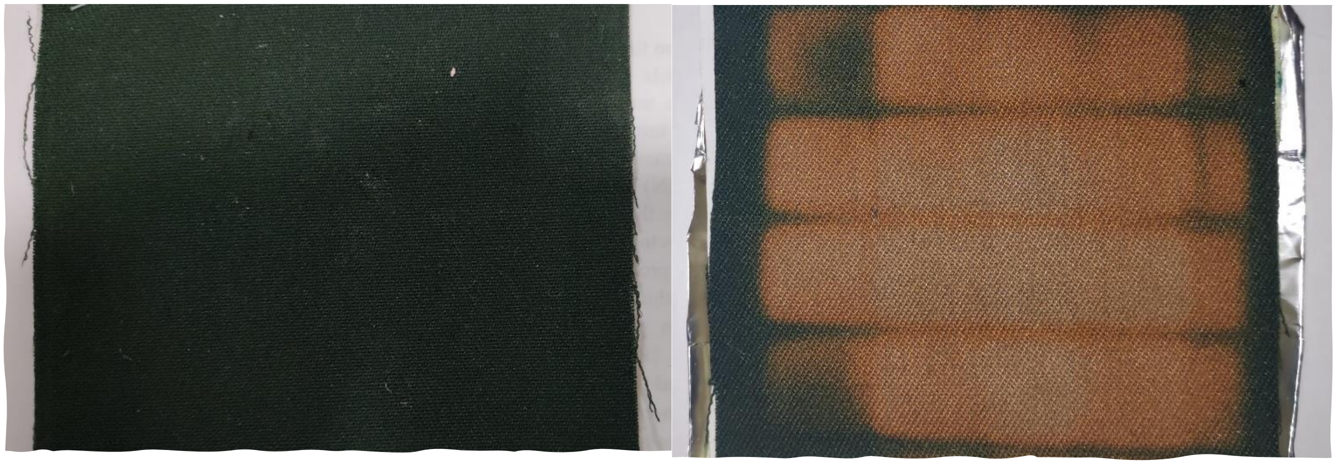
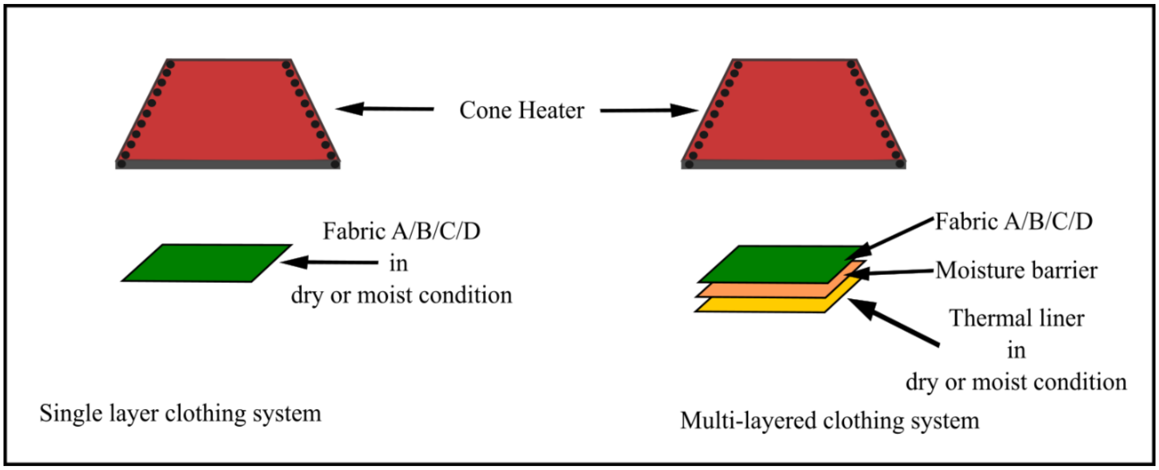


Figure 3b

Schematic Diagram of Heat Exposure of Single and Multi-layered Fabric System



3.3 Tensile Strength Tester

Tinius Olsen H5K tensile strength tester (Figure 4) manufactured by SDL Atlas, SC, U.S., was used to measure the tensile strength in Newton (N) of the fabric before and after radiant heat exposure. ASTM D5034 Grab Test method was used to measure the tensile strength of the fabric (ASTM International, 2017c). Grab test method was chosen over strip test method (ASTM International, 2019b) since Zanelli et al. (2019) mentioned that the strip test sometimes lead to clamp fractures. This same research also concluded that for testing textile clothing, the grab test is sufficient (Zanelli et al., 2019). The distance between the jaws was 40 mm, and tensile speed was 50 mm/min. Tensile strength of the fabrics was measured in the warp direction only. The required tensile strength of warp yarn is usually higher than the weft yarn due to the weaving mechanism. Therefore, the strength of woven fabric in warp direction is usually higher than the weft direction. If the warp yarn does not satisfy the minimum requirement after the heat exposure, then it can be said that weft will not satisfy either, since tensile strength of weft is lower than the warp. Therefore, the tensile strength was measured only in the warp direction.

Figure 4

Tensile Strength Tester

Tensile strength of fabrics A, B, C, and D was measured after each fabric was exposed to moisture and heat as part of a single layered system (the fabric itself) and as part of multi-layered systems AEF, BEF, CEF, and DEF, respectively. In single layer fabric system fabrics, A, B, C, and D were exposed to different radiant heat level in dry and moist condition. After the five minutes of heat exposure, samples were immediately placed in zip-top bags. Before measuring the tensile strength, all samples were conditioned in the textile lab for 24 hours. Similarly, in the three-layered fabric system, AEF, BEF, CEF and DEF fabric systems were exposed to radiant heat. Fabric combination were exposed either in dry condition or with the presence of moisture in the thermal liner. Similarly, after the five minutes of heat exposure samples, were secured in zip-top bags. The outer layer was then removed from the three-layered system and conditioned for 24 hours at the textile lab before measuring the tensile strength.

Table 4

Fabric Combination and Tensile Strength Measuring Layers

Fabric System	Heat Flux	Fabric Samples for Heat Exposure	Moisture Addition	Tensile Strength Measuring Layer
Single Layer	0 kW/m^2	A	0/20/50/100 %	A
		B		B
		C		C
		D		D
	10 kW/m^2	A	0/20/50/100 %	A
		B		B
		C		C
		D		D
	15 kW/m^2	A	0/20/50/100 %	A
		B		B
		C		C
		D		D
	20 kW/m^2	A	0/20/50/100 %	A
		B		B
		C		C
		D		D
Multi-layered	0 kW/m^2	AEF	0/20/50/100 %	A
		BEF		B
		CEF		C
		DEF		D
	10 kW/m^2	AEF	0/20/50/100 %	A
		BEF		B
		CEF		C
		DEF		D
	15 kW/m^2	AEF	0/20/50/100 %	A
		BEF		B
		CEF		C
		DEF		D
	20 kW/m^2	AEF	0/20/50/100 %	A
		BEF		B
		CEF		C
		DEF		D

3.4 Moisture Application

Two different scenarios for moisture application were followed. Moisture was added in the fabrics (A, B, C, and D) to simulate the wearers' sweating during the heat exposure in the single layer fabric system. However, moisture was applied on the thermal liner to simulate the sweat of the wearers in three-layered fabric system. For the single layer, weight of the dry fabric samples was measure first, then the necessary amount of distilled water was sprayed on the fabric surface until the added moisture content reached at 20%, 50% and 100% respectively. For the three-layered fabric system, the weight of the dry sample (three layers together) was measured first, then with the help of a dropper, the required amount of distilled water was added on the thermal liner. Water was added by spray or dropper until the weight balance showed the required weight. Distance between the fabric and the spray nozzle was approximately 6 inches to ensure that water droplets fell over the whole fabric evenly. Water was added in the thermal liner (three-layered fabric system) by using a dropper. Drops of water were added in different sections (four corners, center, middle of the four sides) of the fabric to ensure even distribution of the water in the fabric. Figure 5a and 5b show the application of water in the fabrics A, B, C, and D in single layer system and also in the thermal liner of the three-layered fabric system to simulate the firefighter's sweating. Fabrics were treated in three different moisture content levels: 20%, 50% and 100%. Samples were left on the weight balance for five minutes before being exposed to heat to ensure that the required amount of moisture is present in the fabric. In this time period, the sample remained on the weight balance and final weight was checked before the exposure to ensure required amount of water is present in the fabrics. By using the dropper, it was possible to apply the water all over the thermal liner uniformly. The amount of water needed to be added in the single layer fabric system was comparatively lower than the water added in the three-layered fabric system. A spray was used to ensure the even distribution of the small amount water on the single layer system fabric and a dropper was used to apply water in the three-layered fabric system. Table 5 shows the fabric combination with moisture addition.

Figure 5a

Addition of Water in the Fabrics by Spray and Dropper

Figure 5b

Schematic Diagram of Addition of Water in the Fabrics by Spray and Dropper

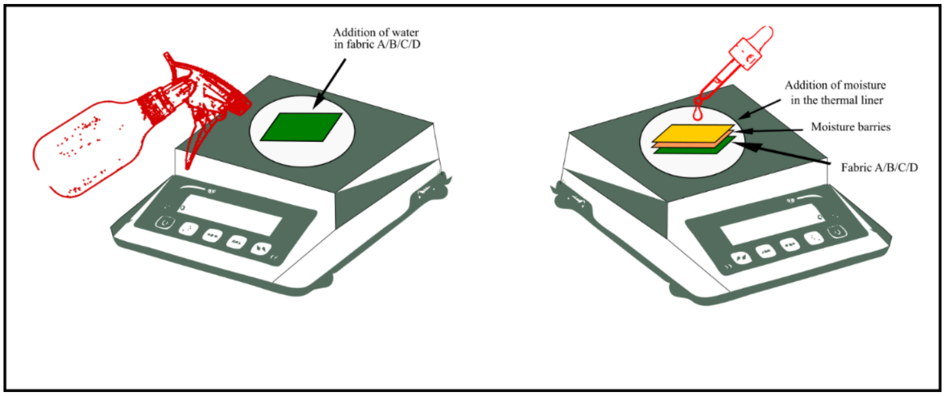


Table 5

Moisture Application Layers in Single and Three-layered Fabric Systems

Fabric System	Heat Flux	Fabric Sample(s)	Moisture Application Layer	Moisture Addition
	0 kW/m^2	A	A	0/20/50/100 %
		B	B	
Single Layer		C	C	
		D	D	
	10 kW/m^2	A	A	0/20/50/100 %
		B	B	
		C	C	
		D	D	
Single Layer	15 kW/m^2	A	A	0/20/50/100 %
		B	B	
		C	C	
		D	D	
	20 kW/m^2	A	A	0/20/50/100 %
		B	B	
		C	C	
		D	D	
	0 kW/m^2	AEF	F	0/20/50/100 %
		BEF	F	
		CEF	F	

Fabric System	Heat Flux	Fabric Sample(s)	Moisture Application Layer	Moisture Addition
		DEF	F	
Multi-layered	10 kW/m^2	AEF	F	0/20/50/100 %
		BEF	F	
		CEF	F	
		DEF	F	
	15 kW/m^2	AEF	F	0/20/50/100 %
		BEF	F	
		CEF	F	
		DEF	F	
	20 kW/m^2	AEF	F	0/20/50/100 %
		BEF	F	
		CEF	F	
		DEF	F	

3.5 Test Protocol

Sixteen different testing scenarios were created for each of the single and three-layered combinations in each heat flux level. Each testing was repeated three times, therefore there were forty-eight samples in each fabric combination. Each fabric combination was exposed to three different heat exposure levels 10 kW/m^2, 15 kW/m^2 and 20 kW/m^2. For each exposure level there were four different moisture levels. Details of test scenarios are given in Table 6. Three repetitions of the test were conducted in each scenario.

Table 6

Details of Test Scenarios

Fabric System	Heat Flux	Fabric Combination	Moisture Addition	Time of Heat Exposure	Test Scenarios
	0 kW/m^2	A	0/20/50/100 %	5 minutes	4
		B			4
		C			4
		D			4

Fabric System	Heat Flux	Fabric Combination	Moisture Addition	Time of Heat Exposure	Test Scenarios
Single Layer	10 kW/m^2	A	0/20/50/100 %	5 minutes	4
		B			4
		C			4
		D			4
	15 kW/m^2	A	0/20/50/100 %	5 minutes	4
		B			4
		C			4
		D			4
	20 kW/m^2	A	0/20/50/100 %	5 minutes	4
		B			4
		C			4
		D			4
Multi-layers	0 kW/m^2	AEF	0/20/50/100 %	5 minutes	4
		BEF			4
		CEF			4
		DEF			4
	10 kW/m^2	AEF	0/20/50/100 %	5 minutes	4
		BEF			4
		CEF			4
		DEF			4
	15 kW/m^2	AEF	0/20/50/100 %	5 minutes	4
		BEF			4
		CEF			4
		DEF			4
	20 kW/m^2	AEF	0/20/50/100 %	5 minutes	4
		BEF			4
		CEF			4
		DEF			4

3.6 Analyzing the Experimental Data

The data were analyzed using the SPSS Statistics Analysis tool and were categorized into three groups.

1. In the first group, the tensile strength data of all four different fabrics A, B, C, and D in dry condition were analyzed. The tensile strength of all four fabrics exposed at three different heat fluxes falls under this group. The properties of the fabrics (i.e., weight/unit length, thickness, fabric count) and the heat flux intensity were the independent variables, and tensile strength was the dependent variable.
2. In the second group, the single layer fabric system with the presence of moisture was analyzed. Under this category the amount of added moisture and the heat flux intensities were the independent variables along with the above-mentioned fabric properties (i.e., weight/unit length, thickness, fabric count), and the tensile strength was the dependent variable.
3. The three-layered fabric system where the moisture was added in the thermal liner falls under the third category. Variables in the third group are same as the second group, where the only difference is that the multi-layer fabric system was analyzed within this group instead of the single layer fabric system, where moisture was applied in the thermal liner fabrics.

Properties (i.e., weight/unit length, thickness, fabric count) and tensile strength of the fabrics have been normalized between -1 to +1, while the average value is set to zero. The normalized variable $X_{i,norm}$ is expressed in the equation below. Normalization process reduces the redundancy rates in the data by pulling out the abnormal factors.

$$X_{i,norm} = \frac{X_i - X_{i,avg}}{R_{i,\max}}$$

Where, $R_{i,max}$ = Maximum [($X_{i,max}$ - $X_{i,avg}$),($X_{i,avg}$ - $X_{i,min}$)]. In the above equation the X_i is the value of selected variable (thickness, air permeability, thermal and evaporative resistance, and tensile strength), $X_{i,avg}$ is the average value of that particular variable, $X_{i,min}$ is the minimum value of that variable, $X_{i,max}$ is the maximum value of that variable, and $R_{i,max}$ is the maximum range between the average value and either the minimum or the maximum of that variable. A multi-linear regression analysis of the normalized data set of the fabric properties and the tensile strength was conducted by using SPSS Statistics Analysis tool in order to understand the relation between the fabric properties and the change in tensile strength. The properties of the fabric (i.e., weight, thickness, and fabric count) were considered as the independent variables and tensile strength as dependent variable for the linear regression. It has been hypothesized that these fabric properties can represent the linear regression with tensile strength. Different studies were found where linear regression analysis was used to model the relation between fabric properties and performance (Çelik, 2017; Üreyen & Gürkan, 2008). The amount of moisture added, and the heat intensity levels were considered as the ordinal independent variables for the regression analysis. Among the three independent variables (i.e., weight, thickness and fabric count), the properties that showed highest absolute regression coefficient was considered the key property affecting the tensile strength. This analysis was carried out at 95% Confidence Interval. P-value obtained from regression analysis was analyzed to identify the fabric properties that have significant effect on the tensile strength loss. Scatter plot and normal probability plot were run to check if the data satisfy the model. Scatter plot and normal probability plot of standardized predicted value vs standardized residual value were generated by using the SPSS analyze tool. In the scatterplot, a rectangular or nearly rectangular shape formed by the data suggests that the data satisfy the model. In addition, having most of the observed values very close to the predicted line in the normal probability plot indicates that standardized residuals are normally distributed. Significance test was carried out at 0.05 significance level. Thus, if obtained value is less than 0.05, then the properties are significant.

CHAPTER IV

RESULTS

The results section has been divided into three sub-sections. In the first section, change of tensile strength of the fabrics A, B, C and D in dry condition is discussed. In the second section, the tensile strength change of the fabrics A, B, C, and D is discussed while only single layer (A, B, C and D) fabrics were exposed with moisture. In the third section, change of tensile strength of the outer layers (fabrics A, B, C, and D) in three-layered fabric system while this system was exposed with moisture in the thermal liner is discussed. The radiant heat-treated fabrics were conditioned for 24 hours in the textile lab before measuring tensile strength. The tensile strength (warp direction) of the fabrics A, B, C and D were measured by the tensile strength tester using the standard method ASTM D 5034.

4.1 Effect of Radiant Heat on Tensile Strength of the Fabrics in Dry Condition

The summary of the effect of radiant heat on tensile strength is summarized in Table 7. Fabric D – the FR Cotton, had the least resistance to radiant heat flux. Fabric D lost 98% of its strength at 10kW/m^2 (from 470 N initial strength to 9 N) and 100% of its strength at 20 kW/m^2. At low radiant heat flux (10 kW/m^2) fabric A had the lowest tensile strength loss, which was about 3.7%. However, the strength loss increased significantly ($p < 0.05$) with increased heat flux for fabric A. Strength loss for fabric A increased from 3.7% at 10 kW/m^2 radiant heat flux to 49% at 15 kW/m^2 radiant heat flux. The strength loss was also significant ($p < 0.05$) at 10 kW/m^2, which was 98%. Fabric B and fabric C showed similar trends in tensile strength loss at different radiant heat flux. Fabric B lost 23% strength at 10 kW/m^2 which was 13% for the fabric C at the same heat flux.

Table 7

Effect of Radiant Heat on Tensile Strength (Dry Condition)

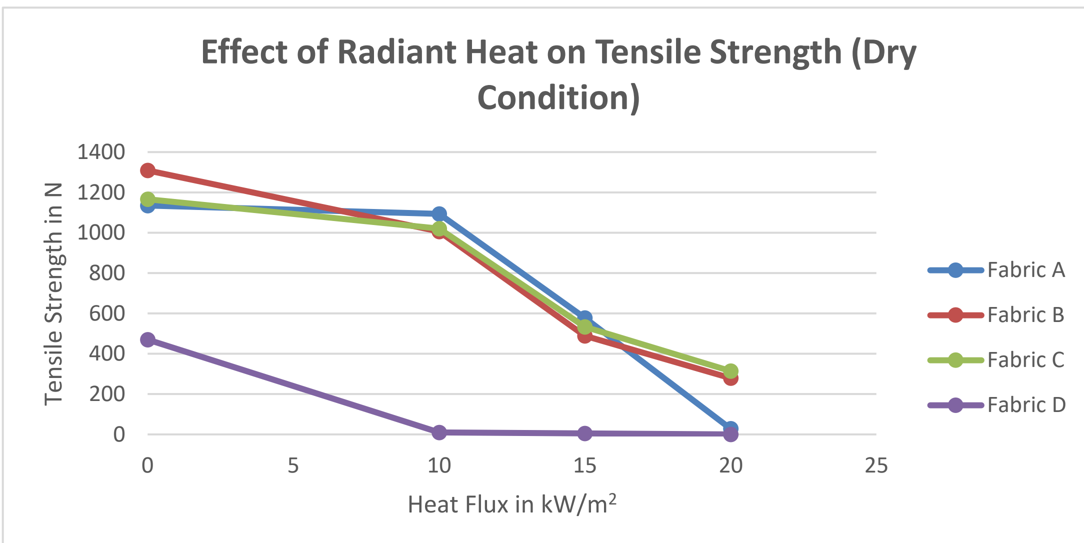
Samples	Initial Strength (Before any heat exposure)	Heat Flux					
		10 kW/m^2 0% Moisture	Tensile Strength Loss %	15 kW/m^2 0% Moisture	Tensile Strength Loss %	20 kW/m^2 0% Moisture	Tensile Strength Loss %
Fabric A	1135 N	1093	3.7%	578	49%	28	98%
Fabric B	1309 N	1006	23%	489	63%	279	79%
Fabric C	1166 N	1020	13%	533	54%	314	73%
Fabric D	470 N	9	98%	4.4	99%	0	100%

There was a 40% increase in tensile loss for fabric B when heat flux increased to 15 kW/m^2 from 10 kW/m^2. The tensile strength loss of B and fabric C were 63% and 54% respectively at 15 kW/m^2. There was 79% and 73% of strength loss respectively by fabric B and fabric C at 20 kW/m^2. Though fabric B and fabric C showed similar trends in tensile strength loss the overall strength loss of fabric C was lower compared to the fabric B.

Effect of radiant heat exposure in dry condition on tensile strength of all four fabrics has been illustrated in Figure 6.

Figure 6

Effect of Radiant Heat on Tensile Strength (Dry Condition)



Multiple Linear Regression analysis tool was used to find out the R square and t-test (t and p) values by using SPSS Statistics software. As mentioned earlier, data were grouped into three categories. In the first category, tensile strength of all four fabrics A, B, C and D exposed in three different heat fluxes in dry condition was analyzed.

Independent variables: i) Fabric properties (Weight/unit length, thickness, fabric count).

ii) Heat flux intensities (0, 10, 15, and 20 kW/m^2) are the ordinal variables.

Dependent variable: Tensile strength of the fabrics. The results are as shown in Table 8. In the scatterplot, the value of standardized predicted values was between -2 to 1.5, and the standardized residual was between -1.5 to 1.5. This rectangular distribution of predicted value vs residual value represents a good fit of the data into the model. Normal probability plot was also generated by using the analyze tools to find out the distribution of the residuals. This plot also suggested that the standardized residuals are normally distributed.

Table 8

Statistical Analysis of Tensile Strength of the Fabrics in Dry Condition

Model Summary

R^2 Value	*F*	*p*
0.83	8.82	0.007

Coefficients	*t*	*p*
Weight/unit Length	2.21	0.063
Thickness	-1.92	0.096
Fabric Count	0.102	0.921
Heat Intensity Level	-3.790	0.007

Individual R Square Values Between the Fabric Properties and Tensile Strength

Fabric Properties	R^2 Value
Weight/unit length	0.225
Thickness	0.379
Fabric Count	0.358

The t-test value matches with the earlier discussion. The negative t value of the heat intensity levels indicated that increase of heat flux reduces the tensile strength of the fabric where exposure time was fixed 5 minutes. The p-value suggests the significance of the effect on tensile strength. From the R square values, it can be seen that thickness has the highest value compared to linear density and fabric count. Therefore, it can be said that thickness is the most important property when considering the tensile strength of the fabric. Fabric count is the second most important property in terms of tensile strength.

4.2 Effect of Moisture and Radiant Heat on Tensile Strength of the Fabrics (Single Layer Fabric System)

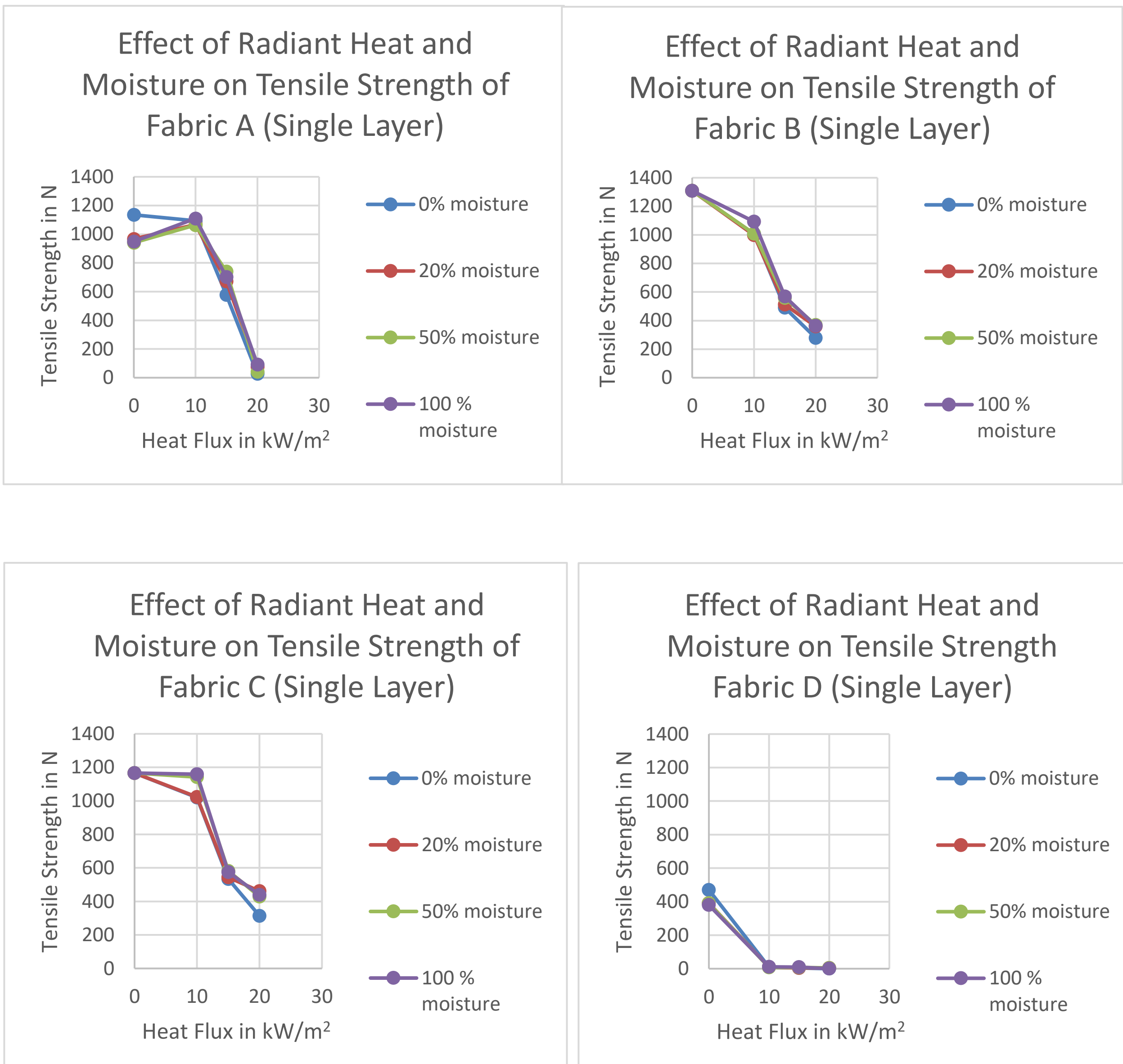
The strength the fabric A increased at 10 kW/m^2 compared to initial tensile strength. Initial strength of the fabric in moist conditioned was lower than the dry conditions. Therefore, the strength of the fabric showed an increase at lower heat flux. Fabric B blend behaved similarly to Fabric C (Figure 7). The absorbency test result (Table 3) also supports this identical behavior. The tensile strength of the fabrics was almost identical after exposure in dry condition or with different amount of moisture in the fabrics. This is because both the fabrics had polymer finishing on their surface, that is why the both the fabrics did not absorb the applied water. Most of the water were sitting on the fabric surface, which was evaporated quickly.

At lower heat flux, a slightly improved tensile strength was shown by fabric C for 50% and 100% moisture addition. Otherwise, at lower moisture addition (20%) and higher heat fluxed (15 and 20 kW/m^2) the fabric behaved similarly to dry fabric (Figure 7). For fabric D, no difference could be seen between dry and moist fabric (Figure 7).

The moisture did not have any effect on the tensile strength when moisture is in the single layer.

Figure 7

Effect of Moisture and Radiant Heat on Tensile Strength of the Fabrics (Single Layer)



In the second group, single layer fabric system with the presence of moisture during the exposure has been analyzed. Same linear regression analysis tool has been used to determine the R square and t-test value (t and p values). The independent and dependent variables are as follows and results are shown in Table 9:

Independent variables: i) Fabric properties (Weight/unit length, thickness, fabric count)

ii) Heat flux intensities (0, 10, 15, and 20 kW/m^2) and moisture percentages (0, 20, 50, and 100%) are the ordinal independent variables.

Dependent variable: Tensile strength of the fabrics A, B, C, and D. In the scatterplot, the value of standardized predicted value was between -2 to 1.5, and the standardized residual was between -2 to 1.5. This rectangular distribution of predicted value vs residual value represents a good fit of the data into the model. Normal probability plot was also generated by using the analyze tools to find out the distribution of the residuals. This plot also suggested that the standardized residuals are normally distributed.

Table 9

Statistical Analysis of Tensile Strength of the Fabric in Moist Condition (Single Layer)

Model Summary

R Square	*F*	*p*
0.84	30	0.001

Coefficients	*t*	*p*
Weight/unit length	4.415	0.000
Thickness	-3.642	0.001
Fabric Count	0.037	0.970
Heat Intensity Level	-7.97	0.0001
Moisture Level	0.431	0.670

Individual R Square Values Between the Fabric Properties and Tensile Strength

Fabric Properties	R Square Value
Weight/unit length	0.245
Thickness	0.392
Fabric Count	0.374

In the single-layered fabric system the moisture had minimum or no effect on the tensile strength, the statistical values also suggesting a similar result. The t-values for the moisture are positive and almost near to zero. This suggests that moisture in the single layer has minimum effect on the tensile strength of the fabrics.

The summary of the effects of moisture and radiant heat in single layer fabric system is shown in the table below (Table 10).

Table 10

Effect of Moisture and Radiant Heat on Tensile Strength of Fabrics (Single Layer)

Samples	Heat Flux																							
	10 kW/m^2								15 kW/m^2								20 kW/m^2							
	0 %	Δ%	20 %	Δ%	50 %	Δ%	100 %	Δ%	0 %	Δ%	20 %	Δ%	50 %	Δ%	100 %	Δ%	0 %	Δ%	20 %	Δ%	50 %	Δ%	100 %	Δ%
Fabric A	1093	3.7	1067	-10	1064	-13	1110	-17	578	49	672	30	741	21	702	26	28	98	77	92	42	96	93	90
Fabric B	1006	23	997	23.80	1007	23	7093	16.5	489	63	512	61	559	57	568	57	279	79	359	73	369	72	363	72
Fabric C	1020	13	1024	12	1142	3	1159	0.60	533	54	544	53	581	50	575	51	314	73	461	60	429	63	439	62
Fabric D	9	98	9.6	98	8.4	97.8	10.6	97.1	4.4	99	5	98.7	6.8	98.3	9.2	97.6	0	100	4.5	99	4.7	99	0	100

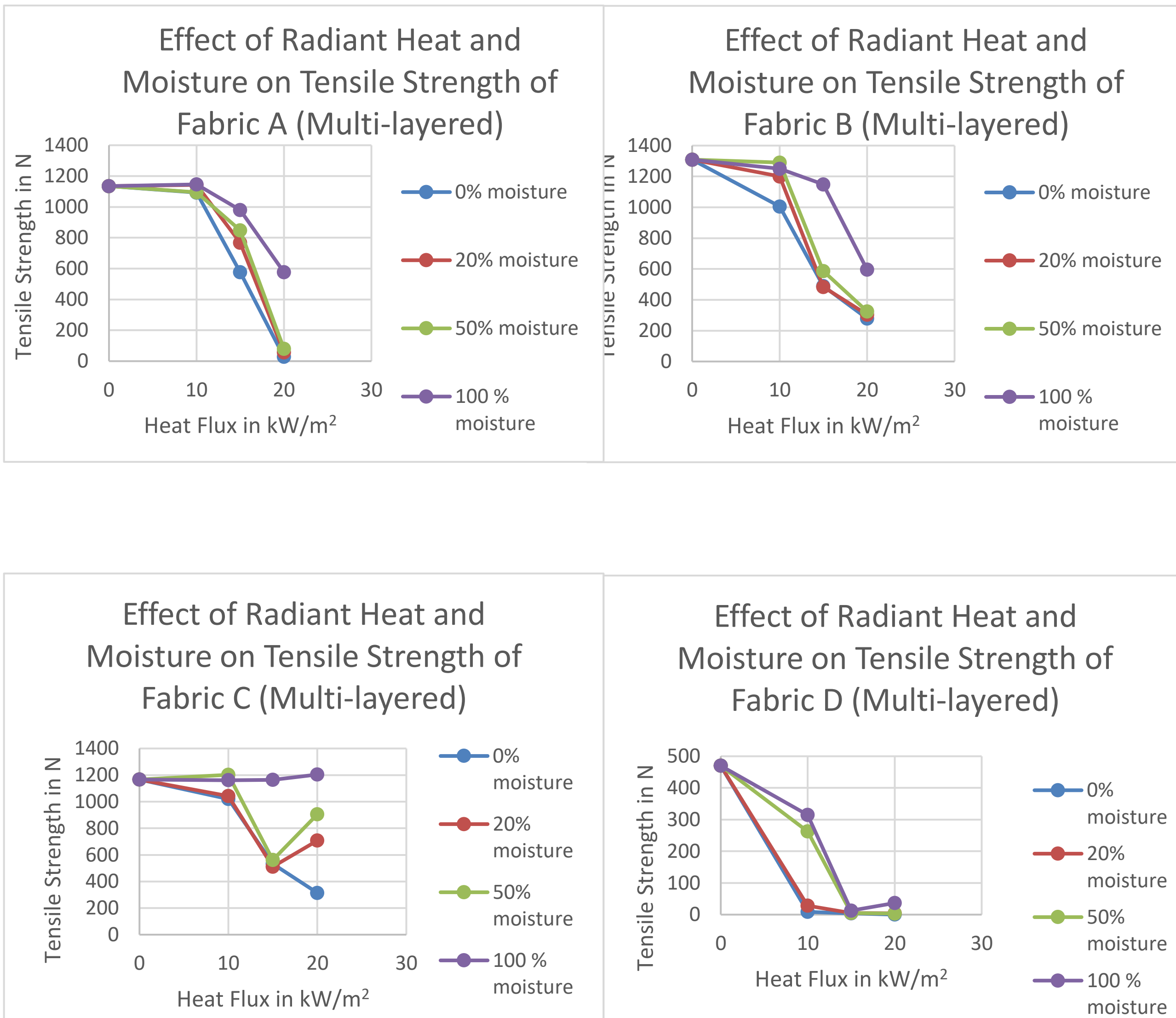
Δ%: Change of tensile strength (compared to the initial strength in moist condition before the heat exposure)

4.3 Effect of Moisture and Radiant Heat on Tensile Strength of the Fabrics (Three-Layered Fabric System)

Added moisture had considerable positive effect on the strength loss of fabric A depending upon the heat flux. Fabric A showed excellent resistance to radiant heat at 10 kW/m^2 even at dry condition (Figure 8). In wet condition, there are very small strength loss or slight gain in strength shown by this fiber. Tensile strength data show that the strength loss percentage was negative for both 20% and 100% moisture addition. The strength loss was also significantly lower at 15 kW/m^2 and 20 kW/m^2 with the presence of moisture compared to the dry fabrics. With the increased moisture the strength loss percentage decreased. The strength losses were 32%, 25% and 14% respectively, for 20%, 50% and 100% moisture addition at 15 kW/m^2. However, at highest radiant flux at 20 kW/m^2 the strength loss percentages were 95% and 93% for 20% and 50% moisture addition. At higher heat flux, lower moisture content (20% and 50%) did not affect the tensile strength significantly. However, at 100% moisture addition the heat loss percentage was only 49% which is half compared to 98% at dry condition at 20 kW/m^2. The moisture helped the samples to retain their tensile strength especially at lower temperature. Absorbed moisture evaporated eventually, and the required energy was provided by the heat energy. Since most of the heat energy has been used to evaporate the moisture, the temperature inside the exposed samples did not increase significantly. Therefore, the loss of tensile strength was considerably lower than the dry condition.

Figure 8

Effect of Moisture and Radiant Heat on Tensile Strength of the Fabrics (Three-layered)



Fabric B showed excellent resistance to heat with the presence of moisture at lower heat level (Figure 8). Where the strength loss was 23% at dry condition at 10 kW/m^2, with the presence of moisture the strength loss was below 10% in same radiant heat exposure. However, the strength loss was almost same for dry, and 20% moisture absorbed fabrics at 15 and 20 kW/m^2. The 20% moisture content did not help much to retain the tensile strength at higher radiant heat.

The 50% moisture addition had a very minor effect on the tensile strength at 15 and 20 kW/m^2. The difference was below 10% at this moisture level compared to the dry condition. However, the 100% moisture level showed significant effect even at higher heat flux. The tensile strength loss was 12% and 54% at 15 and 20 kW/m^2 respectively, which were 63% and 79% for the same fabric in dry condition.

The results of fabric C at lower radiant heat 10 kW/m^2 and with 20% moisture addition, showed a strength loss of 11% which was 13% at dry condition. Therefore, 20% moisture did not change the result significantly at lower heat flux. However, for the 50% and 100% moisture addition, there was no loss or increase of the tensile strength (Figure 8). Therefore, the amount of moisture can play significant effect on the tensile strength at low radiant heat. At 20% and 50% moisture there was no effect at 20 kW/m^2 heat exposure. The heat loss percentage were same for the 20% and 50% moisture when compared to the dry fabric. However, 100% moisture played significant role at 20 kW/m^2. At higher heat flux 20 kW/m^2, this fiber behaved very differently compared to the other fibers.

The strength loss of the fiber was lower at 20 kW/m^2 compared to the 15 kW/m^2. At 100% moisture content and 20 kW/m^2 radiant heat the fiber behaved similar to the 50% moisture content and 10 kW/m^2 radiant heat exposure, which is a slight increase in tensile strength. Moisture played a significant role at higher heat flux 20 kW/m^2 as the strength loss decreased to 39% with 20% moisture addition which was 73% at dry condition. Overall results come down to 22% loss at 50% moisture, and then 3% increase at 100% moisture addition.

As discussed above, fabric D has least resistance to radiant heat exposure (Figure 8). Fabric D in dry condition lost almost 100% of its strength even at 10 kW/m^2. The moisture had a positive effect only at the lower radiant heat exposure 10 kW/m^2. The tensile strength loss was 44% and 33% respectively for 50% and 100% moisture content compared to the 98% at dry condition. However, at higher heat flux 15 and 20 kW/m^2 moisture did not play any significant role. The strength loss of the moist fabrics at all percentages were similar to the dry fabrics. Moisture did not help much in retaining the tensile strength at higher temperature because once the moisture evaporated the temperature inside the sample raised during five minutes exposure. Fabric D loses its strength even at lower heat flux of 10 kW/m^2. Therefore, at 15 and 20 kW/m^2, moisture could not help much in retaining the tensile strength. Once the moisture evaporated, the temperature increased, and fabric D lost its tensile strength immediately.

In the third group, multi-layered fabric system with the presence of moisture in the thermal liner during the exposure was analyzed. Same linear regression analysis tool was used to determine the R square and t-test value (t and p values). The independent and dependent variables are as follows and shown in Table 11:

Independent variables: i) Fabric properties (Weight/unit length, thickness, fabric count)

ii) Heat flux intensities (0, 10, 15, and 20 kW/m^2) and moisture addition amount (0, 20, 50, and 100 %) are the ordinal independent variables.

Dependent variable: Tensile strength of the fabrics A, B C, and D. In the Scatterplot, the value of standardized predicted values was between -2 to 1.5, and the standardized residual was between -2 to 2. This rectangular distribution of predicted value vs residual value represents a good fit of the data into the model. Normal probability plot was also generated by using the analyze tools to find out the distribution of the residuals. This plot also suggested that the standardized residuals are normally distributed.

Table 11

Statistical Analysis of Tensile Strength of the Fabrics in Moist Condition (Three-layered)

Model Summary		
R Square	*F*	*p*
0.81	26.02	0.001
Coefficients	*t*	*p*
Weight/unit length	3.434	0.002
Thickness	-2.703	0.011
Fabric Count	-0.642	0.526
Heat Intensity Level	-5.941	0.0001
Moisture Level	3.214	0.003
Individual R Square Values Between the Fabric Properties and Tensile Strength		
Fabric Properties	R Square Value	
Weight/unit length	0.303	
Thickness	0.452	
Fabric Count	0.446	

From the earlier discussion, we have seen that in the three-layered fabric system with the presence of moisture in the thermal liner, moisture has positive effect on the tensile strength when the exposure time was five minutes. On the other hand, the level of heat intensity has a negative effect on the tensile strength. The t-test value in Table 11 shows the same result. For all four fabric layers, t-values for moisture have a positive value, and heat intensity values have a negative value. Almost all the t-test values are statistically significant when p-value is 0.1 or lower. Also, the R^2 values of three-layered fabric system is lower compared to the single layer fabric system. This suggests the moisture in the thermal liner plays crucial part in determining the effect on tensile strength of the outer layer fabrics compared to the presence of moisture in the single layer. Since moisture in the single layer did not affect the tensile strength, the strength depended on the heat flux intensities solely. Therefore, the R square values are greater in single-layered fabric system compared to the three-layered fabric system. Similar to the previous discussion, the thickness is the most important property when we consider the fabric tensile strength, with fabric count as the second most important property. Table 12 summarizes the combined effect of radiant heat and moisture on the tensile strength of all four outer layer fabrics.

Table 12

Effect of Moisture and Radiant Heat on Tensile Strength of the Fabrics (Three-layered)

Samples	Heat Flux																							
	10 kW/m^2								15 kW/m^2								20 kW/m^2							
	0%	Δ%	20%	Δ%	50%	Δ%	100%	Δ%	0%	Δ%	20%	Δ%	50%	Δ%	100%	Δ%	0%	Δ%	20%	Δ%	50%	Δ%	100%	Δ%
Fabric A	1093	3.7	1143	-0.7	1095	3.5	1146	-0.97	578	49	768	32	849	25	980	14	28	98	58	95	80	93	577	49
Fabric B	1006	23	1200	8.3	1291	1.4	1251	4.4	489	63	483	63	588	55	1149	12	279	79	304	77	325	75	596	54
Fabric C	1020	13	1042	11	1202	-3	1161	0.4	533	54	511	56	562	52	1163	0.3	314	73	707	39	904	22	1204	-3.3
Fabric D	9	98	28	94	263	44	315	33	4.4	99	5.3	98.9	5.1	98.9	12.8	97	0	100	4.2	99	3.3	99	36.5	92

Δ: Change of tensile strength (compared to the initial strength before the heat exposure and dry condition)

CHAPTER V

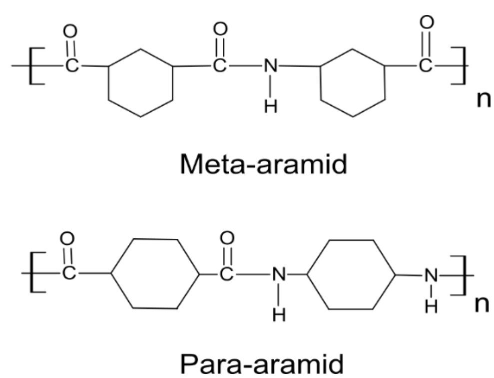
DISCUSSION

5.1 Effect of Radiant Heat on Tensile Strength of the Fabrics in Dry Condition

Initial strength of the fabric usually depends on the fabric and yarn properties such as count, twist, ends and picks per inch, cover factor, weave structure, etc. and the type of fiber present in the fabric (Backer, 1948; Dimitrovski, 2008; Malik et al., 2009; Realff et al., 1997; Teli et al., 2008). Since three of the experimented fabrics (A, B, and C) were made from synthetic fiber and fabric D was made from a natural fiber, the initial tensile strength of these two categories of fabrics was significantly different. In addition, the changing behavior of tensile strength after the radiant heat exposure also can be categorized into two groups. The fabrics A, B, C behaved similarly while fabric D behaved completely different. Fabric D, which was made from FR Cotton fiber, the showed highest tensile strength loss in single layer fabric system in dry condition. In general, natural fibers have lower strength compared to the synthetic fibers (Jamir et al., 2018). The tensile strength mostly depends on the crystallinity and spiral angle of the polymers. Higher crystallinity and lower spiral angle in general leads to higher strength. Usually, cotton has lower crystallinity than the synthetic fibers, moreover, spiral angle of the polymers in cotton fiber is around or steeper? than 20 degree (Möller & Popescu, 2009; Yu, 2015). Though fabrics A and B showed similar trends in tensile strength loss at higher heat flux (15 & 20 kW/m^2), the overall strength loss of fabric B was lower compared to fabric A. The reason that fabric B shows higher resistance to radiant heat compared to the fabric A lies in their polymer structure. Fabric B, which is made from para-aramid fiber, connects at the para-position of the phenyl link, whereas fabric A meta-aramid fibers connect at the meta-position. Therefore, polymers in para-aramid fiber are highly compacted compared to the meta-aramid fibers. Due to the lower compactness of the meta-aramid fiber compared to the para-aramid fiber, the meta-aramid fiber is not as strong and more flexible than the para-aramid fiber. Figure 9 shows the polymer structure of both meta-aramid and para-aramid fibers.

Figure 9

Structures of Meta-Aramid and Para-Aramid Fibers



The tensile strength of the fabric is mostly dependent on the organization of the polymer chains and the macro structure (Hayashi, 1975; Hearle, 1967; Krigbaum et al., 1964). Similar pattern of loss of tensile strength with increased temperature is observed from the Figure 9. The loss of tensile strength can be explained due to the fibrillar to the lamellar transformations within the fibers which causes an increase in crystallinity with lamellar spacing (Maurya et al., 2021).

5.2 Effect of Moisture and Radiant Heat on Tensile Strength of the Fabrics (Single Layer Fabric System)

The tensile strength of fabric A increased initially with respect to moisture during the heat exposure at 10 kW/m^2. This increasing tensile strength phenomenon could be explained based on the initial strength of the fabric A in moist condition. Initial tensile strength of fabric A in moist condition was lower than the dry condition. This is likely due to moisture reduced the friction between the fibers which resulted lower tensile strength of the fabric in moist condition before the heat exposure. Moisture of the fabrics B and C evaporated quickly compared to the fabrics A and D, resulting in increased temperature in the fabric system, which led it to behave similarly to the dry fabric. Fabric B behaved similarly to fabric C. These blend fabrics were highly hydrophobic, and therefore applied moisture was mostly sitting on the fabric surface. Therefore, the water evaporated very quickly after the start of the heat exposure, resulting in thermal degradation of the polymer chain. Since the moisture evaporated very quickly, the tensile strength of the moist fabric was similar to the dry fabric. A slightly improved tensile strength was shown at 10 kW/m^2 when the moisture percentage was 100 %. For the fabric D, there was always more than 90% strength loss, and at maximum heat flux the fabric completely degraded and tensile strength loss was 100%. This is because fabric D comprises of natural cotton fiber, which has least resistance to radiant heat among all tested fabrics.

5.3 Effect of Moisture and Radiant Heat on Tensile Strength of the Fabrics (Three-Layered Fabric System)

Moisture in the thermal liner had significant positive effect ($p<0.05$) on the tensile strength of all four fabrics during the five minutes of heat exposure. It took much heat energy to evaporate the moisture of the thermal liner, since water vapor cannot pass easily through the moisture barrier. Since energy required in transition water molecule into vapor was provided by the heat energy, the temperature of the fabric system did not rise high enough to degrade the polymer structure especially in lower heat flux and higher moisture content. At lower temperature with the presence of moisture some orientation change of polymer chain may have occurred, which led to an increase in crystalline region and increased the strength of the fiber.

For both single and multi-layer fabric systems radiant heat exposure had negative effect on the tensile strength. Tensile strength of fabrics A, B, and D decreased when heat intensity was increased at five minutes heat exposure time. Depending on the presence of fiber in the fabric the level of tensile strength losses were different in different fabrics. However, all fabrics showed the similar trend of decreasing tensile strength. Effect of moisture in the tensile strength was different in single and multi-layer fabric system. Moisture in the single layer did not contribute positively towards the tensile strength loss. Only a slightly improved tensile strength was seen for the fabrics A and C when moisture addition was 100% at lower heat flux of 10 kW/m^2. On the other hand, in the three-layer fabric system where moisture was present in the thermal liner, a noticeable effect was seen. In this case, moisture had positive effect on the tensile strength of fabrics A, B, C and D. Strength loss of the outer layer fabrics decreased with the increased moisture in the thermal liner. Both heat flux intensity and moisture had noticeable effect on the tensile strength of the high-performance fabrics used in firefighters' turn-out gear, which should be considered to evaluate the overall integrity of the gear.

CHAPTER VI

CONCLUSION

This study investigated the change of tensile strength of the fabrics used in firefighters' bunker gear under radiant heat exposure and with different percentages of added moisture. The tensile strength of the fabrics was characterized under different heat fluxes in dry and moist conditions. In doing so, four different types of high-performance fabrics were selected. Both single and multi-layered fabric systems were considered during the testing. Thickness and the fabric count were found as the key fabric properties affecting the tensile strength. Presence of moisture also played a complicated role in determining the change of tensile strength depending on the amount and location of the moisture. Moisture had significant positive effect on the tensile strength when the moisture was in the thermal liner and the amount of moisture was higher. This research will help to understand the overall integrity of the firefighters' thermal protective fabric after being worn at fire sites.

However, the change of tensile strength may not be directly related to the protective performance, which is how quickly these fabrics could generate burn injuries on the wearers body. Therefore, further research may be done to develop the relation between the change of tensile strength and protective performance of thermal protective fabrics in consideration with moisture and radiant heat flux. The changes of tensile strength also could not be quantified in terms of orientational changes of polymer chains, which could be another interesting study for further development of this research.

Moreover, in this research distilled water was used to simulate the sweating of the firefighters. However, human sweat contains not only pure water but also tiny amount of ammonia, urea, salt and sugar (*"What's Sweat?", (n.d.)*). The pH of the sweat could be either acidic or alkaline (ISO 105-E04) (ISO, 2013). The presence of actual sweat in the clothing system could give different results compared to the presence of distilled water. Therefore, this research could further develop by using the alkaline and acidic perspiration solution instead of distilled water, which are closest mimic to human sweat. Kneel and crawl activities are also common during extinguishing fire, which cause compression in clothing especially in the elbows, knees, and lower-leg areas (Mandal, Batcheller, et al., 2021). Therefore, another line of future research could be developed while including the pressure along with heat and moisture.

It is expected that this research will help to understand the change of tensile strength of the fabric used in thermal protective clothing after being exposed to radiant heat. It is hoped that this research will eventually help to identify the overall integrity of the firefighters' thermal protective clothing through the development of improved fabrics that maintain better integrity of the firefighter's bunker gear. This effort could help to improve occupational health and safety for firefighters.

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