University of Alberta

Thermal Protection and Thermal Comfort: An Evaluation of the Fabrics Used in Chefs' Uniforms against Thermal Hazards in the Kitchen

by

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ABSTRACT

Workers in kitchens are at risk of burn injuries and thermal discomfort related to the hot and humid kitchen environment. However, thermal protective performance of chefs' uniforms has received limited research attention. The purpose of the current research was to investigate how effective textiles used in chefs' uniforms are in providing thermal comfort and protection against thermal hazards. Four fabrics and two aprons used in chefs' uniforms plus one control fabric were tested regarding thermal protection (ease of ignition, protection against hot surfaces, steam and hot liquid) and thermal comfort (air permeability, thermal resistance, and water-vapour resistance). Findings showed that single-layered fabrics were generally less protective than multiple-layer fabrics. However, layering of fabrics increased protection against hot surface contact but not necessarily against hot water or steam. A waterproof apron covering a chefs' garment fabric provided protection against hot water burns and steam, but it was highly flammable.

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LIST OF ABBREVIATIONS

CGSB	Canadian General Standards Board
OSHA	Occupational Safety & Health Association
ASTM	American Society for Testing and Materials
WBGT	wet bulb globe temperature
RH	relative humidity
FR	flame resistant
M	mean
NS	not significant
SD	standard deviation
SEM	standard mean error
cm	centimeter
df	degree of freedom
g	grams
g/m^2	grams per square metre
g/cm^3	grams per cubic metre
N/m	Newton per meter
Pa·s	pascal second
°C	degrees Celsius
%	percent
R_{ct}	thermal resistance in square metres kelvin per watt
R_{et}	water-vapour resistance in square metres pascal per watt
SL	Single-layer
1L	one-layer
2L	two-layers
3L	three-layers
4L	four-layers
NA	not applicable
PPE	personal protective clothing
PU	polyurethane
PTFE	polytetrafluoroethylene

CHAPTER 1. INTRODUCTION

1.1 Background

The culinary industry is a significant industry with a considerable number of people employed. Over one million workers are currently employed in the accommodation and food industry in Canada (Statistics Canada, 2012) and 23,000 of these in Alberta (Flakstad, 2004). Chefs and cooks held over 2,050,800 jobs in 2010 in the United States. Food preparation and serving related occupations were the third-largest occupational group in 2010 (Lockard & Wolf, 2013). However, food services have been reported to have the highest number of recordable injuries and illnesses of all occupations (Jaskolka, Andrews, & Harold, 2009; Personick, 1991). According to Alberta Human Resources and Employment's summary of occupational injuries and diseases in 2002, chefs and cooks ranked the third highest in time-away-from-work injury with 512 claims (Flakstad, 2004). Occupational injuries and diseases related to heating and cooking appliances rose steadily from 1999 to 2002 according to the Worker's Compensation Board of Alberta.

Several factors contribute to the high injuries rate within the culinary industry, in particular to chefs and cooks. First, kitchen workers are naturally more exposed to various hazards, which may be categorized as thermal hazards, including: 1) extreme conditions with high temperatures and high humidity; 2) close contact with flames, hot liquids, steam and hot surfaces (e.g., stoves, oven, and deep fryers); and non-thermal hazards, including: 1) contamination from raw meat and poultry; 2) exposure to cleaning or pest control products or other toxic substances; 3) operation of sharp and powerful equipment (e.g., knives and food slicers); and 4) wet floors and stairs which may lead to slips, trips or falls (Canadian Centre for Occupational Health and Safety [CCOHS], 2004; Cassells, Kerr, & Traeger, 2011; Courtney et al., 2010; Ehnes, McQueen, & Strickfaden, 2012; Flakstad, 2004; Halpin, Forst, & Zautke, 2008; Verma et al., 2012).

Second, inexperience on the job may also lead to the increase of injuries. Horwitz and McCall (2004) found that almost 50% of all burn claimants had less than one year of job tenure and over 70% had less than five years. A gap was identified in the literature regarding effective injury prevention strategies and program models for teen restaurant workers (Ward et al., 2010). It is also likely that food service workers may typically receive less training regarding safe working conditions than people from industries in more commonly recognized “harsh environments”, such as firefighting and oil and gas industries. For instance, many kitchen workers have reportedly not been able to receive formal health and safety training, such as how to handle potentially harmful products (i.e., caustic soap and detergents), fire safety and dealing with hot or heavy items (Flakstad, 2004).

Third, the frantic pace and rush to satisfy clients and serve hot food can sometimes push safety to the backburner (Cassells et al., 2011; Flakstad, 2004; Young & Corsun, 2010). In addition to adequate training in safety procedures, the kitchen workers may be able to benefit from an increase in protection using personal protective equipment (PPE) and compensate for the lack of awareness of hazards in kitchens.

PPE is designed to be used to control exposure to hazardous substances or conditions, or to prevent accidental injuries or serious harm to employees working in hazardous or potentially hazardous conditions or areas. In the culinary industry, PPE for chefs includes the chefs' uniform (coat/jacket and pants), chef shoes, functional aprons, chef hats, oven mittens and potholders, etc. Long sleeves of chefs' jackets are intended to protect arms from hot surfaces and hot splashes of liquids. Chef pants are designed for loose fit aiming at easy removal during accidents. Slip resistance shoes are commonly required in most commercial kitchens. Functional aprons are recommended to be worn along with the chefs' uniform for an extra layer of protection against splatter and stains.

Within commercial kitchens, thermal hazards are critically related to worker's health and safety. The food service industry experiences the highest number of burns among all occupations (Horwitz & McCall, 2004; Hunt, Calvert, Peck, & Meyer, 2000). The dominant burn injuries have been found to be scald injuries to the hands and upper extremities (Riina et al., 2000). Contact burns with hot surfaces have also been reported as being common (Halpin et al., 2008), as well as burn injuries from steam (Burling, 2004). Heat strain may also be encountered by kitchen staff (Bongarde, 2010; Burling, 2004), from working in hot and humid conditions, which diminish the evaporation of sweat and reduce evaporative cooling. Under these conditions, there is increased potential for heatstroke or heat exhaustion to occur (Haruyama et al., 2010; Livchak, Schrock, & Sun, 2005; Matsuzuki et al., 2011). The mentioned potential thermal hazards above, which are common within commercial kitchens, highlight the significance of PPE for food service workers and the importance of research investigating the effectiveness of the chefs' uniform as PPE, considering both the thermal protection and thermal comfort.

The necessity of using PPE properly and correctly against workplace hazards is mandated by provincial legislation under health and safety laws within Canada (Bongarde, 2010). When it comes to protecting workers from a hazardous environment, the first choice is control of the hazard at the source (Government of Alberta, 2009). There are effective ways to reduce the potential risks within kitchens, such as keeping the floor dry and clean at all times, discontinuing the use of electrical appliances with damaged cords, and keeping textiles or other combustibles away from stoves and other such appliances. The second choice is control along the path. For example, detecting the temperature and the amount of smoke in a kitchen environment is essential for the prevention of incidents. After considering and taking other measures to prevent risks, PPE is the “last line of defense” (Bajaj & Sengupta, 1992). If a risk assessment shows that, there are health and safety risks that cannot be controlled at the source of the hazard and or along the path, employers must provide suitable PPE for the employees. Use of chefs’ uniforms with long sleeves may prevent hot water or flame related regional burns and reduce incident rates of burn injuries; wearing slip-resistant shoes may prevent workers from falling and tripping; mesh (Kevlar®) gloves could help to reduce cuts incidents (Burling, 2004).

Improper use of PPE can be a potential safety risk (Bird, 2000) and the garment may not be able to provide a high level of protection (Holmér, 2006). For example, shoes, which are not slip-resistant, may contribute to the likelihood of a trip and fall; chefs’ uniforms without flame resistant properties could be potentially combustibles when exposed to different types of heat sources within kitchens (Hoschke, Holcombe, & Plante, 1986). However, carefully designed and sized garments or equipment can reduce the incident rates and provide higher level of protection for kitchen workers.

Little research has been carried out to address the thermal protective performance of chefs’ uniforms towards thermal hazards (i.e., high temperature and humidity, flames, hot liquid splashes, steam and hot surfaces) systematically within commercial kitchens. Characterization of thermal performance of the fabrics used in current chefs' uniforms is an important step towards finding better protection for kitchen workers and establishing kitchen safety interventions. In the study herein, the effectiveness of selected chefs' uniforms was investigated from the perspectives of both thermal protection and thermal comfort.

1.2 Statement of problem and purpose

Kitchen workers are confronted with conditions with one or a combination of thermal hazards, including heat, flames, hot liquids, steam, and hot surfaces. Chefs' uniforms have been primarily designed for aesthetics meanwhile providing a certain a level of protection for chefs and cooks (Anonymous, 2012), but the thermal protection they provide may be limited. However, scarce academic research has been conducted to address the effectiveness of PPE used in kitchens on protecting against kitchen related accidents and injuries (Ehnes et al., 2012). Furthermore, no work has been conducted on the effectiveness of fabrics used in garments in current chefs' uniforms regarding protection of kitchen workers from thermal hazards and providing thermal comfort.

Can current chefs' uniforms provide effective protection for workers in the kitchen towards all kinds of thermal hazards within a commercial kitchen? The purpose of this research was to gain insight into how well textiles used in chefs' uniforms provide protection against these thermal hazards. Thermal insulation and water vapour permeability and air permeability were compared among different fabric systems in order to evaluate the thermal comfort of current chefs' uniforms. Ease of ignition of fabrics was estimated. Hot water and oil splash tests were conducted according to customized parameters in order to differentiate the thermal performance of the fabrics. Steam tests with low pressure were applied to fabrics in order to assess how fabrics would protect wearers from steam burns. Different fabric systems (e.g., impermeable apron and multiple layers) were evaluated to determine the most effective way to wear chefs' uniforms. Based on the obtained data from bench scale tests, recommendations were made in order to improve the thermal protective performance and thermal comfort of fabrics used in chefs' uniforms.

1.3 Justification

This research addresses the general issues of how well the food service workers are protected from thermal hazards, given the lack of scientific research in evaluating the effectiveness of current uniforms. It is unknown whether the fabrics used in current chefs' uniforms are able to provide an adequate level of thermal protection against thermal hazards and thermal comfort for the wearers.

This study bears immediate relevance to the health and safety of kitchen workers, especially chefs. This study is a significant contribution to determining the thermal protection provided by current chefs' uniforms. Findings may contribute to a comprehensive understanding about the thermal performance of chefs' uniform. Recommendations may shed light on the necessity of providing food service workers with a higher level of thermal protection and better design of uniform fabrics.

1.4 Objectives

The purpose of this study was to determine the effectiveness of fabrics used in selected chefs' uniforms towards the thermal hazards likely to be encountered within commercial kitchens. Fabric properties relating to thermal comfort were investigated as well.

Specific objectives of this study were to:

1. study the thermal comfort issues related to fabrics used in chefs' uniform, using thermal insulation and water vapour permeability and air permeability tests;

2. examine the flammability of fabrics sued in chefs' uniforms, using ease of ignition testing method from two different flame positions (i.e., surface ignition and bottom edge ignition);

3. determine the time to predicted second-degree burn and absorbed energy for different fabric systems when exposed to hot surfaces, steam and hot liquid splashes;

4. determine the relationship between the fabric characteristics (i.e., thickness, density and fabric compositions) and thermal performance of chefs' uniforms; and

5. make recommendations for improving the thermal comfort and thermal protective performance of current chefs' uniforms towards thermal hazards in the kitchen.

1.5 Limitations and delimitations

1.5.1 *Limitations*

1. No chefs' uniforms made from flame resistant fabrics were available on the market. Instead, a flame resistant coverall fabric (used for firefighter

gear) with similar weight and thickness as the fabrics in chefs' uniforms was used as a representative of FR fabrics.

2. The lowest pressure which could be achieved by the current steam tester was 10 psi and the temperature was 108 ± 5 °C. This pressure is higher than the normal steam generated from pots but is similar to the pressure of the normal steam cooker.

3. Considering the consistency and feasibility of the hot water splash test, 85 °C was used as the test temperature to avoid the boiling and evaporating of the water.

4. The hot oil splash test was also conducted at 85 °C due to the feasibility of the current apparatus and safety of operators rather than higher temperatures of 175-190°C which is more typically used within commercial kitchens.

1.5.2 *Delimitations*

1. This study was limited to mainstream products on the market, 100% cotton and 65%/35% polyester /cotton blends. Conclusions drawn from this study cannot be generalized to all chefs' uniforms available on the market.

2. This study did not focus on the design features of chefs' uniforms but examined the thermal protection properties of fabrics used in chefs' uniforms towards common thermal hazards encountered within commercial kitchens.

1.6 Definitions

- heat flux – the thermal intensity indicated by the amount of energy transmitted divided by area and time, W/m^2 (Canadian General Standards Board, 2010).
- ignition – initiation of combustion (Canadian General Standards Board, 2010).
- melting – a material response evident by softening of the polymer (Canadian General Standards Board, 2010).
- shrinkage – a decrease in one or more dimensions of an object or material (Canadian General Standards Board, 2010).
- afterflame – persistence of flaming of a material, under specified test conditions, after the ignition source has been removed (Canadian General Standards Board, 2010).
- afterflame time – the length of time for which a material continues to flame, under specified test conditions, after the ignition source has been removed (also called duration of flame) (Canadian General Standards Board, 2010).
- second-degree burn: involves damage extending from the epidermis to dermis layers of skin. The damaged site becomes red and blistered; also called partial thickness burn. In this degree, severe pain and swelling are produced (Walls et al., 2009).

CHAPTER 2. REVIEW OF LITERATURE

2.1 Health and safety in kitchens

2.1.1 *Hazards in kitchens*

"Floors were sometimes wet or sticky, and sometimes there were supplies blocking the path. Many of the coffee machines had lights that went on when the coffee was done dripping; however, there was still excess water in the machine, and spills could occur. In the machines without lights, a substantial amount of hot water was seen to be splashing out when the filter was removed. Fryers were not covered, and in one vendor, the salt and peppershakers were located on a shelf above the fryers. " (Halpin et al., 2008)

As described above, kitchen environments can be a hazardous place, no matter where they are located (e.g., hotel, school, restaurant). As a result, culinary workers are potentially exposed to many dangerous conditions, such as thermal hazards, including: 1) extreme conditions with high temperatures and high humidity; 2) close contact with flames, hot liquids, steam and hot surfaces (e.g., stoves, oven, deep fryers); and non-thermal hazards, including: 1) contamination from raw meat and poultry; 2) exposure to cleaning or pest control products or other toxic substances; 3) operation of sharp and powerful equipment (e.g., knives and food slicers); and 4) wet floors and stairs which may lead to slips, trips or falls (Canadian Centre for Occupational Health and Safety [CCOHS], 2004; Cassells et al., 2011; Courtney et al., 2010; Ehnes et al., 2012; Flakstad, 2004; Halpin et al., 2008; Verma et al., 2012).

Hazards can be categorized into short-term exposure to extreme conditions associated with acute injury events and long-term exposure to conditions associated with chronic health issues (Holmes, 2000). Thermal hazards such as flames, hot surfaces, and hot liquids are categorized into the former group, as they are short-term exposures to extreme conditions. A hot and humid environment can be categorized into the latter group, as it is a long-term exposure, more related to kitchen workers' thermal comfort.

2.1.1.1 *High heat and humidity*

Because of the very nature of the cooking process, devices in kitchens (e.g., furnaces, stoves, ovens) keep generating heat and moisture. Most of the heating devices create a high radiant heat and sometimes flames. Therefore, it is common that kitchens are hot and also humid. The extent of which can be influenced by the areas within the kitchen, cooling devices, heating methods and heat sources (Matsuzuki et al., 2011). For example, the heat sources themselves can vary in modern commercial kitchens, with the two main types being electric and gas. Temperatures surrounding the cook in commercial kitchens have been reported to be higher in kitchens using gas (i.e., gas kitchens at 29.6 ± 2.2 °C compared with electric kitchens at 25.7 ± 2.4°C) (Haruyama et al., 2010; Matsuzuki et al., 2011).

These conditions can have an adverse effect on culinary workers by causing discomfort and fatigue (Bongarde, 2010; Haruyama et al., 2010; Livchak et al., 2005). Humidity coupled with poor ventilation diminishes the evaporation of sweat and reduces the effectiveness of evaporative cooling. Corresponding reactions, such as loss of concentration, irritability, muscle cramps and fainting may potentially occur during working with high intensity in such environments (Government of Alberta, 2012).

2.1.1.2 *Flames*

Among commercial kitchens, it is common to have flames, both due to the use of gas cookers and also due to the ignition of cooking oil and grease (Ackland, 2012). Burns caused by the ignition of grease has been found to be an important cause of burn injuries (Fiebiger, Whitmire, Law, & Still, 2004). In addition, flames can result in the ignition of clothing, which could lead to full thickness skin burns (Hermans, 2005).

2.1.1.3 *Hot surfaces*

Another significant burn injury can be attributed to contact with hot surfaces (e.g., stoves, grills, ovens). It was reported that burn injuries caused by skin contact were typically not recorded by safety organizations, such as Occupational Safety and Health Administration (OSHA), with enough details to determine the conditions leading to the injury (Halpin et al., 2008). In many cases, these burns are severe because the combination of pressure and sometimes prolonged exposure to heat sources can contribute to major injuries (Hermans, 2005). The human skin, the hot surface and the nature of the contact determine the heat transfer and thus extent of burn (Parsons, 1993). It has been reported that when a solid surface is below about 43 °C, discomfort and pain sensation can be avoided and with no skin damage occurring (Parsons, 1993). However, the temperatures of ovens in kitchens are much greater than this as they typically tend to vary in the range of 107 °C to 246 °C (Joachim, 2001). Furthermore, heating devices within commercial kitchens are mostly made from metals (e.g. steel and aluminum) with high thermal conductivity and therefore the rate at which heat transfers from the hot surface to the skin is high. Other thermal properties (i.e., surface temperature, wet or dry, thermal conductivity and diffusivity and specific heat) also has an influence on skin burns (Parsons, 1993).

2.1.1.4 *Steam*

Steam is an important and potential source for causing scald burns within kitchens (Burling, 2004). Little research has been done in investigating steam burns in kitchens from the perspective of textiles. Due to the fact that steam in kitchens is typically generated from pots with boiling water, the pressure of steam is much lower than the steam encountered in the oil and gas industry which can be up to 800 kPa (Crown & Dale, 2005). However, a steam cooker pressure usually varies from 10-15 Psi (69-103 kPa) (Riina et al., 2000).

Steam can easily penetrate a single layer of fabric, such as that making up chefs' uniforms, due to the sufficient spaces between yarns and fibres. Burns resulting from steam are mainly due to the transfer of relatively large amounts of energy when evaporated moisture condenses on the cooler skin surface. The condensed water cools to skin temperature and a large amount of energy can be released that can result in a most unpleasant burn (Newbugh, 1949). Steam burns may be more intense than dry burns since human skin may absorb hot moisture, which can be transferred to deeper skin layers (Rossi, Indelicato, & Bolli, 2004). However, little research has been done to investigate this particular hazard within commercial kitchens.

2.1.1.5 *Spilling and splashing of hot liquids*

Scald burns are a leading cause of burn injuries within the culinary industry (Safety & Health Assessment & Research for Prevention, 2009). Scald burns in a kitchen are mainly due to spillages of hot liquids (Halpin et al., 2008).

Almost one third of all scalding burns occurring in restaurants has been found to be caused by slips, trips and falls, which result in a spill or splash of hot liquids (Courtney et al., 2010; Flakstad, 2004; Verma et al., 2012). The spillages of hot liquids and foods count as short-term exposure since the liquids can quickly run off the skin. However, often the duration of exposure does not predict how severe a burn injury could be as short exposure periods can still lead to serious burns (Huyer & Corkum, 1997). In most cases, this kind of burn injury is partial thickness and therefore considered as a second-degree burn (Hermans, 2005).

The most frequent site for scalds to occur have been found to be distributed to the hands, arms and feet, although other parts of the body could still be burnt (Halpin et al., 2008). This gives an indication for textile and garment researchers: when improving the protection of current chefs' uniforms, extra protection of these more vulnerable spots should be taken into consideration by using impermeable or semipermeable fabrics, or multiple layers of fabrics.

2.1.1.6 *Hot water*

Hot water is a necessary requirement when cooking food and preparing hot beverages within commercial kitchens. The temperature of boiling water (100°C) is well above temperature that results in immediate, potentially severe burn injuries. Water at 66°C can reportedly cause second-degree burns within three seconds and third-degree burns within six seconds (Huyer & Corkum, 1997). This is due to the high heat capacity of water, which conducts heat very rapidly. Hot water may burn the skin while wood and even metal surfaces heated to the same temperature would not cause a burn at the same temperature (Newbugh, 1949).

According to experimental work conducted by Lu et al. (2012), among three common hot liquid hazards in the oil and gas industry (i.e., hot water, oil and drilling mud) (all measured at 85 °C), hot water was found to show the highest heat flux and therefore would cause the most severe burn injury. This may be attributed to: 1) the lower viscosity of water, which made water the easiest liquid to penetrate the fabrics, leading to much more penetration than canola oil and drilling mud; and 2) the higher heat capacity, which can lead to the highest stored energy and therefore discharge the most to the skin simulant sensor (Lu, Song, Ackerman, Paskaluk, & Li, 2012).

2.1.1.7 *Hot oil/grease*

A larger number of burns are attributed to kitchen grease every year (Fiebiger et al., 2004). Scald injuries caused by hot oil were most frequently due to the hot devices containing oil such as deep fryers. The temperature of oil used in deep fryers is much higher than that of water, usually ranging from 175 to 190°C.

Canola oil (at 85 °C) was found to show lowest heat flux and cause the least burn injury, among three common hot liquid hazards in oil and gas industry (i.e., hot water, oil and drilling mud) (Lu, Song, Ackerman, et al., 2012). Generally, scalds from hot oil are more severe than injuries from hot water (Safety & Health Assessment & Research for Prevention, 2009). This is because oil used in deep fryers is around 175-190 °C, which is at a much higher temperature than hot water (maximum 100 °C) used in kitchens. With the increase of temperature, the viscosity of vegetable oil decreases (Fasina & Colley, 2008; Miller, Singh, & Farkas, 1994). As a result, hot oil can penetrate the fabric system more easily than cool oil.

Furthermore, as oil is greasy, it clings to skin and fabrics more so than water, which means it was in contact with the skin for longer (Fiebiger et al., 2004). This was demonstrated in the experimental work conducted by Lu et al. (2012) when they investigated the stored energy in fabrics after hot liquids exposure. The cooling period of canola oil was longer than hot water because the fabric absorbed more oil than water, which lead to the continuation of heat transfer from the fabric to the sensor and then hindered the cooling of the sensor.

2.1.2 *Human skin and burn injuries*

Burns may be thermal, chemical, and electrical in nature. Within commercial kitchens, the majority of burn cases have been reported as thermal burns (Centers for Disease Control and Prevention, 1993; Halpin et al., 2008; Hunt et al., 2000). Furnaces with high radiant heat, flames from stoves, hot surfaces in the oven and boiling water are all common heat sources.

Human skin consists of three layers, the epidermis, dermis, and the subcutaneous layer. Among these layers, the epidermis acts as the barrier layer and the dermis provides strength and elasticity. The subcutaneous layer is to stabilize the position of the skin in relation to underlying tissues (Montagna & Parakkal, 1974). At 44 °C, human skin cells can be damaged if the exposure is sufficient; at 72 °C, second-degree burns or complete destruction can occur to the epidermis and dermis virtually instantaneously (Bull, 1963; Stoll & Chianta, 1969). However, it is a nonlinear relationship between the extent of skin damage and skin temperature. While skin temperature increases linearly, the extent of burn injuries intensifies exponentially. The Stoll curve was used to quantify the level of heat and the duration of time required for a second-degree burn (Stoll & Chianta, 1969).

Burn injuries are categorized as first, second, third, and fourth degree burns according to the extent of damage (Diller, 1985; Greenhalg, 2002):

- First degree burns (superficial partial thickness): cause damage to the outmost layer of skin, for example, sunburns caused by ultraviolet radiation.
- Second degree burns (deep partial thickness): includes damage extending through epidermis to dermis skin layers. The burn site can be red, peeling blistering and swelling with fluid leaking from the skin, and is very painful.
- Third degree burns (whole thickness): involves damage to both epidermis and dermis layers, extending to the underlying tissues, muscle, bone and organs. Generally, the appearance of the burn sit can be black or charred with white exposed fatty tissue or bone.
- Fourth degree burns (subdermal): extends through skin, subcutaneous tissue and into underlying muscle, tendon and bone.

Human skin, with its large surface area all over the human body, is highly sensitive to thermal exposure. Both the temperature and the exposure duration significantly influence the extent of burns (Stoll & Greene, 1959). Skin burn injuries can occur under the exposure of either, high heat fluxes over short periods, or low heat flux over long periods. A mixed degree of burns may occur according to the amount of energy transferred from the energy source to the skin.

Burn injuries can be caused by the direct contact with the heat source and a burning garment. This kind of burn injury is a complex function influenced by the following: 1) factors related to heat source (i.e., temperature and thermal properties) and 2) factors related to clothing properties (i.e., ease of ignition of fabrics, rate and direction of flame spread and ease of extinguishment) (Hoschke et al., 1986).

2.1.3 *Thermal strain*

Thermal comfort refers to the thermal balance between the human body and the environment, and also the proper balance between body heat production and heat dissipation (Song, 2009). It is one of the most important parameters in the field of thermal protective clothing (Rossi, 2005). The demand of thermal protection and thermal comfort are often contradictory because protective clothing creates a barrier to protect the wearers from hazards, meanwhile it also creates a barrier for reduction of heat and moisture dissipation between the body and the environment (Bajaj & Sengupta, 1992; Rossi, 2005; Song & Barker, 2004). Wearing a chefs' uniform in the kitchen can keep human skin from directly contacting with the hazards (i.e., flames, hot liquid splashes, and chemical detergents). At the same time, it reduces the rate of heat exchange between the skin and the environment. By creating a humid microenvironment, clothing can both inhibit evaporation and diminish the cooling effect of evaporation (Nunneley, 1989).

Generally speaking, the goal of designing thermal protective clothing (e.g., garment design and textiles design) is to provide the wearers the highest level of protection without compromising thermal comfort. Meeting certain ergonomics requirements of PPE (e.g., wearing the right size) is of great importance for the purpose of solving this thermal protection/thermal comfort contradiction (Rossi, 2005).

Some protective equipment (e.g., aprons, masks, and chef hats) may cause discomfort and unsafe conditions, affecting performance and contributing to the harm of the worker's health (Haruyama et al., 2010; Holmér, 2006; Tanaka, 2007). For instance, the apron and double-breasted design of the chefs' uniform may create an extra barrier of protection; meanwhile it impedes the transfer of heat and hence diminishes the heat dissipation from the human body. Because of the large surface area of the human head, the heat dissipation through the skin in the head is significant. Therefore, wearing a hat in hot conditions will largely decrease the heat dissipation and can sometimes even lead to heat stroke, in worse case scenarios (Katch, McArdle, & Katch, 2006).

Thermal comfort involves body heat generation and heat and moisture transfer (among the body, the microenvironment, and the environment). The heat exchange barrier includes the materials of clothing, the air enclosed and the still air, which is bound to its outer surface (Havenith, 1999). Heat transfer occurs in the presence of a temperature gradient among the body, clothing, and environment. Kitchen workers may be potentially exposed to conductive, convective, or radiative modes of heat transfer or to any combination of these modes (Haruyama et al., 2010; Matsuzuki et al., 2011).

Heat production and heat dissipation occurs in a dynamic manner in order to preserve heat balance (Katch et al., 2006), which is presented by equation 1 (Holmér, 2006). An overheated body may lead to thermal strain, impaired performance, increased discomfort, or even heat stroke. The energy metabolism, clothing thermal properties and ambient climatic condition are factors determining this balance (Holmér, 2006). Holmér (2006) and Rossi (2005) concluded that clothing properties could be one of the most critical factors that influence heat balance of the human body. For example, absorption, condensation, and ventilation in clothing have an impact on its insulative and evaporative properties. Ideally, the heat and moisture transport through the garment should be as efficient as possible in order to avoid heat stress.

$$S = M - W \pm RES \pm E \pm R \pm C \pm K \quad (1)$$

Note: S is the change in energy content of the body, M is the energy metabolism, W is external mechanical work, RES is respiratory heat exchange, E is evaporative heat exchange, R is radiation heat exchange, C is convective heat exchange and K is conductive heat exchange.

Thermal strain can often be encountered by kitchen workers within commercial kitchens (Haruyama et al., 2010) due to warm and humid conditions in this environment. Haruyama carried out a cross-sectional study to elucidate the subjective thermal stress of workers in kitchen working environments in Japan. The researchers applied a self-reporting questionnaire and subjective judgment scales (SJS) to investigate the thermal strain in two types of commercial kitchens (i.e., electric kitchens and gas kitchens). A follow up study by the same research group measured environmental variables, including air temperature, radiant heat index, wet bulb globe thermometer index (WBGT) in front of the cookers and ambient temperature and estimated ambient WBGT around the workers (Matsuzuki et al., 2011). Their results indicated that workers in gas kitchens might be exposed to higher heat stress than those in electric kitchens. The SJS indicated that the subjective feelings of workers could reflect the magnitude of thermal stress within the kitchen environment. Although the working environments are critical to physiological response of kitchens workers, from the viewpoint of clothing and textiles, we cannot overlook the influence of the properties of fabrics used in chefs' uniforms, such as thickness, air and moisture permeability, wicking properties, and ventilation.

2.2 Protection afforded by current kitchen uniforms

The chefs' uniform is a highly developed and standardized uniform which has been used since the mid-19th century. Although with the development of aesthetics and demands of people today, there are different styles and designs on the current market. For example, chefs' uniforms are manufactured in a variety of colours, and the design of the front could be double-breasted, snap front or other casual clothing design (e.g., angel front). The fabrics used to manufacture chefs' uniforms typically tend to be 100% cotton or 65% polyester/35% cotton (Gray & Jones, personal communication, December 5, 2012). The mass and thickness of the fabrics have different levels (e.g., 170 gsm and 250 gsm) as well. Chemical finishes may also be applied to provide soil resistance (Burling, 2004).

Initially, white was the only colour used for chefs' uniforms because this showed obvious soil or stains. The oil retained by soiled garments could be an additional hazard since it may make it easier for the fabric to catch fire if exposed to flame. The double-breasted design was adopted because it can easily be reversed to hide stains that may accumulate throughout the day; and it also provides an extra layer of insulation against the stove or an accidental splattering or hot liquids or hot food (Anonymous, 2012). With the development of legislation (Government of Alberta, 2012) and awareness of safety, chefs' uniform, as an important component of chefs' PPE (Canadian Centre for Occupational Health and Safety [CCOHS], 2004), should provide a higher level of thermal protection for kitchen workers.

Ideally and functionally, the chefs' uniform should be worn to reduce thermal impact and to prevent the local burning of the skin. However, as a highly standardized uniform, very little scientific research evidence exists to prove the effectiveness of this uniform as PPE around the hazardous areas within kitchens. Clothing that was not intended to provide thermal protection from thermal hazards may be insufficient to prevent thermal injuries. Although research has been conducted on steam and hot liquid protection by fabrics used in oil and gas industries (Ackerman et al., 2012; Desruelle & Schmid, 2004; Gholamreza & Song, 2013; Lu, Song, & Li, 2012; Murtaza, 2012; Rossi et al., 2004), there has been no research focus on fabrics used in chefs' uniforms. There has been a rise in the need to improve the chefs' uniform to make it more thermally comfortable and functional (Zahler, 2010).

Protective gloves that can provide protection for the forearm are highly recommended since the contact burn injuries mostly occur to hands and distal upper extremities (Burling, 2004; Halpin et al., 2008). Wearing protective gloves is a temporary measure when chefs purposely are handling hot items, such as trays from the oven. Wearing protective gloves all the time would restrict movement and dexterity required during cooking. However, some inadvertent contacts with hot surfaces may occur under the circumstances without wearing protective gloves. Providing more protection via clothing design (e.g., adding layers to vulnerable locations) and fabric modification (e.g., flame and heat resistance) are the two possible ways to reduce the burn injury against hot surface contact.

Zahler (2010) introduced a patent aiming to improve the wearing comfort of chefs' uniforms by modifying the jacket and pants ensemble. This clothing system included an upper torso jacket and liner attached to the pants in order to optimize comfort by eliminating a fitted waist. In variations, the pants were adapted to be adjustable in length or to have a length limiting feature to prevent undesirable wear and soiling of the cuffs (Zahler, 2010). This feature may also help prevent an accidental fall due to improper length of the pants. However, this patent was not intended to improve the garment features in terms of wearer safety or thermal comfort.

Ehnes et al. (2012) investigated the merits and demerits of the current chefs' clothing, which included a double-breasted jacket, apron, two side towels, slip-free shoes, chefs' pants, necktie and chefs' hat. In a focus group among nine culinary arts students, three issues (i.e., protective clothing, comfort and injuries in the workplace) were evaluated. Ehnes et al (2012) suggested the design, functionality and protectiveness of the chefs' jacket needed to be revaluated in order to find solutions for current demerits, such as the non-proportional sleeve-to-size fit. This research served as an exploratory and qualitative study to address the performance of chefs' PPE. In the research herein, quantitative methods characterizing the thermal protective performance of fabrics, was applied to contribute to the evaluation of PPE in kitchens.

2.3 Heat transfer associated with chefs' uniforms

In the kitchen environment, the ambient temperature is potentially higher than the microenvironment of the human body; therefore, heat transfer from the environment to the human body may occur through the fabric system. There are four possible heat transfer modes between, a human body, the chefs' uniform and the environment: conduction, convection, radiation, and evaporation (Holmér, 1995; Rossi, 2005).

Conduction is heat exchange within a substance or between the skin and surrounding surfaces with which it is in direct contact (Lienhard & Lienhard, 2000). In thermal protective clothing, the conductive heat transfer occurs when the clothing comes into direct contact with the heat source, such as the human body, hot surfaces, or hot liquids. The conduction process can also occur between two contact fabrics, for instance, the thermal liner and moisture barrier in firefighter protective clothing. Temperature differences between the two interfaces are the driving force of conduction (e.g., body with fabric, fabric with fabric). Conductive heat exchange in clothing depends on the thermal conductivity and thickness of fabrics (Rossi et al., 2004).

Convection is the transfer of energy between a surface and the bulk motion of a fluid (gas or liquid) over it (Lienhard & Lienhard, 2000). Convection can be either forced, which is caused by an external source (e.g., wind) or natural, which is caused by temperature differences. In protective clothing, convective heat exchange is caused by the air movement around the fabrics. In the kitchen environment, the presence of ventilation devices, such as fans, would accelerate the rate of convective heat exchange between the human body with the microenvironment and the environment. Good ventilation of clothing increases convective heat transfer through ventilating the microenvironment with ambient air. It is important for the thermal comfort of the wearer.

Radiation is the energy emitted by matter in the form of electromagnetic waves as a result of the changes in the electronic configurations or the atoms or molecules (Lienhard & Lienhard, 2000). The kitchen environment is characterized by high levels of radiant heat due to the presence of flames and hot surfaces. Radiation does not need an intervening medium to transfer energy. Smooth and flat fabric surfaces can be good barriers to reflect radiant heat. For example, metallic surfaces were typically used to reflect radiant heat in thermal protective clothing (Holmér, 1995).

Evaporation is the process by which energy transforms liquid to gas. Evaporative heat exchange occurs by the transfer of latent heat of evaporated sweat from the skin to the environment (Holmér, 1995). Even at rest, a human loses approximately 500-850 mL of fluid through the skin daily, so called insensible sweating. In the kitchen environment, the human body consistently generates sweat and the water vapour pressure in the microenvironment reaches the saturation pressure (i.e., 100% RH) where condensation occurs within the clothing layers. In this process, as moisture collects in inner layers of clothing, wetting of fabrics gradually undermines clothing insulation and increasing heat conduction, meanwhile causing discomfort to the wearer.

Regarding hot liquid protection, if a fabric is permeable or semi-permeable, with the penetration of hot liquids, both heat and mass transfer could occur (Ackerman & Song, 2011; Lu, Song, Ackerman, et al., 2012; Lu, Song, Li, & Paskaluk, 2013). Liquids may potentially be repelled, absorbed, penetrated, and vapourized due to the elevated temperature of the liquids during this process. Therefore, the modes of heat transfer under this circumstance could include conduction through the fabrics, penetrating hot liquids and condensation of transferred vapour (Lu, Song, Ackerman, et al., 2012). When it comes to impermeable fabrics, heat conduction through dry fabric has been found to be the dominant mode of transfer due to no penetration of liquids occurring (Ackerman & Song, 2011; Jalbani, Ackerman, Crown, Keulen, & Song, 2012; Lu, Song, Ackerman, et al., 2012).

From the discussion above, mass transfer of penetrating liquids contributes to the majority of heat transfer in steam resistance tests. If it is possible to block mass transfer in a chefs' uniform, thermal protection of fabrics against hot liquid splashes could be significantly improved. However, considering the necessary thermal comfort of the wearers, impermeable fabrics are unrealistic for use in the kitchen environment. More effort needs to be put to improve the thermal protection towards hot liquids of chefs' uniforms without compromising the thermal comfort. Lu et al. (2013) compared the protective performance of a series of fabrics (permeable, semipermeable and impermeable fabrics) with and without a spacer when conducting the hot liquids test. They concluded that among impermeable or semi-permeable fabrics, with the presence of a six-mm spacer, thermal protection towards hot liquids was significantly improved. This was attributed to the change of heat transfer modes: the heat transfer from the back of fabrics to the sensor was mainly radiation and conduction through air (Lu et al., 2013).

Heat transfer properties of fabric layers have been shown to be influenced by moisture in the fabric system (Keiser, Becker, & Rossi, 2008; Lawson, Crown, Ackerman, & Dale, 2004; Song & Barker, 2004). Lawson et al., (2004) investigated the effect of moisture on heat transfer by exposing multiple-layer fabric systems for firefighters to both low and high radiant heat flux (i.e., 10 kW/m^2 and 83 kW/m^2, respectively). At low heat flux, moisture located in the internal layer potentially decreased heat transfer through the fabric system, but the influence of moisture located in the external layer was inconclusive. At high heat flux, moisture located in the external layer decreased heat transfer while moisture located in the internal layer increased heat transfer. With the presence of water, the fabric has increased both thermal conductivity and heat capacity. Therefore, heat and mass transfer through fabrics are normally treated as coupled heat and moisture transfer due to its complexity. Both thermal resistance and water-vapour resistance of fabrics critically influence heat exchange (Holmér, 2006). The impact of protective clothing on heat stress depends on the extent of clothing's influence on the heat and moisture transfer between the human body and the environment. Thermal resistance (R_{ct}) and water-vapour resistance (R_{et}) are used to quantify the heat transfer in order to determine the fabric performance related to thermal comfort (International Organization for Standardization, 2012).

2.4 Factors determining thermal protection and comfort of fabrics

Thermal protection and thermal comfort afforded by fabrics are determined by: 1) fabric physical properties (i.e., fibre type, fabric construction, fabric weight and thickness, fabric density, thermal conductivity, fabric surface properties); and 2) fabric system components (i.e., number of layers, lamination or coating) (Celcar, Meinander, & Gersak, 2008; Crown, Ackerman, Dale, & Tan, 1998; Gu, 2009; Holmér, 1995; Lee & Barker, 1987; Torvi & Dale, 1998).

2.4.1 *Fabric system construction*

Due to differences in fabric construction (i.e., knitted, woven, non-woven), fabric density, porosity, air volume fractions, and thickness may also vary correspondingly. Lee and Barker (1987) found that with comparable weight, needle felt and knit fabrics presented better thermal insulation than woven fabrics, in spite of increased transfer of radiant and convective heat energy. This was because the knitted fabrics and needle felt had larger air volume, which led to better thermal insulation. When exposed to flame-dominated heat sources, the amount of entrapped air dominated the heat transfer since the thermal conductivity of air is about one-sixth that of fibres (Lee & Barker, 1987). However, Sun et al. (2000) concluded that plain-woven fabrics provided better protection than knitted ones at the same thickness but they did not provide an adequate interpretation of this finding. This could possibly be due to the higher porosity of knitted fabrics resulting in more energy transfer through radiation (Lee

& Barker, 1987). In a study investigating the radiant heat protection of a variety of fabrics, cotton materials performed better than synthetics (e.g., polyester and nylon, fire-resistant modacrylic). This is possibly because of 1) the natural hollow structure of cotton; and 2) the thermal decomposition of synthetic fibres when exposed to radiant heat (Sun, Yoo, Zhang, & Pan, 2000).

Generally, fabrics system constructed with multiple-layers can provide better protection than a single layer (Barker, Stamper, & Shalev, 1988; Rossi, 2005). In one study carried out to investigate the thermal performance of single layer and multiple-layer fabric systems (Baitinger & Konopasek, 1986), the difference between the two fabric systems was not only attributed to the increase of thickness of the multiple-layered system but also the air layer in between the two layers. This additional air layer was of great significance regarding the increased thermal performance of multiple-layer fabric systems. The heat transfer rate has been shown significantly influenced by the spaces in between textile layers (Crown et al., 1998). Furthermore, to be involving impermeable and semi-permeable layers in the fabric system, thermal protection against steam and hot water can be highly improved (Ackerman et al., 2012; Jalbani et al., 2012). Fabrics used in chefs' uniforms may be composed of multiple layers when they are worn (e.g., apron over chefs' jackets, double-breasted design). Therefore, the construction of the fabric system used in chefs' uniform will influence the thermal protection and thermal comfort within the commercial kitchen environment.

2.4.2 *Fabric thickness/density/weight*

Generally, as the thickness and mass of fabric increases, the effectiveness of a thermal barrier improves (Jalbani et al., 2012; Lee & Barker, 1987; Rossi et al., 2004; Sun et al., 2000; Torvi & Dale, 1998). Lee and Barker (1987) reported that when exposed to high intensity of radiative heat flux (84 kW/m^2), thermal protection was positively correlated to fabric thickness, but this was not a linear relationship. However, Torvi and Dale (1998) concluded that among the thickness range of 0.3 mm and 2.0 mm, the time to second-degree burn against radiant heat was linearly correlated with the fabric thickness. With the increase of fabric thickness the temperature of a fabric tended to increase in a slower manner, which resulted in the decreased rate of heat transfer within the fabric. As a result, radiant protection was found to have a positive correlation with fabric thickness (Torvi & Dale, 1998).

The data from Lee and Barker (1987) showed that in the fabric weight range from 135 to 305 g/m^2, with decreasing density, thermal protection increased. Comparing fabrics with similar weight, the one with higher density indicated a higher fraction of fibres, thus leading to more conductive heat transfer. Fabrics with lower density tended to allow penetration of convective and radiant energy transfer through the fabrics.

In Jalbani et al.'s study (2012), it was concluded that among semi-permeable fabrics, the fabric with higher density provided better protective performance towards streams of hot water. In addition, Lu et al. (2013) indicated that there was no significant correlation between thickness and second-degree burn time under exposure to hot liquids (i.e., water, canola oil and drilling mud) (Lu et al., 2013).

2.4.3 *Air permeability*

A review of several studies has identified that air permeability has a negative effect on thermal protection in both convective and radiant exposures (Gibson, 1993; Havlova, 2013; Lee & Barker, 1987). With higher air permeability, air would more easily penetrate the fabric, leading to higher convective heat transfer. Air permeability is highly related to fabric porosity, thickness, and construction of fabrics. Gholamreza and Song (2013) concluded that air permeability is a dominant factor influencing the thermal protective performance of fabrics when exposed to hot liquids. This is because air permeability is highly related to water permeability of a fabric system, which is critical to the mass transfer and hence the thermal protective performance of hot liquid exposure. With the increasing of the air permeability, the resistance to liquid penetration decreased (Lu, Song, Ackerman, et al., 2012; Lu, Song, & Li, 2012).

2.4.4 *Water vapour permeability*

In general, the higher the water vapour resistance, the higher the level of thermal protection fabrics can provide against hot water and steam (Ackerman & Song, 2011; Jalbani et al., 2012; Lu, Song, Ackerman, et al., 2012; Rossi et al., 2004). Rossi (2004) and Murtaza (2012) concluded that to provide a certain level of steam or hot water protection, a fabric system should have at least a semi-permeable or impermeable layer. However, for semi-permeable fabrics, partial steam still went through the fabrics and then transferred heat directly to the sensor; for impermeable fabrics, only dry heat transfer occurred. Jalbani et al. (2012) concluded that among semi-permeable fabrics, the orientation of the membranes (e.g., polytetrafluoroethylene (PTFE) or PU facing towards the water stream or facing away) is critical regarding hot water protection. In steam protective garments, water vapour permeability is important as mass transfer of penetrated liquids leads to the majority of heat exchange.

The fabrics used in chefs' uniforms are usually water permeable. However, with the wearing of PU coated nylon apron, the certain parts of the fabric system (e.g., the front torso) can be impermeable. Most areas of chefs' uniforms are designed as single layers except for the torso (i.e., in a double-breasted design). Jalbani et al. (2012) concluded that one layer of permeable fabrics provide very limited protection against the hazard of hot water. The double-breasted design of chefs' uniform and the presence of a PU coated apron contribute to a multiple-layer and impermeable fabric system, which will potentially decrease the heat transfer through the whole fabric system. However, the thermal protective performance of this fabric system and similar ones (e.g., chefs' uniform with semi-permeable fabrics) towards hot water needs to be further evaluated.

2.4.5 *Surface properties*

According to Olderman's theory, as illustrated in Equation 2, the liquid penetration resistance is proportional to the contact angle, liquid viscosity, surface tension and material thickness (Olderman, 1984). Super hydrophobic surfaces (i.e., lotus leaves, silica-fluoropolymer artificial lotus surfaces, fluoropolymers coated surfaces, rough and flat Teflon coating surfaces and sol-gel nanocomposite coatings) have been found to show remarkably decreasing repellency to hot water (50-80°C) compared to cool water (25°C) (Liu, Chen, & Xin, 2009). This may be attributed to a change in the wetting state of hot water on super hydrophobic surfaces, as illustrated in Figure 2.1. When given a small slope angle (5-15°), the cool water droplet rolls off easily from the surface (Figure 2.1c). However, as the surface tension of water reduces with an increase of water temperature, at the same angle, the hot water droplet is unable to roll off but instead sticks to the surface (Figure 2.1d). The lower surface tension of hot water makes it easier to

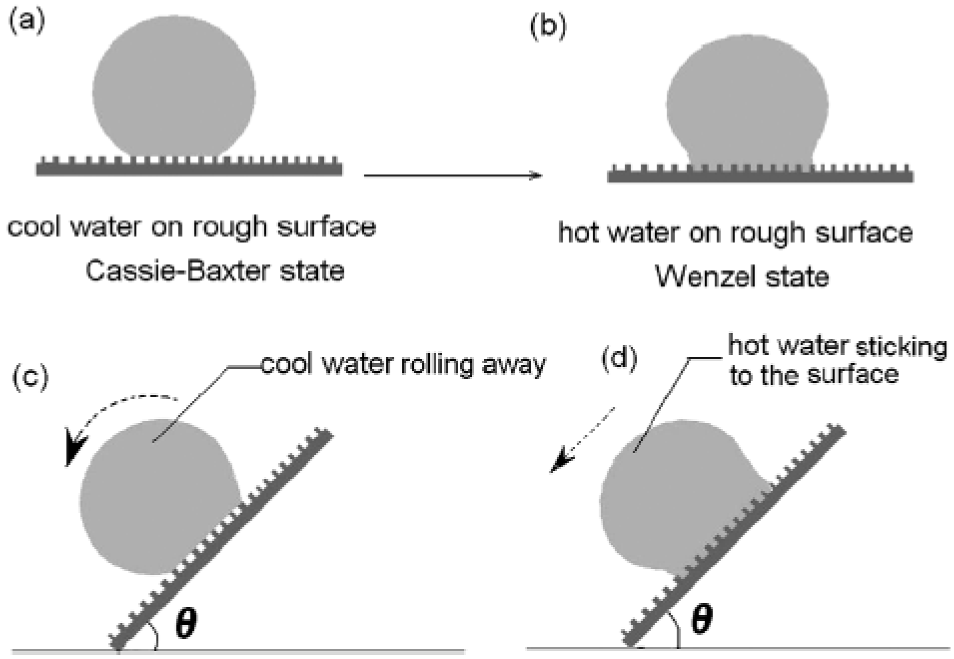


Figure 2.1 Wetting state of cool water and hot water on rough Teflon surfaces (Liu et al., 2009)

wet the surfaces and get into the pores and fissures of rough surfaces, such as water repellent fabrics, which were mostly coated with PTFE or PU. Surface energy is the dominant factor contributing to the wettability and subsequent repellency of a surface to liquids. Water repellent fabrics may further to be subjected to degradation of protection levels after contact with hot water, possibly due to the destruction of the surface structure (Liu et al., 2009).

$$Penetration\ resistance = \frac{liquid\ surface\ tension, viscosity, contact\ angle, material\ thickness}{pressure\ , duration, material\ pore\ radius} \text{…………..…..(2)}$$

Liu et al. (2009) also compared hot water repellency of DuPont Teflon PTFE 30N treated fabrics and Teflon-Carbon Nanotubes (CNT) treated fabrics against hot liquids (i.e., water, milk, coffee, and tea) at a temperature range of 50-80°C. Two kinds of fabrics were used in this experiment, 100% cotton and 80%/20% cotton/polyester blends. Teflon PTFE 30N treated fabrics failed the spray test when the temperature of water was above 50°C. The hot water droplet could not slide away from the textile surface. However, Teflon-CNT treated fabrics showed improved repellency to hot water and hot beverages (Liu et al., 2009). This was due to the superior waterproof performance of CNTs, i.e., difficulty to be wet, even towards boiling water (Werder, Walther, & Koumoutsakos, 2002). As a result, it may also be promising to produce Teflon-CNT treated fabrics for protective clothing against scalding injuries for chefs and even workers in oil and gas industries who are at risk of hot water and steam burns.

In order to investigate the thermal performance of fabrics towards hot liquid splashes, Lu et al. (2012) measured the liquid contact angles (i.e., water, canola oil, drilling mud) at room temperature, instead of at an elevated temperature. This may lead to one of the inaccuracies of the study when discussing the liquid contact angle, the impact penetration, and time to second-degree burn. The reasons are that: 1) contact angles of hot liquids may vary from that of liquids at room temperature (Liu et al., 2009); and 2) hot liquids contact fabric surfaces, hot liquids show different flow patterns along the fabric surface compared to cold liquid flow patterns (Lu, Song, Ackerman, et al., 2012). This was determined by fabric surface properties, liquid temperature and liquid properties.

2.5 Thermal protective clothing against thermal hazards

Thermal protective clothing for protection against heat and flames has been studied for decades, mainly concentrating on firefighting or oil and gas industries (Crown et al., 1998; Keiser, 2007; Rossi & Bolli, 2005; Torvi & Hadjisophocleus, 1999). Technically speaking, chefs' uniforms are not thermal protective clothing in the same way that we usually consider firefighter garments and hot liquids/steam protective clothing as thermal protective clothing. Workers in the oil and gas industry are potentially exposed to the following hazards: "impact from machinery parts or falling objects, exposure to toxic or injurious gases or chemicals, exposure to conductive and radiant heat transfer from machinery or pipes in processing, and exposure to thermal stress from climatic environments". Steam can be presented at very high pressures (up to 800 kPa) and of high temperature (over 100 °C) due to impurities (Crown & Dale, 2005). Protective clothing in the oil and gas industry was imperative to minimize the extent and severity of injury, or even loss of life when exposed to the above hazards. The environment encountered in the kitchen is not as extreme as the conditions where firefighters and workers in oil and gas industry are exposed. This is possibly one of the reasons that not much attention has been drawn to the development of protective chefs' uniforms and there is limited scientific literature associated with thermal protective performance of chefs' uniforms.

Nevertheless, the thermal hazards encountered in the kitchen are similar in some part to the oil and gas industry. Materials, including Kevlar®, Nomex® and FR cotton, are commonly used in the oil and gas industry because of the harsh environments. Compared with these high performance fabrics, the protection level of FR cotton or cotton/polyester blend fabrics afforded is inferior. Evidence exists that even the protective clothing in oil and gas injuries has not been able to provide satisfactory protection for workers against steam and hot water (Ackerman & Song, 2011; Lu, Song, Ackerman, et al., 2012). This highlights the need to investigate the thermal performance of fabrics used in chefs' uniforms and thus the urgency to improve the thermal performance as well.

CHAPTER 3. METHODS

3.1 Experimental design and variables

In this research the independent variables were uniform fabric, apron type and number of fabric layers. The dependent variables were the various fabric properties related to thermal comfort: air permeability, thermal resistance and water vapour resistance; and properties related to thermal protective performance tests (i.e., hot surface contact, steam and hot liquid) such as time to predicted second degree burn and absorbed energy.

Up to three experimental designs were carried out to determine the effect of fabric type, the effect of apron and the effect of number of layers on selected thermal protective performance properties. A one-way experimental design was adopted with the independent variable being the fabric type (i.e., F1, F2, F3, F5, F9, F10, F14) for thermal comfort properties of air permeability, thermal resistance and water vapour diffusion resistance, as well as thermal protective performance properties of time to second-degree burn and absorbed energy. A two-way factorial design to determine the effect of single layers of fabric with aprons (i.e., five fabrics: F1, F2, F3, F5, F9; and three aprons: none; F10, F14) was carried out on air permeability and time to second-degree burn and absorbed energy. Finally a three-way factorial design was carried out to determine the effect of fabric, apron and number of layers (i.e., two fabrics: F2, F3; three aprons: none, F10, F14; and three layers: single, 2L, 4L) on time to second degree burn and absorbed energy.

3.2 Materials

Fabrics, which differed in fibre content and weight, were selected for this research (Table 3.1). The selected fabric types represented the more popular types of chefs' uniforms on the North American market according to personal communication with several manufacturers. The fabrics were sourced from The Happy Chef, Inc. (Butler, NJ, USA), Unisync group limited (Mississauga, ON, Canada), and Mark's Work Warehouse (Welland, ON, Canada).

3.3 Preparation of fabrics

All fabrics used in the chefs' uniforms (F1, F2, F3, F5, and F9) and the apron F10 were pre-laundered to remove any residual oils and water soluble finishing chemicals according to CAN/CGSB-4.2 No.58-2004 (Canadian General Standards Board, 2004b). The washing and drying process parameters included: moderate mechanical action, water temperature at 50 °C, synthetic detergent (Tide®), and tumble dry. The garments and aprons were laundered five times prior to all tests. Apron F14 was not prewashed because of the laminated structure, which showed evidence of being degraded by the laundering process.

Fabric samples were cut from the garments and aprons. No fabric specimens contained the same warp or weft yarns. Fabrics samples were conditioned a minimum of 24 hours in standard atmosphere conditions at a temperature of 20 ± 2 °C and a relative humidity of 65 ± 2%, according to CAN/CGSB-4.2 No.2-M88 (Canadian General Standards Board, 2001).

Table 3.1 Fabric description and physical properties

Fabric code	Fabric content	Fabric counts (yarns/cm)		Mass/unit area (g/m^2)	Thickness (mm)	Density (g/cm^3)	Garment type	Source
		Warp	Weft					
F1	100% FR cotton twill	39	20	266	0.73	0.363	Fabric roll	Cedro®
F2	65% polyester/ 35% cotton plain	37	20	193	0.53	0.366	Chefs' jacket	York® from Unisync
F3	65% polyester/ 35% cotton twill	50	24	261	0.63	0.411	Chefs' jacket	York® from Unisync
F5	100% cotton twill	61	44	167	0.49	0.343	Chefs' jacket	Happy Chef®
F9	100% cotton twill	42	22	311	0.79	0.394	Chefs' jacket	Happy Chef®
F10	65% polyester/ 35% cotton twill	44	22	258	0.74	0.350	Apron	Mark's®
F14	PU coated nylon plain	17	17	106	0.18	0.606	Apron	Happy Chef®

3.4 Procedures

3.4.1 *Physical properties of fabrics*

Fabric weight (unit mass) for all fabrics was measured in accordance with CAN/CGSB-4.2-M90 (Canadian General Standards Board, 2004a). Fabric thickness was measured in accordance with CAN/CGSB-4.2 No.37-2002 (Canadian General Standards Board, 2002b). Number of threads per unit area was determined in accordance with CAN/CGSB-4.2 No.6-M89/ISO 7211/2:1984 (Canadian General Standards Board, 1989). Density of fabrics was calculated using the data obtained from thickness and mass. Fabric physical properties are shown in Table 3.1.

3.4.2 *Performance properties of fabrics*

3.4.2.1 *Air permeability*

Air permeability of fabrics was measured in accordance with CAN/CGSB-4.2 No.36-2002 (Canadian General Standards Board, 2002a). The testing device used in this experiment was a Frazier high-pressure air permeability apparatus. The air pressure differential was adjusted to 12.7 mm of water gauge pressure (125 Pa). Ten specimens of each sample were tested. In addition, the air permeability of the multiple-layered fabric systems (i.e., fabrics covered by an apron fabric; multiple layers of F2 and F3 fabrics) were measured.

3.4.2.2 *Thermal resistance R_{ct}*

The thermal resistance R_{ct} of each fabric was determined in accordance with ISO 11092:1993/Amd.1:2012(E), using a sweating guarded-hotplate apparatus (Measurement Technology Northwest) (Figure 3.1). The temperature of the measuring unit (T_m) was 35 °C and the air temperature (T_a) was set at 20 °C 65% RH. Air speed (v_a) was set at 1 m/s. Three specimens were tested. The thermal resistance of fabric system (i.e., single layers with and without aprons, 2L, 3L and 4L of all fabrics used in chefs' jackets) was tested.

3.4.2.3 *Water-vapour resistance R_{et}*

The water-vapour resistance R_{et} of each fabric was determined in accordance with ISO 11092:1993/Amd.1:2012(E), using the sweating guarded-hotplate apparatus (Measurement Technology Northwest). Both the temperature of the measuring unit (T_m) and the air temperature (T_a) were set at 35°C, at 40% RH. Air speed (v_a) was held at 1 m/s. Three specimens were tested. Only single layer fabrics were tested.

3.4.2.4 *Ease of ignition*

Ease of ignition was conducted in accordance with CAN/CGSB-4.2 No.27.4-2010/ISO 6940:2004 (Canadian General Standards Board, 2010). Twelve test specimens were prepared with dimensions of 200±2 mm × 80±2 mm and in the direction of warp. Surface ignition procedure was used for testing single layer fabrics. The specimens procedure were tested with the length direction placed vertically and the outer surface of the fabrics towards the ignition flame. Bottom edge ignition was used in testing single layer fabrics and the swatches of simulated chefs' uniform cuffs.

Figure 3.1 Sweating guarded hot plate

The test flame was applied to approximate the shortest time to cause ignition. The flame application time was recorded and the occurrence of ignition was observed. A fresh specimen was mounted in the same orientation in the specimen holder. If ignition occurred with the previous specimen, then test flame was applied for one second less to the next specimen; if ignition did not occur with the previous specimen, the test flame was applied for one second more to the next specimen. The test was continued until there were at least five instances of ignition and five instances of non-ignition. The recorded times for ignition or non-ignition, which ever was less frequent, were used to calculate the mean ignition time.

3.4.2.5 *Hot surface contact test*

Hot surface contact of fabrics was conducted in accordance to ASTM F1060-08 (American Society for Testing and Materials, 2008a). This method was originally used to measure the thermal insulation properties of protective clothing when exposed for a short period to a hot surface at a temperature of 316°C. Considering the real scenario of the kitchen environment and the melting point of polyester fibres, the hot plate was set at a lower temperature of 200 ± 3°C. Five specimens, in the size 100± 2 mm × 150± 2 mm, were prepared for this test (American Society for Testing and Materials, 2008a). The specimen was placed in between the heated surface plate and the sensor, with copper sensor on top. Multiple layers of specimens were placed in an order as they would be worn, with the surface worn next to the skin facing up. The test was continued until the sensor response exceeds the values of the copper calorimeter equivalent temperature rise for second-degree burn (temperature rise of 20 to 25°C). Any physical damage produced by hot surface exposure was observed during the tests. Temperature over time data was recorded by the data acquisition system and burn injury prediction about second-degree burn was made according to Stoll curve criteria.

3.4.2.6 *Steam test*

In order to investigate the performance properties of fabrics used in chefs' uniform towards hot steam, the test apparatus developed by Ackerman et al. (2012) was applied in the research. The apparatus was constructed with hot steam jet assembly, sensor, and support (Figure 3.2a). A computer data acquisition system was attached to the sensor, recording the temperature as a function of time. A skin simulant sensor (heat flux transducer) was mounted in a perforated PTFE support (Figure 3.2c), which allows transfer of vapour. This steam test apparatus and test procedures were initially developed to simulate of the pressurized hot steam found in the oil and gas industry. The pressure could be set as high as 90 Psi. Considering the real kitchen condition with very low pressure of steam and the pressure of steam cooker, steam pressure and temperature were set at 10 Psi and 108±3°C respectively.

Five specimens of each fabric types or combinations were tested. Specimens were cut to size of 200±2mm × 200±2 mm. The conditioned specimens were placed on the skin simulant sensor and below the hot steam jet assembly (Figure 3.2b). The face of the fabric was placed 62 mm from the steam jet outlet. A sample restraint was placed on top of the fabric to avoid displacement. As for multiple layer samples, each specimen was placed in an order that it would be worn, with the surface of the material to be used as the outside of the garment facing up. Temperature and pressure of steam could be controlled and monitored consistently.

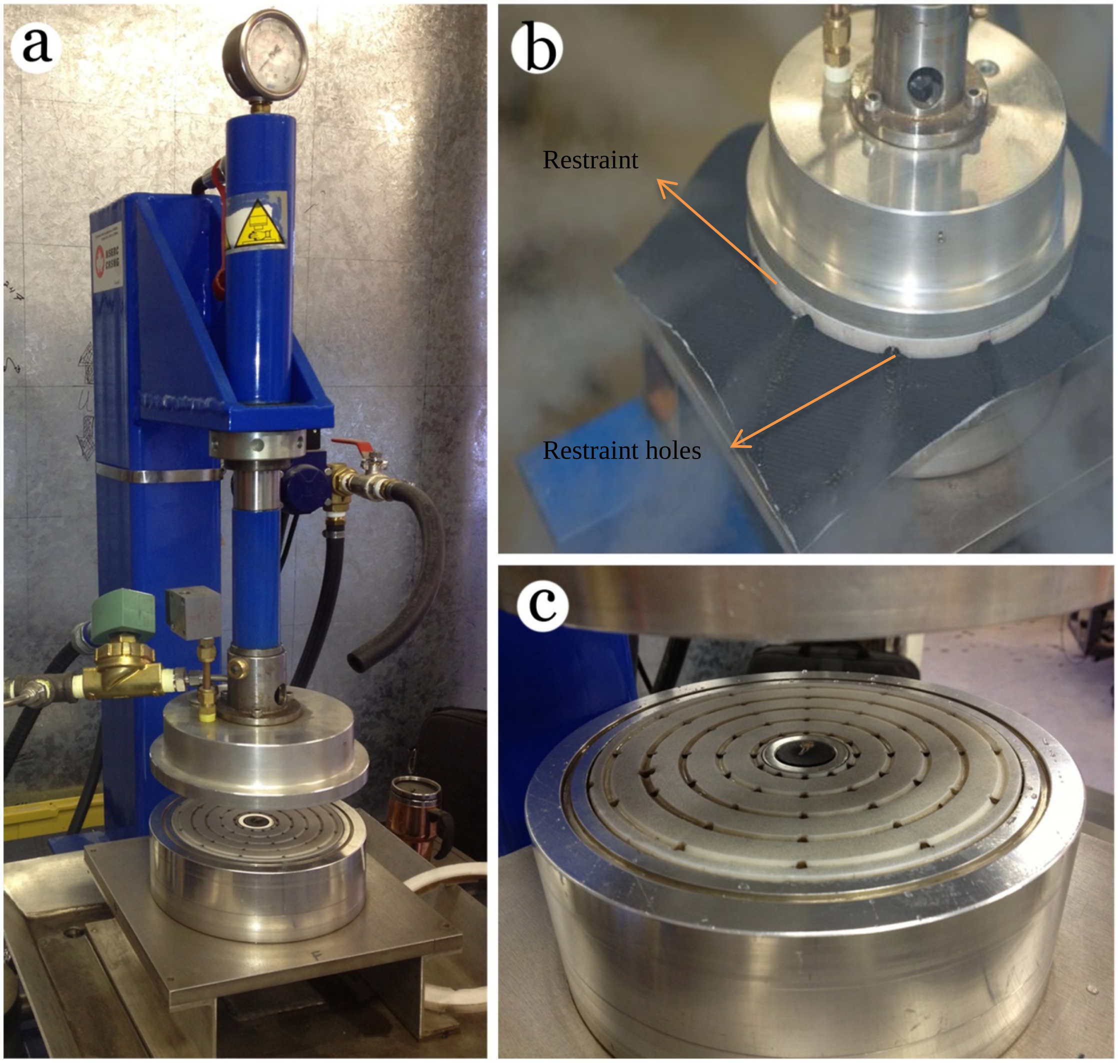


Figure 2.2 a) Steam resistance test apparatus; b) steam exposure during test; c) sensor and support

The data collection period lasted 60 seconds, including ten seconds exposure time and 50 seconds after exposure. Heat flux sensor data was recorded during this period. Total absorbed energy was calculated from the heat flux data. The time to second or third-degree burn was estimated by using heat flux history in a multi-layer skin model. Physical damage of the fabrics were observed and recorded. If there was no predicted thermal injury during data recording period, the result was recorded as ≥ 60s (Ackerman et al., 2012).

3.4.2.7 *Hot liquid test*

A modified apparatus in accordance with ASTM F 2701-08 was used to measure the heat energy transmission through fabrics that are exposed to a hot liquid splash, as shown in Figure 3.3 (American Society for Testing and Materials, 2008b). The test apparatus consists of a water jet, an inclined specimen mount, temperature controlled heating and pumping container, exposure board with skin simulant sensors, which is connected to a data acquisition system (Figure 3.3). The angle of the exposure board was at 45°. Temperature, flow rate and exposure time of hot liquids were able to be controlled and monitored consistently.

Three specimens (254 mm× 406 mm) were prepared for this test. The conditioned specimen was placed on the skin simulant sensor and below the funnel, centered horizontally over the calorimeters with the top of the specimen extending about 50 mm. As for multiple layer samples, each specimen was placed in an order that they would be worn, with the surface of the material to be used as the outside of the garment facing out and exposed to the hot liquids.

Distilled water and canola oil were used for the hot liquid test. The water jet and oil jet temperature were both set at 85 °C. Flow rate was set at 100 mL/s.

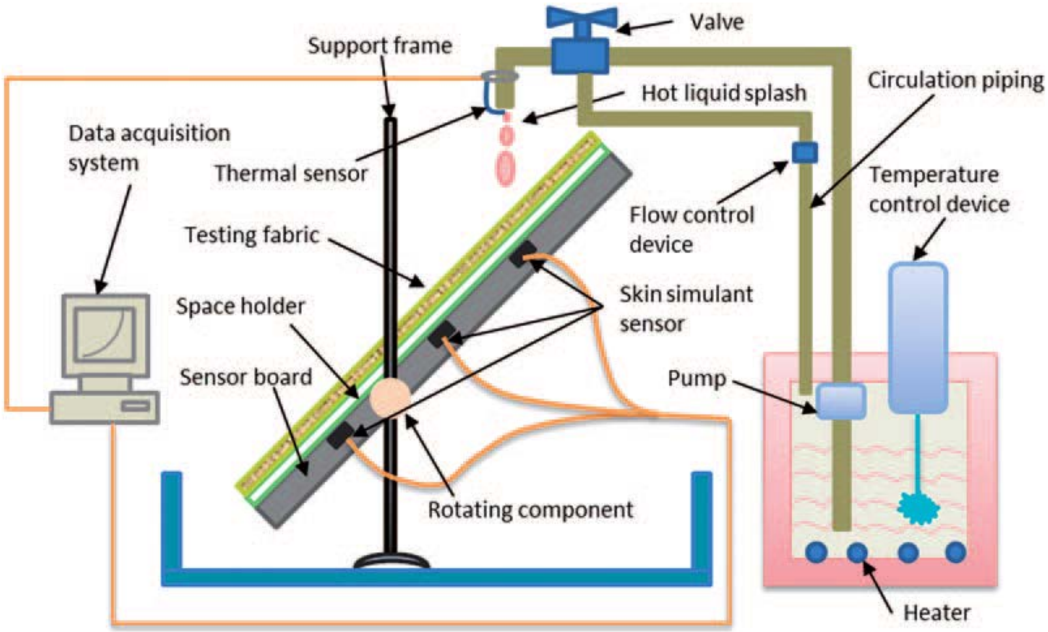


Figure 3.3 Schematic of hot liquid splashes test apparatus (Lu, Song, Ackerman, et al., 2012)

Table 3.2 Physical properties of exposure liquids at 85°C

Liquids	Density (g/cm^3)	Specific heat capacity (kJ/(kg·K))	Thermal conductivity (W/(m·K))	Surface tension ($\times 10^{-2}$ N/m)	Dynamic viscosity (Pa·s)
Water	0.96	4.19	0.67	6.17	0.00034
Canola oil	0.87	2.35	0.23	2.7	0.075

Exposure time was set at 10s and the data recording period extended 50 seconds after exposure. The sensors were cooled to approximately 30 °C after exposure to hot liquids. The characteristics of hot liquids, water and canola oil, are displayed in Table 3.2. Temperatures of each sensor (i.e., upper, middle, and lower sensor) were recorded, but only the upper sensor data was reported in this research due to the large amount of data obtained. Heat flux and absorbed energy were calculated. Time (s) to second or third-degree burn against hot liquids (distilled water and canola oil) was estimated. Visual observation regarding physical damage was also recorded.

CHAPTER 4. RESULTS

4.1 Thermal comfort performance of fabrics used in chefs' uniforms

4.1.1 *Air permeability*

The mean values (±SEM) of air permeability for single-layered fabrics are displayed in Figure 4.1. The one-way ANOVA for the effect of fabric type on air permeability is shown in Table 4.1. The PU coated nylon apron F14 had the lowest air permeability (effectively zero) and non-coated polyester/cotton blend apron F10 had the greatest air permeability at 10.31 $cm^3/cm^2/s$ (Table 4.2). It was noted that the air permeability of single-layered fabrics differed to a large extent from each other ($F_{6,63}=657.14$, $p \leq 0.001$) (Table 4.1), with all fabric types being significantly different from each other with the exception of F1 and F2 which did not differ (Table 4.2). It was also observed that 100% cotton lightweight F5 exhibited the lowest air permeability among all the fabrics used to make chefs' jackets (i.e., F2, F3, F5 and F9).

The comparison of air permeability among single-layered fabrics covered by aprons is presented in Figure 4.2. The effect of fabric and apron on air permeability is depicted in Table 4.3. Both fabric type and apron affected air permeability ($F_{4,135}=425.28$, $p \leq 0.001$ and $F_{2,135}=5306.67$, $p \leq 0.001$, respectively) (Table 4.3). Overall, the fabrics without aprons had the highest air permeability (M=5.66 $cm^3/cm^2/s$) and all fabrics covered by F14 had the lowest air permeability (M=0.00 $cm^3/cm^2/s$) (Table 4.4). A significant interaction effect between the types of fabric and apron was also observed for air permeability ($F_{8,135}=129.37$, $p \leq 0.001$).

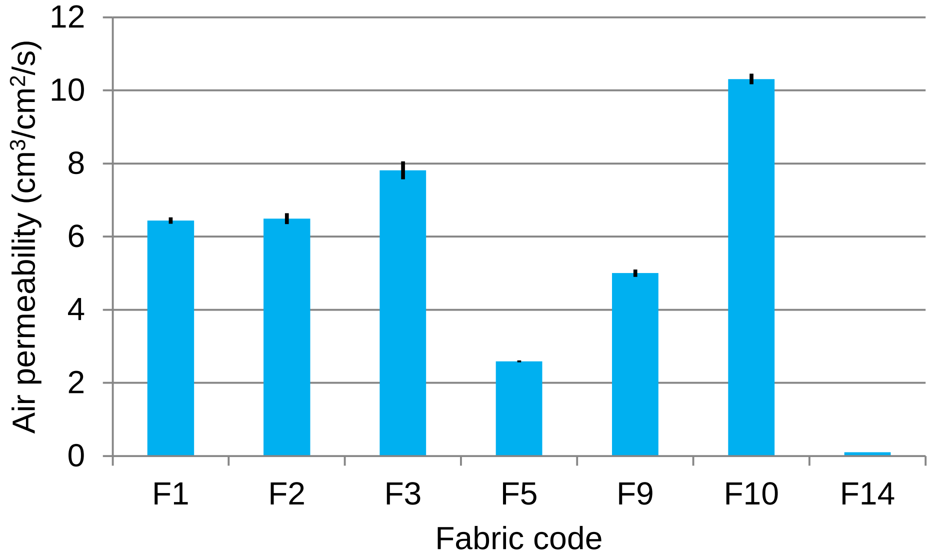


Figure 4.1 Means (±SEM) of air permeability of single-layered fabrics

Table 4.1 Fabric affecting air permeability - ANOVA

Source	df	SS	MS	F	p≤
Between groups	6	692.81	115.47	657.14	0.001
Within groups	63	11.07	0.18		
Total	69	703.88			

Table 4.2 Differences in air permeability for fabrics - Tukey's range test

Interactions	Mean	n	Tukey's groupings
Fabric			
F14	0.00	10	
F5	2.59	10	
F9	5.00	10	
F1	6.44	10	
F2	6.49	10	
F3	7.81	10	
F10	10.31	10	

Means grouped by lines are not significantly different at $p \leq 0.05$

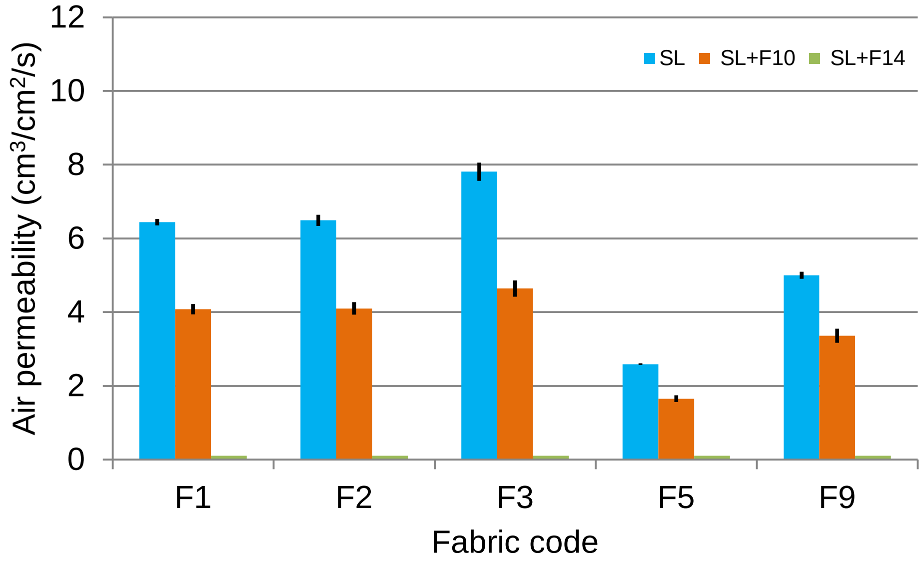


Figure 4.2 Comparison of means (±SEM) of air permeability among single-layered fabrics with and without aprons.

Table 4.3 Significance of fabric and apron on air permeability - ANOVA

Source	df	SS	MS	F	p≤
Fabric	4	131.45	32.86	425.28	0.001
Apron	2	820.10	410.05	5306.67	0.001
Fabric/Apron	8	79.97	10.00	129.37	0.001
Error	135	10.43	0.08		
Total	150	2462.08			

Table 4.4 Differences in air permeability for fabric and apron - Tukey's range test

Interactions	Mean	n	Tukey's groupings
Fabric			
F5	1.42	30	
F9	2.79	30	
F1	3.51	30	
F2	3.53	30	
F3	4.15	30	
Apron			
F14	0.00	50	
F10	3.57	50	
None	5.66	50	
Fabric/Apron			
F1/F14	0.00	10	
F2/F14	0.00	10	
F3/F14	0.00	10	
F5/F14	0.00	10	
F9/F14	0.00	10	
F5/F10	1.65	10	
F5/None	2.59	10	
F9/F10	3.36	10	
F1/F10	4.08	10	
F2/F10	4.10	10	
F3/F10	4.64	10	
F9/None	5.00	10	
F1/None	6.44	10	
F2/None	6.49	10	
F3/None	7.81	10	

Means grouped by lines are not significantly different at $p \leq 0.05$

Figure 4.3 shows the mean values of air permeability for multiple-layered F2 and F3 fabric systems, with and without aprons, and the effect of treatment variables on air permeability is shown in Table 4.5. There was a decreasing trend in air permeability as the number of fabric layers increased (Figure 4.3). The types of apron covering the fabric system had a significant effect on air permeability ($F_{2,162}$=4891.07, $p \leq 0.001$) as all the fabrics covered by apron F14 was effectively zero (regardless of whether they were single or multiple layers) (Table 4.5). The number of layers also had a significant impact on air permeability ($F_{2,162}$= 1875.63, $p \leq 0.001$). Overall, the air permeability of multiple-layer heavyweight F3 fabric systems (M=2.55 $cm^3/cm^2/s$) was higher than that of lighter-weight F2 multi-layer fabric systems (M=2.19 $cm^3/cm^2/s$) (Table 4.6) as with the increase of number of layers, air permeability decreased. There were significant interaction effects among fabric, the number of layers and apron on air permeability (Table 4.5). For instance, there was a significant interaction between apron and number of layers for air permeability of fabric systems ($F_{4,162}$= 617.89, $p \leq 0.001$) (Table 4.5), this strong interaction related to F14 fabric systems all being effectively zero (Table 4.6).

4.1.2 *Thermal resistance*

The mean values (±SEM) of thermal resistance for single-layered fabrics are displayed in Figure 4.4. Thermal resistance ranged from 0.071 m^2K/W for fabrics, F5, F9, and F14 to 0.076 m^2K/W for F10. The one-way ANOVA for the effect of fabric on thermal resistance is presented in Table 4.7. Fabric type did not have a significant effect on thermal resistance ($F_{6,14}$=7.06, NS).

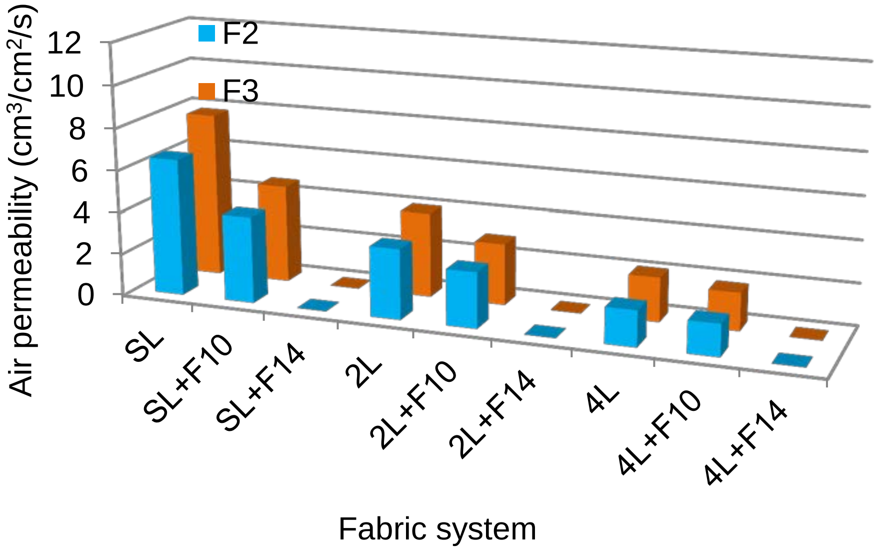


Figure 4.3 Comparison of means of air permeability for multiple-layer fabrics

Table 4.5 Significance of fabric, apron and layers on air permeability - ANOVA

Source	df	SS	MS	F	p≤
Fabric	1	6.83	6.83	118.03	0.001
Apron	2	565.64	282.82	4891.07	0.001
Layers	2	216.91	108.46	1875.63	0.001
Fabric/Apron	2	4.87	2.44	42.12	0.001
Fabric/Layers	2	1.24	0.62	10.68	0.001
Apron/Layers	4	142.92	35.73	617.89	0.001
Fabric/Apron/Layers	4	1.18	0.30	5.11	NS
Error	162	9.37	0.06		
Total	180	1977.17			

Table 4.6 Differences in air permeability for fabric, apron and layers -Tukey's range test

Interactions	Mean	n	Tukey's groupings
Fabric			
F2	2.19	90	
F3	2.55	90	
Apron			
F14	0.00	60	
F10	2.93	60	
None	4.24	60	
Layers			
4L	1.18	60	
2L	2.15	60	
1L	3.84	60	
Fabric/Apron			
F2/4L	1.07	30	
F3/4L	1.30	30	
F2/2L	1.99	30	
F3/2L	2.31	30	
F2/1L	3.53	30	
F3/1L	4.15	30	
Fabric/Layers			
F2/F14	0.00	30	
F3/F14	0.00	30	
F2/F10	2.75	30	
F3/F10	3.12	30	
F2/None	3.84	30	
F2/None	4.64	30	
Apron/Layers			
F14/1L	0.00	20	
F14/2L	0.00	20	
F14/4L	0.00	20	
F10/4L	1.65	20	
None /4L	1.90	20	
F10/2L	2.77	20	
None/2L	3.68	20	
F10/1L	4.37	20	
None/1L	7.15	20	

Means grouped by lines are not significantly different at $p \leq 0.05$

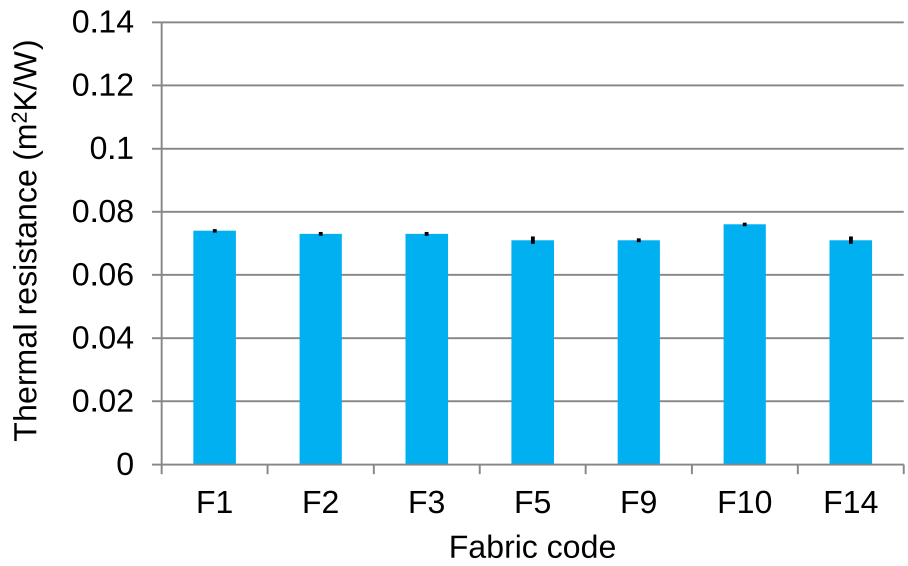


Figure 4.4 Means (±SEM) of thermal resistance of single-layered fabrics

Table 4.7 Fabric affecting thermal resistance - ANOVA

Source	df	SS	MS	F	p≤
Between groups	6	5.2×10^{-5}	0.9×10^{-5}	7.06	NS
Within groups	14	1.7×10^{-5}	0.1×10^{-5}		
Total	20	7.0×10^{-5}			

The comparison of mean values (±SEM) of thermal resistance among single-layered fabrics, with and without aprons is depicted in Figure 4.5. The effect of aprons on thermal resistance was highly significant of the fabric systems ($F_{2,30}$=1208.67, $p \leq 0.001$) (Table 4.8). The Tukey's post hoc test results show that apron type (i.e., F10, F14, None) covered by the F14 system exhibited the highest thermal resistance among all the fabric systems tested (M=0.128 m^2K/W) and the single-layered fabrics ranked the lowest (M=0.071 m^2K/W) (Table 4.9).

In Figure 4.6, thermal resistance of multiple-layered F2 and F3 fabric systems without aprons and single-layered F2 and F3 with aprons are depicted. It is obvious that with the increasing of the number of layers, thermal resistance also increased. For example, the thermal resistance of single-layered F2 increased from 0.073 m^2K/W to 0.107 m^2K/W for four layers of F2 fabrics. In the two-way ANOVA of fabric type by layers, thermal resistance was significantly affected by the number of layers ($F_{3,40}$=1415.36, $p \leq 0.001$) (Table 4.10), with each additional layer resulting in increased thermal resistance (i.e., overall means for 1L=0.072 m^2K/W; 2L=0.081 m^2K/W; 3L=0.091 m^2K/W; 4L=0.101 m^2K/W) (Table 4.11).

4.1.3 *Water vapour resistance*

The mean values (±SEM) of water vapour resistance of single-layered fabrics are shown in Figure 4.7. Water vapour resistance ranged from 10.39 $kPa \cdot m^2/W$ for F10 to 63.24 $kPa \cdot m^2/W$ for F14, which was considerably higher than all of the other fabrics. Therefore, fabric type had a significant influence on the water vapour resistance ($F_{6,14}$=49.00, $p \leq 0.001$) (Table 4.12), as the impermeable apron fabric F14 was significantly different from all other fabrics (Table 4.13).

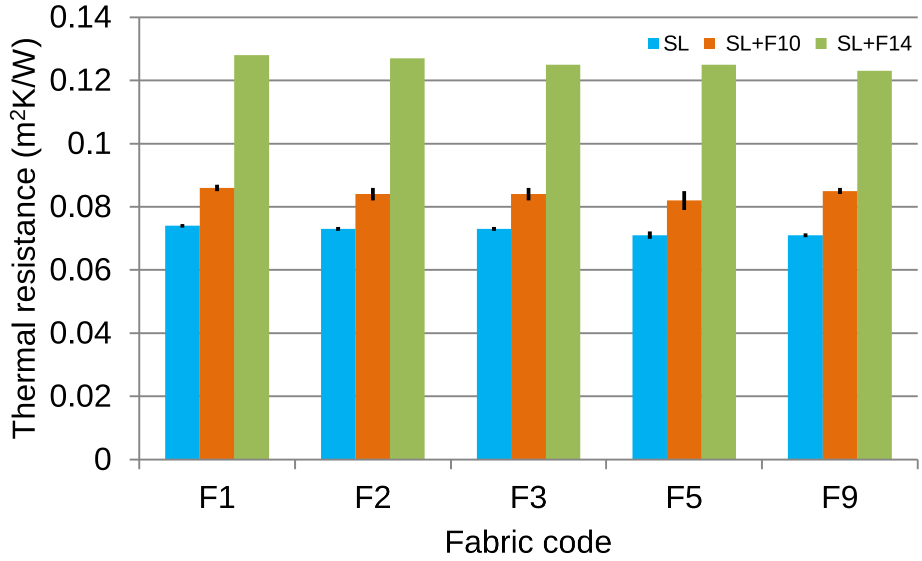


Figure 4.5 Comparison of means (±SEM) of thermal resistance among single-layered fabrics with and without aprons.

Table 4.8 Significance of fabric and apron on thermal resistance - ANOVA

Source	df	SS	MS	F	p≤
Fabric	4	5.5×10^{-5}	1.4×10^{-5}	1.31	NS
Apron	2	2.6×10^{-3}	1.3×10^{-3}	1208.57	0.001
Fabric/Apron	8	2.4×10^{-5}	3.0×10^{-5}	2.87	NS
Error	30	3.2×10^{-5}	1.1×10^{-5}		
Total	45	4.3×10^{-3}			

Table 4.9 Differences in thermal resistance for apron -Tukey's range test

Interactions	Mean	n	Tukey's groupings
Apron			
None	0.072	15	]
F10	0.084	15	]
F14	0.128	15	]

Means grouped by lines are not significantly different at p≤0.05

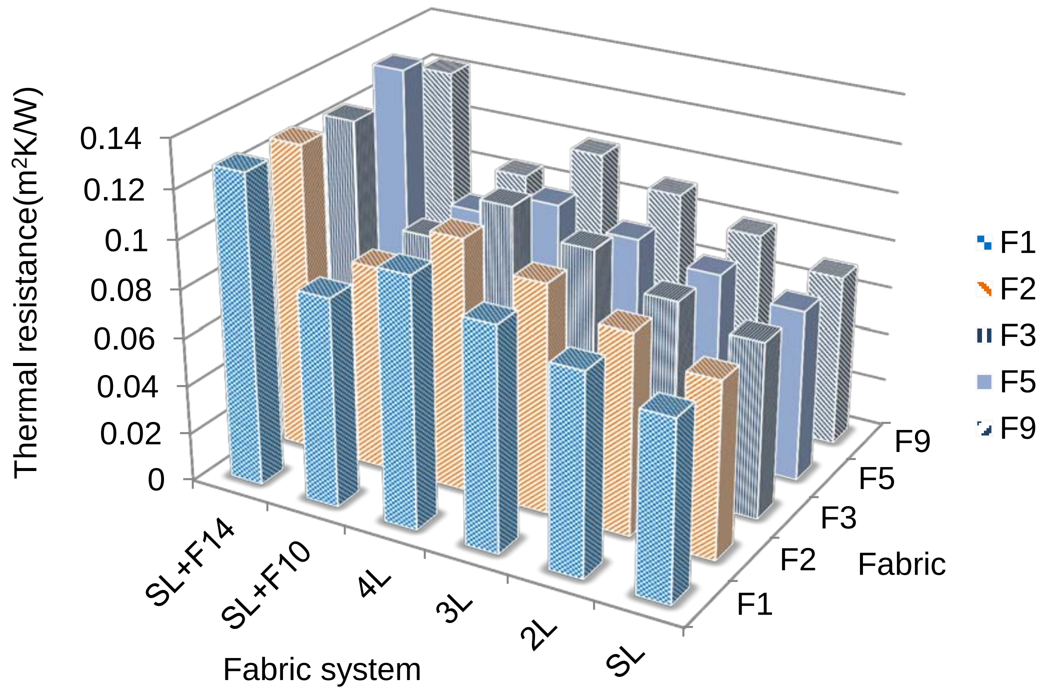


Figure 4.6 Comparison of means of thermal resistance of different fabric systems.

Table 4.10 Significance of fabric and layer on thermal resistance - ANOVA

Source	df	SS	MS	F	p≤
Fabric	4	3.9×10^{-5}	9.9×10^{-5}	60.07	0.001
Layers	3	0.7×10^{-3}	0.2×10^{-3}	1415.36	0.001
Fabric/Layers	12	1.4×10^{-5}	1.2×10^{-5}	7.29	0.001
Error	40	6.6×10^{-5}	1.6×10^{-5}		
Total	60	4.6×10^{-1}			

Table 4.11 Differences in thermal resistance for fabric and layer -Tukey's range test

Interactions	Mean	n	Tukey's groupings
Fabric			
F5	0.817	12	
F9	0.086	12	
F1	0.088	12	
F3	0.088	12	
F2	0.089	12	
Layers			
1L	0.072	15	
2L	0.081	15	
3L	0.091	15	
4L	0.101	15	
Fabric/Layers			
F5/1L	0.071	3	
F9/1L	0.071	3	
F3/1L	0.073	3	
F2/1L	0.073	3	
F1/1L	0.074	3	
F5/2L	0.078	3	
F3/2L	0.081	3	
F9/2L	0.081	3	
F1/2L	0.083	3	
F2/2L	0.083	3	
F5/3L	0.085	3	
F9/3L	0.091	3	
F1/3L	0.092	3	
F5/4L	0.092	3	
F2/3L	0.094	3	
F3/3L	0.094	3	
F9/4L	0.101	3	
F1/4L	0.103	3	
F2/4L	0.104	3	
F3/4L	0.104	3	

Means grouped by lines are not significantly different at $p \leq 0.05$

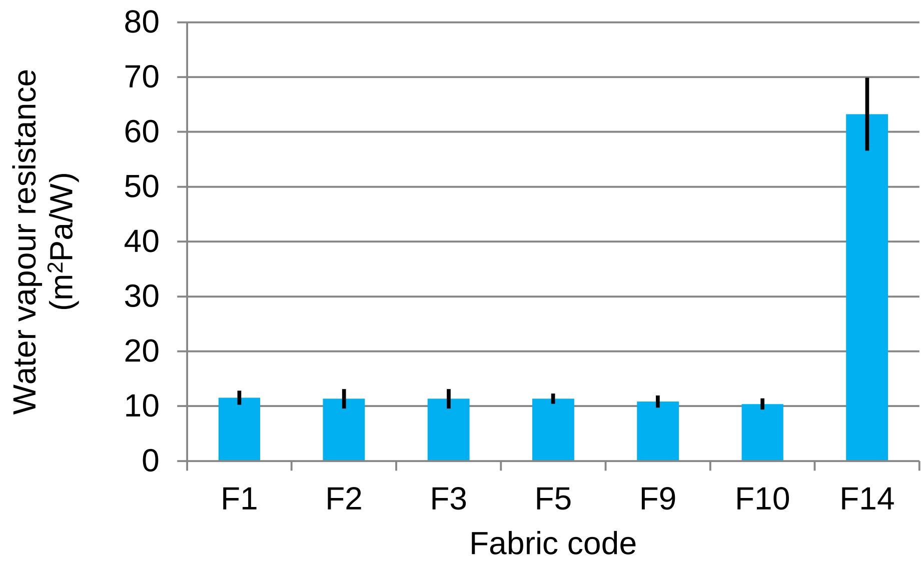


Figure 4.7 Means (±SEM) of water vapour resistances of single-layered fabrics

Table 4.12 Fabric affecting water vapour resistance - ANOVA

Source	df	SS	MS	F	p≤
Between groups	6	6986.17	1164.36	49.00	0.001
Within groups	14	332.65	23.76		
Total	20	7318.82			

Table 4.13 Differences in water vapour resistance for fabrics –Tukey's groupings

Interactions	Mean	n	Tukey's groupings
Fabric			
F10	10.39	3	A
F9	10.83	3	A
F2	11.34	3	A
F3	11.34	3	A
F5	11.34	3	A
F1	11.54	3	A
F14	63.24	3	B

Means grouped by lines are not significantly different at p≤0.05

4.2 Thermal protective performance of fabrics used in chefs' uniform

4.2.1 *Ease of ignition*

All fabrics were subjected to the ease of ignition test in order to evaluate their ability to burn after exposure to a flame. A summary of the time to ignition of the single-layered fabrics towards surface ignition and single-layered fabrics and simulated cuffs against bottom edge ignition are displayed in Table 4.14. With the exception of F1, all fabrics tested sustained combustion, giving an afterflame time of five seconds or more or reaching the top or vertical edges in less than five seconds (Canadian General Standards Board, 2010). Therefore, all fabrics (except F1) were completely burned as a result of this test. Of the four fabrics cut from the chefs' jackets, F2 and F3 (the 65% cotton/35% polyester fabrics) burned more intense compared to F5 and F9 (100% cotton). The onset of ignition for the flame retardant F1 fabric could not be obtained because it quickly self-extinguished. Figure 4.8 demonstrates the burn pattern of F1 against a flame applied to the surface of the fabric. It was evident that the burn length increased by extending the duration of contact.

For the surface ignition, the heavier fabrics F3 and F9 required the longest time to ignite at six seconds, whereas apron F14 fabric was the easiest to ignite with an ignition time of two seconds. The lightweight fabrics F2 and F5 took four and three seconds, respectively to ignite when the flame was applied to the fabric surface (see Table 4.14). Bottom edge ignition was performed on both single layers (all fabrics) and four layers of fabrics sewn together to simulate jacket cuffs (fabrics obtained from chefs' jackets only). There was a decrease in time to ignition in all fabrics when the flame approached from the bottom edge of the fabric compared to the flame approaching from the surface. For instance, it took six seconds for F3 to ignite in the surface ignition procedure, while it required only one second to ignite in the bottom edge.

Table 4.14 Time to surface and bottom edge ignition of fabrics used in chefs' uniform

Fabric Code	Time to surface ignition (s)	Time to bottom edge ignition (s)	
	SL	SL	Simulated cuffs
F1	ND	ND	ND
F2	4	1	1
F3	6	1	2
F5	3	1	2
F9	6	1	3
F10	3	1	NA
F14	2	0	NA

Note: "ND" = "not detectable": because of the inherent flame retardant properties, FR cotton fabric extinguished itself very quickly after the ignition and therefore did not sustain combustion and therefore it was not possible to determine the time of ignition.

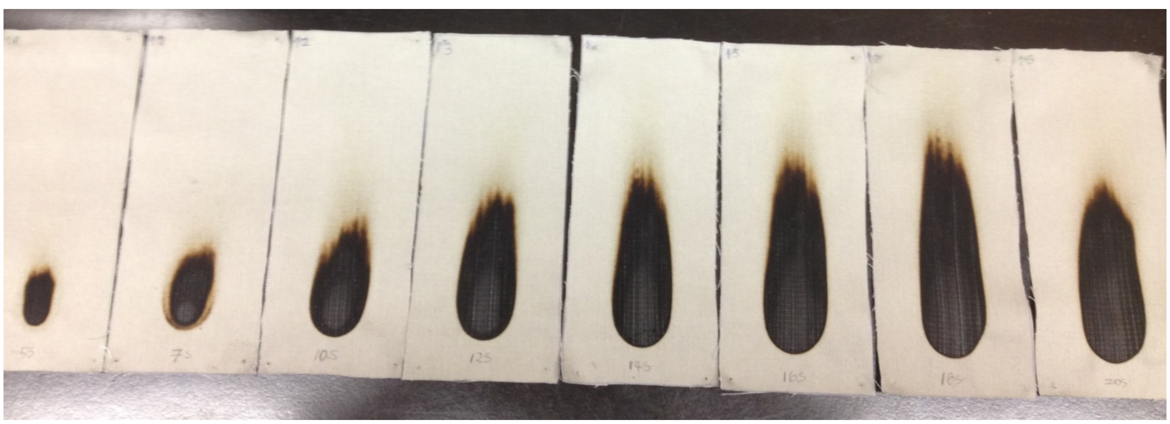


Figure 4.8 Surface ignition pattern of F1 (FR cotton) specimens. From left to right, the time of applied flame is 5, 7, 10, 12, 14, 16, 18 and 20 seconds, respectively.

The single layer specimens of apron F14 ignited as soon as the flame approached from the bottom edge. The simulated cuffs of F3, F5 and F9 performed better than the single layers of the same fabrics against a flame approaching from the bottom edge. For instance, it took the simulated cuff made from F9 three seconds to ignite but only about one second to ignite as a single layer. However, there was no difference in the time to ignition of F2 between single-layered fabric and the simulated cuff.

4.2.2 *Thermal protective performance against hot surface contact*

The mean values (±SEM) of time to second-degree burn for single-layered fabrics against hot surface contact (200±3°C) are depicted in Figure 4.9. The time to second-degree burn ranged from 0.84 seconds in the case of F14 to 2.20 seconds for F10. The effect of fabric type on time to second-degree burn against hot surface contact is shown in Table 4.15. The type of fabric had a significant influence on time to second-degree burn ($F_{6,28}$=54.53, p≤0.001). As three groups were apparent in the Tukey's post-hoc analysis with F3 and F10 performed the best at 2.08 and 2.20 seconds respectively, and were not significantly different, whereas fabrics F14 and F5 reached second-degree burn more rapidly at 0.84 and 0.88 seconds respectively (Table 4.16). Fabrics F1, F2 and F9 reached second-degree burn between 1.50 seconds (F1) to 1.64 seconds (F9) and were not significantly different from one another (Table 4.16).

The comparison of mean values (±SEM) of time to second-degree burn among single-layered fabrics, with and without aprons is displayed in Figure 4.10. The effect of fabric type and apron on time to second-degree burn against hot surface contact is shown in Table 4.17 with post-hoc analysis of significant differences displayed in Table 4.18. The effect of apron type significantly affected the protectiveness of fabric systems against hot surface ($F_{2,60}$=689.10, p≤0.001) (Table 4.17). Generally, the fabrics covered by the F10 apron performed the best, showing the longest time to second-degree burn (M=4.20

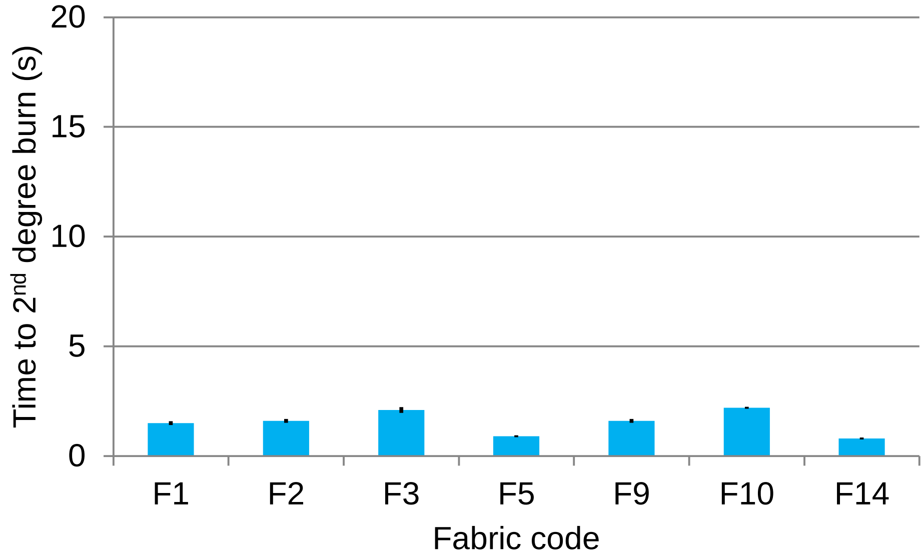


Figure 4.9 Means (±SEM) of time to second-degree burn against hot surface contact for single-layered fabrics.

Table 4.15 Fabric affecting time to second-degree burn against hot surface - ANOVA

Source	df	SS	MS	F	p≤
Between groups	6	8.32	1.39	54.53	0.001
Within groups	28	0.71	0.06		
Total	34	9.03			

Table 4.16 Differences in time to second-degree burn for fabrics against hot surface - Tukey's range test

Interactions	Mean	n	Tukey's groupings
Fabric			
F14	0.84	5	a
F5	0.88	5	a
F1	1.50	5	b
F2	1.56	5	b
F9	1.64	5	b
F3	2.08	5	c
F10	2.20	5	c

Means grouped by lines are not significantly different at p≤0.05

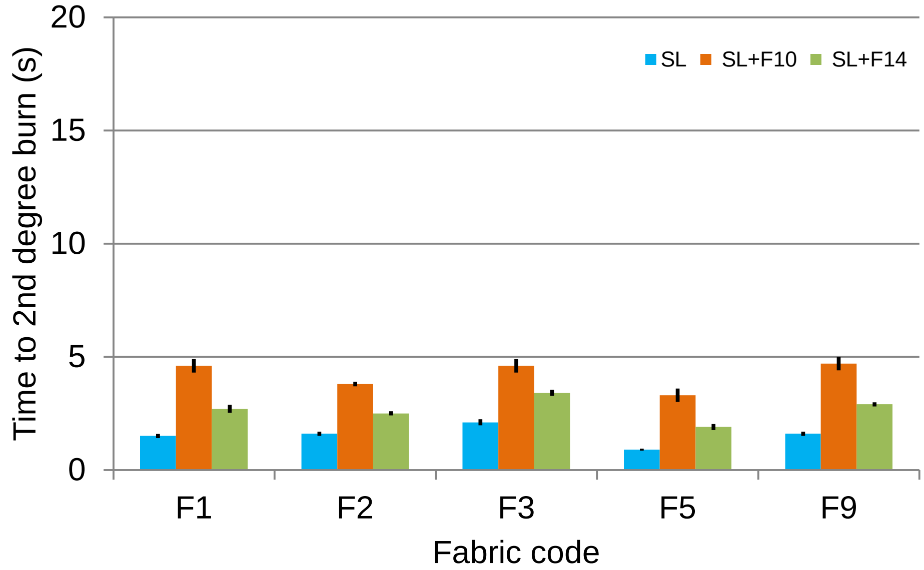


Figure 4.10 Comparison of means (±SEM) of time to second-degree burn against hot surface contact between single-layered fabrics with and without aprons

Table 4.17 Significance of fabric and apron on time to second-degree burn against hot surface - ANOVA

Source	df	SS	MS	F	p≤
Fabric	4	15.51	3.88	59.47	0.001
Apron	2	89.86	44.93	689.10	0.001
Fabric/Apron	8	1.93	0.24	3.70	NS
Error	60	3.91	0.07		
Total	75	70..89			

Table 4.18 Differences in time to second-degree burn for fabric and apron against hot surface - Tukey's range test

Interactions	Mean	n	Tukey's groupings
Fabric			
F5	2.03	15	
F2	2.62	15	
F1	2.92	15	
F9	3.08	15	
F3	3.38	15	
Apron			
None	1.53	25	
F14	2.68	25	
F10	4.20	25	

Means grouped by lines are not significantly different at p≤0.05

Table 4.19 Differences in time to second-degree burn for fabric, apron and layer against hot surface among multiple-layer fabric systems -Tukey's range test

Interactions	Mean	n	Tukey's groupings
Fabric			
F2	5.91	45	A
F3	8.15	45	B
Apron			
None	5.47	30	A
F14	7.03	30	B
F10	8.59	30	C
Layers			
1L	2.99	30	A
2L	5.52	30	B
4L	12.57	30	C
Fabric/Apron			
F2/None	4.53	15	A
F2/F14	5.87	15	AB
F3/None	6.41	15	AB
F2/F10	7.33	15	AB
F3/F14	8.19	15	AB
F3/F10	9.15	15	B
Fabric/Layers			
F2/1L	2.62	15	A
F3/1L	3.37	15	AB
F2/2L	4.75	15	B
F3/2L	6.30	15	C
F2/4L	10.35	15	D
F3/4L	14.79	15	E
Apron/Layers			
None/1L	1.82	10	A
F14/1L	2.97	10	AB
None/2L	4.11	10	BC
F10/1L	4.19	10	BC
F14/2L	5.41	10	CD
F10/2L	7.05	10	D
None/4L	10.47	10	E
F14/4L	12.71	10	F
F10/4L	14.53	10	F

Means grouped by lines are not significantly different at $p \leq 0.05$

s) and the single-layered fabrics provided the least protectiveness against hot surface (M=1.53 s) (Figure 4.10). For example, time to second-degree burn for F3, F3/F10 and F3/ F14 was 2.1, 4.6 and 3.4 seconds, respectively (Figure 4.10).

In Figure 4.11, the time to second-degree burn of multiple-layered F2 and F3 fabric systems, with and without aprons against hot surface is displayed. The effect of treatment variables on time to second-degree burn through contact with hot surfaces is shown in Table 4.19. All three main factors influenced time to second-degree burn significantly (Fabrics: $F_{1,72}=795.09$, $p \leq 0.001$; Apron: $F_{2,72}=513.23$, $p \leq 0.001$; Layers: $F_{2,72}=5182.86$, $p \leq 0.001$). F3 fabrics took longer to reach second-degree burn (M=8.15 s) than F2 (M=5.91 s) (Table 4.20). There was an obvious increasing trend of time to second-degree burn with the increasing of number of fabric layers (Figure 4.11 and Table 4.20). As a result, the four-layered fabric covered by F10 took the longest time to reach second-degree burn against contact with a hot surface (M=14.53 s), followed by four-layers with F14 (M= 12.71 s) (Table 4.20). The single-layered fabrics took the shortest time to reach second-degree burn among all the fabric systems (Table 4.20). It is also worthwhile to mention that when comparing the single-layered fabrics, the difference of time to second-degree burn between single-layered F2 and F3 was 0.6 seconds. However, with the increasing of layers, the difference extended to 5.2 seconds between the four-layered F2 covered by F10 fabric system and four-layered F3 covered by F10 fabric system. There were significant interaction effects among the fabric, apron, and number of layers on the time to second-degree burn (Table 4.19). For instance, the interaction effect between fabric and number of layers had an influence on the time to second-degree burn against hot surface exposure ($F_{2,72}= 197.61$, $p \leq 0.001$) (Table 4.19).

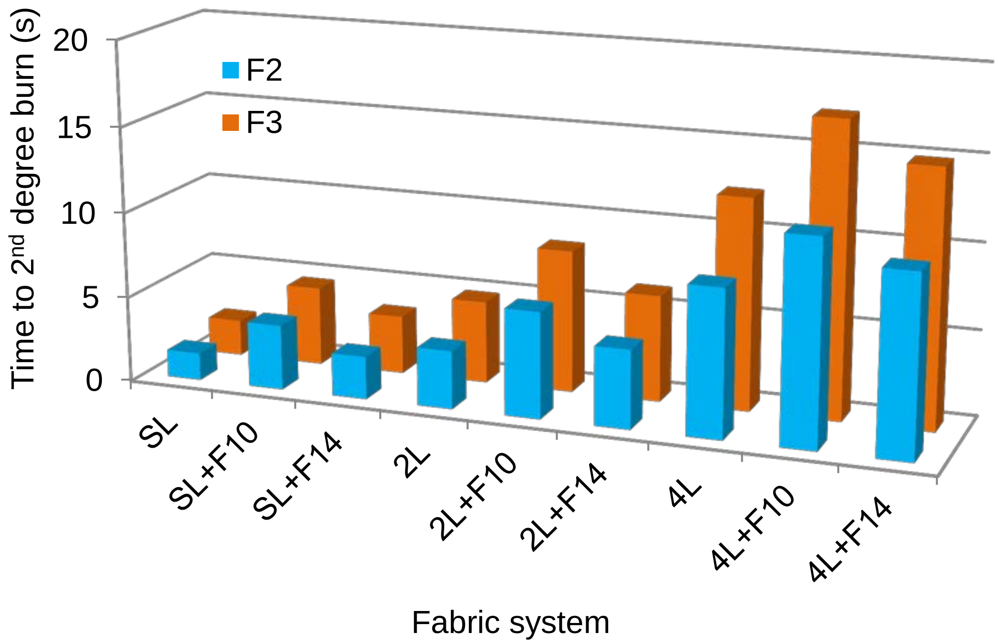


Figure 4.11 Means of time to second-degree burn against hot surface contact for multiple-layer fabrics

Table 4.20 Significance of fabric, apron and layer on time to second-degree burn against hot surface among multiple-layer fabric systems – ANOVA

Source	df	SS	MS	F	p≤
Fabric	1	113.34	113.34	795.09	0.001
Apron	2	146.33	73.16	513.23	0.001
Layers	2	1477.69	738.85	5182.86	0.001
Fabric/Apron	2	1.64	0.82	5.77	0.001
Fabric/Layers	2	56.74	28.17	197.61	0.001
Apron/Layers	4	7.89	1.97	13.83	0.001
Fabric/Apron/Layers	4	1.39	0.35	2.43	NS
Error	72	10.26	0.14		
Total	90	6261.36			

4.2.3 *Thermal protective performance against low pressure steam*

The mean values (±SEM) of absorbed energy and the time to second-degree burn for single-layered fabrics against ten seconds of steam exposure (at 10 Psi, 108±5°C) are depicted in Figure 4.12. The one-way ANOVAs analyzing the effect of fabric type on absorbed energy and time to second-degree burn against steam is showed in Table 4.21. The level of absorbed energy ranged from 475 kJ/m^2 for F2 to 526 kJ/m^2 for F10 (Figure 4.12a). The time to second-degree burn ranged from 0.70 seconds in case of F2 to 1.38 seconds for F9 (Figure 4.12b). It was noted that fabric type did not contribute to a significant difference on either absorbed energy ($F_{6,34}$=1.83, NS) or time to second-degree burn ($F_{6,34}$=3.67, NS) (Table 4.21).

The comparison of mean values (±SEM) of absorbed energy and time to second-degree burn among single-layered fabrics, with and without aprons are displayed in Figure 4.13. Two-way ANOVAs were carried out to determine how fabric and apron affected absorbed energy and time to second-degree burn against steam (Table 4.22). The effect of apron was highly significant on influencing the protectiveness of fabric systems against steam (AE: $F_{2,60}$=232.75, $p \leq 0.001$; time to second-degree burn: $F_{2,60}$=121.60, $p \leq 0.001$) (Table 4.22). Overall, the fabrics covered by apron F14 exhibited a much lower level of absorbed energy and longer time to reach second-degree burn compared to single-layered fabrics and single-layered fabrics shielded by apron F10 (Table 4.23). For example, the absorbed energy of F1/F14 was 275 kJ/m^2 while that of F1 was 478 kJ/m^2 and that of F1/F10 was 476 kJ/m^2 (Figure 4.13). Fabric type did not influence second-degree burn at all (AE: $F_{4,60}$=3.37, NS; time to second-degree burn: $F_{4,60}$ = 2.17, NS) (Table 4.22).

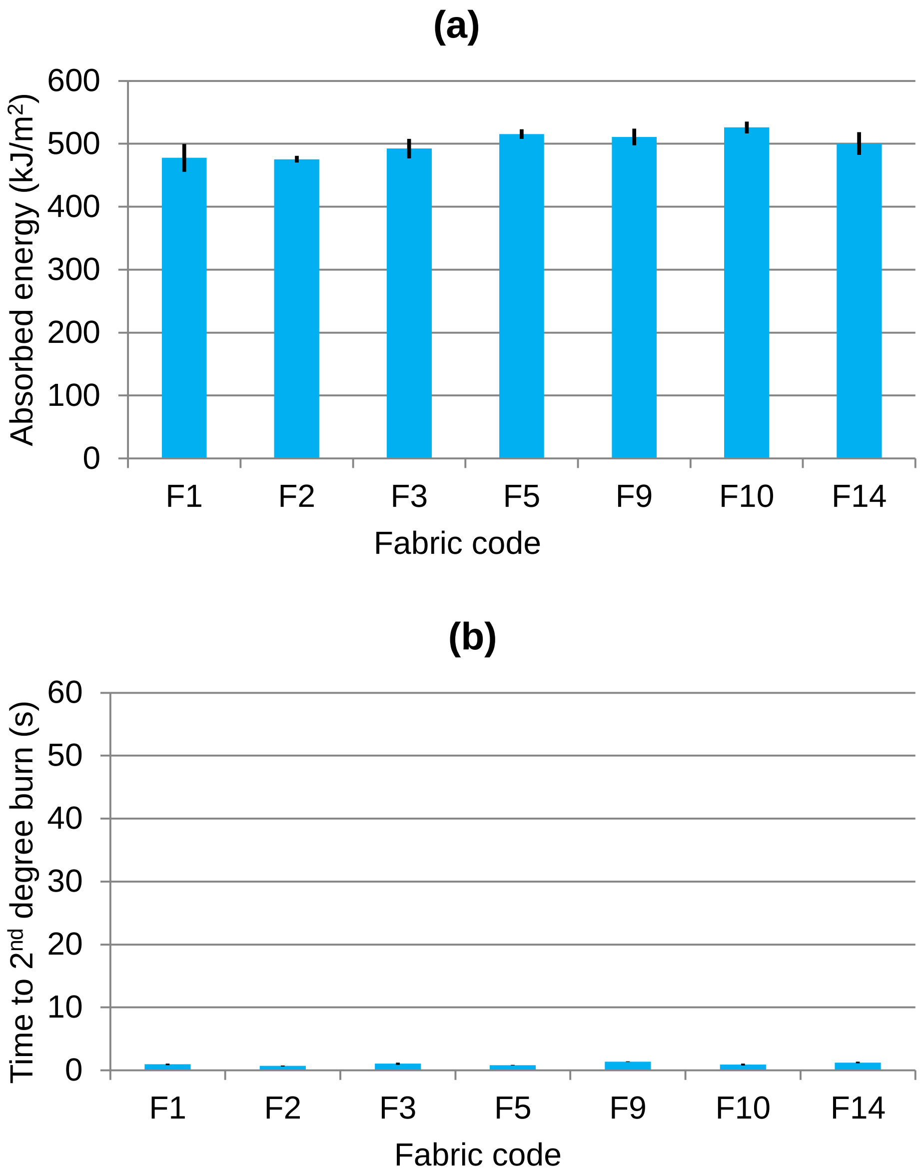
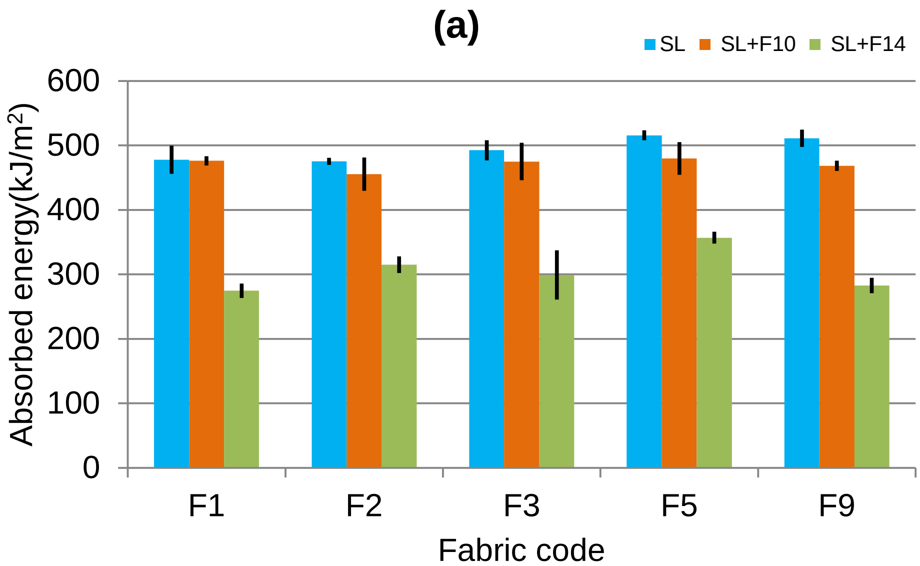


Figure 4.12 Means (±SEM) of (a) absorbed energy and (b) time to second-degree burn of single-layered fabrics against steam at 10 Psi, 108±5°C

Table 4.21 Fabric affecting (a) absorbed energy and (b) time to second-degree burn against steam - ANOVA

Source	df	SS	MS	F	p≤
(a) absorbed energy					
Between groups	6	10972.92	1828.82	1.83	NS
Within groups	28	28065.41	1002.34		
Total	34	39038.33			
(b) time to second-degree burn					
Between groups	6	1.69	0.28	3.67	NS
Within groups	28	2.15	0.08		
Total	34	3.84			



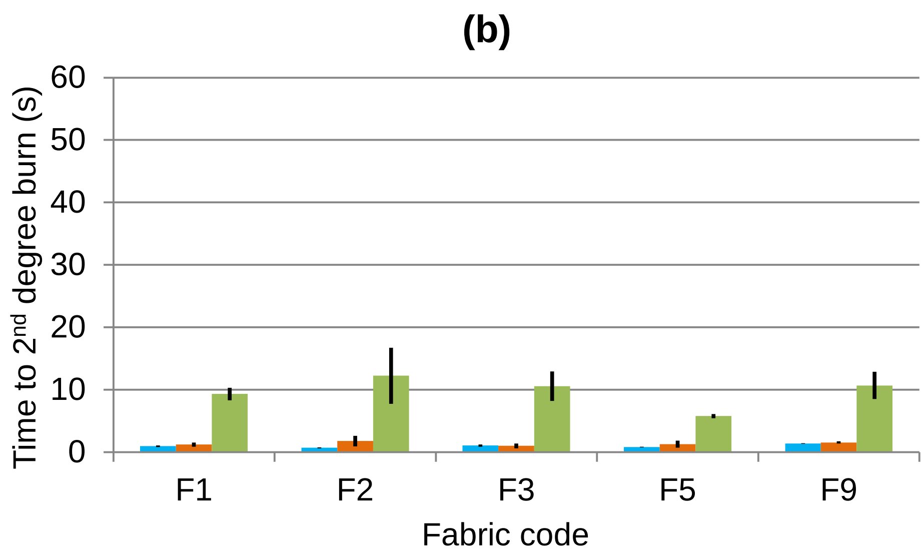


Figure 4.13 Comparison of means (±SEM) of (a) absorbed energy and (b) time to second-degree burn between single-layered fabrics with and without aprons against steam

Table 4.22 Significance of fabric and apron on (a) absorbed energy and (b) time to second-degree burn against steam –ANOVA

Source	df	SS	MS	F	p≤
(a) absorbed energy					
Fabric	4	15925.09	3823.77	3.37	NS
Apron	2	528790.74	264395.37	232.75	0.001
Fabric/Apron	8	14580.22	1822.53	1.06	NS
Error	60	68159.13	1135.99		
Total	75	14083378.09			
(b) time to second-degree burn					
Fabric	4	34.27	8.57	2.17	NS
Apron	2	958.98	479.49	121.60	0.001
Fabric/Apron	8	58.49	7.31	1.85	NS
Error	60	236.59	3.94		
Total	75	2316.49			

Table 4.23 Differences in (a) absorbed energy and (b) time to second-degree burn for apron against steam -Tukey's range test

Interactions	Mean	n	Tukey's groupings
(a) absorbed energy			
Apron			
F14	305	25	
F10	471	25	
None	494	25	
(b) time to second-degree burn			
Apron			
None	0.98	25	
F10	1.37	25	
F14	8.75	25	

Means grouped by lines are not significantly different at $p \leq 0.05$

In Figure 4.14, the comparison of mean values of absorbed energy and the time to second-degree burn of multiple-layered F2 and F3 fabric systems, with and without aprons against steam is shown. Four-layered fabrics covered by apron F14 exhibited the lowest level of absorbed energy and longest time to second-degree burn for both F2 and F3 fabrics (see Figure 4.13 & Table 4.25). The type of apron covering the fabric system had an significant effect on protectiveness against steam (AE: $F_{2,72}$=292.02, $p \leq 0.001$; time to second-degree burn: $F_{2,72}$=237.78, $p \leq 0.001$) (Table 4.24), as reported above for single-layered fabrics F14 was the most protective (Table 4.25). Layering of the fabrics made a significant difference to absorbed energy of multi-layered fabric systems ($F_{2,72}$=27.92, $p \leq 0.001$) and time to second-degree burn ($F_{2,72}$=94.99, $p \leq 0.001$). With the increasing number of layers, the time to reach second-degree burn increased and absorbed energy decreased (Figure 4.14 and Table 4.25). Overall, F3 fabrics took longer to reach second-degree burn (M=11.09 s) compared to F2 fabrics (M=5.89 s) (Table 4.25). In addition, the absorbed energy of F3 fabrics (M= 376 kJ/m^2) was lower than that of F2 fabrics (M= 410 kJ/m^2). There were significant interaction effects among fabric, apron and number of layers. For example, the interaction between fabric and apron had a significant influence on both dependent variables (AE: $F_{2,72}$=10.66, $p \leq 0.001$; time to second-degree burn: $F_{2,72}$=43.07, $p \leq 0.001$).

Plots of temperature over time data for single-layered fabrics with and without aprons are shown in Figure 4.15. In the case of a single-layered fabric and single-layered fabrics with F10, the rise of temperature was much quicker than single-layered fabrics covered with F14 during steam exposure. For example, single-layered F1 reached peak temperature at 2.4 seconds while single-layered F1 covered by F14 reached peak temperature at 10.2 seconds (Figure 4.15). From the temperature over time data curve, it could be noted that the sensor started cooling down right after exposure except in the case of F9 and F14 fabrics.

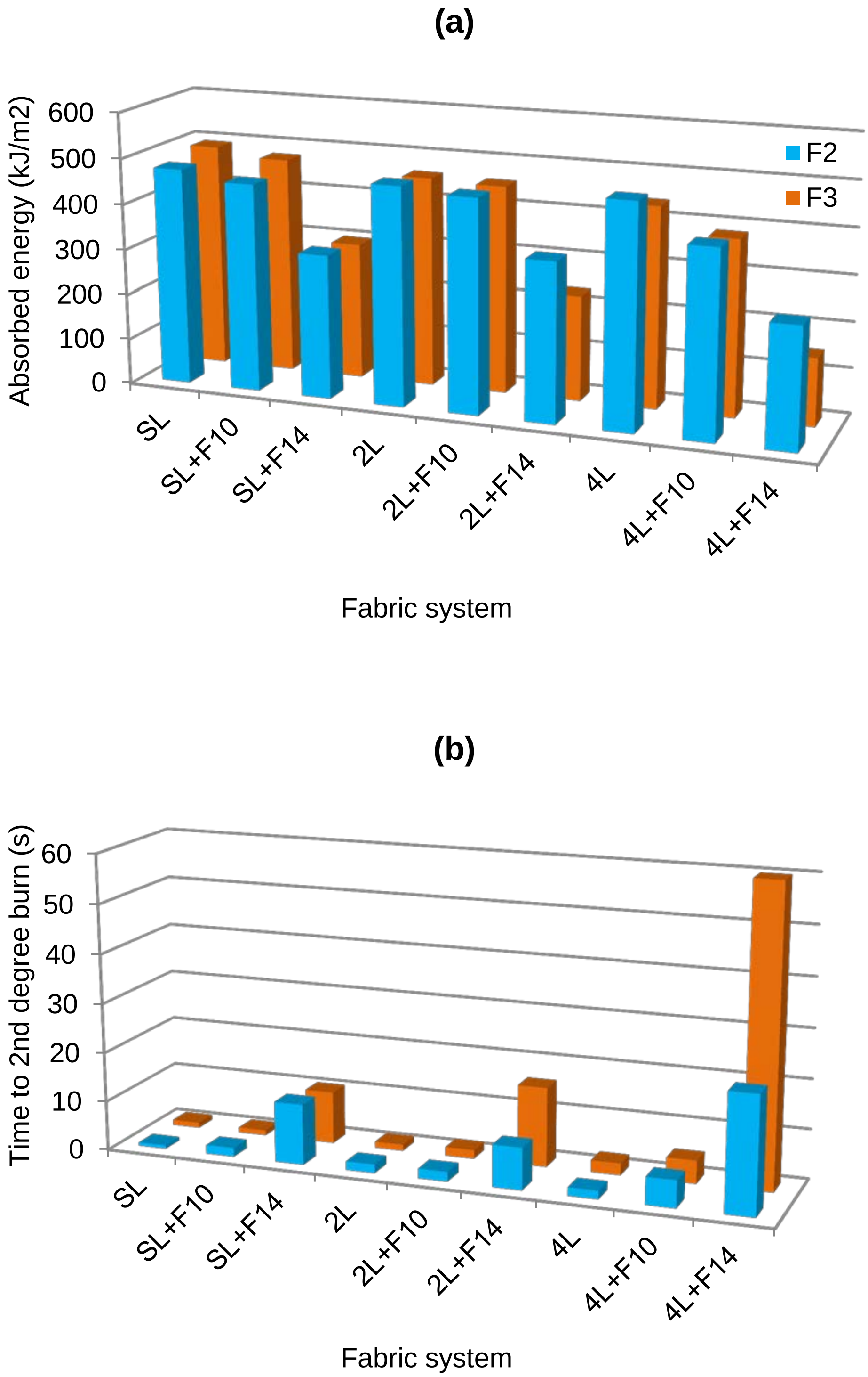


Figure 4.14 Comparison of means of (a) absorbed energy and (b) time to second-degree burn for multiple-layer fabric systems against steam exposure

Table 4.24 Significance of fabric, layer and apron on (a) absorbed energy and (b) time to second-degree burn against steam among multiple-layer fabric systems - ANOVA

Source	df	SS	MS	F	p≤
(a) absorbed energy					
Fabric	1	26895.29	26895.29	21.73	0.001
Apron	2	722868.15	361434.08	292.02	0.001
Layers	2	69119.92	34559.96	27.92	0.001
Fabric/Apron	2	26375.60	13187.80	10.66	0.001
Fabric/Layers	2	19990.78	9995.39	8.08	NS
Apron/Layers	4	21578.27	5394.57	4.36	NS
Fabric/Apron/Layers	4	4289.22	1072.30	0.87	NS
Error	72	89115.63	1237.72		
Total	90	14880532.80			
(b) time to second-degree burn					
Fabric	1	607.57	607.57	39.65	0.001
Apron	2	7287.47	3643.74	237.78	0.001
Layers	2	2911.12	1455.56	94.99	0.001
Fabric/Apron	2	1319.97	659.98	43.07	0.001
Fabric/Layers	2	591.52	295.76	19.30	0.001
Apron/Layers	4	3919.22	979.81	63.94	0.001
Fabric/Apron/Layers	4	1147.43	286.86	18.72	0.001
Error	72	1103.31	15.32		
Total	90	25369.74			

Table 4.25 Differences in (a) absorbed energy and (b) time to second-degree burn for fabric, apron and layer against steam -Tukey's range test

Interactions	Mean	n	Tukey's groupings
(a) absorbed energy			
Fabric			
F2	410.	45	
F3	376	45	
Apron			
F14	268	30	
F10	440	30	
None	471	30	
Layers			
4L	355	30	
2L	406	30	
1L	419	30	
Fabric/Apron			
F3/F14	226	15	
F2/F14	309	15	
F3/F10	437	15	
F2/F10	442	15	
F3/None	463	15	
F2/None	480	15	
(b) time to second-degree burn			
Fabric			
F2	5.89	45	
F3	11.09	45	
Apron			
None	1.48	30	
F10	2.79	30	
F14	21.19	30	
Layers			
1L	3.76	30	
2L	5.26	30	
4L	16.46	30	

Table 4.25 Differences in (a) absorbed energy and (b) time to second-degree burn for fabric, apron and layer against steam -Tukey's range test (continued)

Interactions	Mean	n	Tukey's groupings
Fabric/Apron			
F2/None	1.39	15	
F3/None	1.57	15	
F3/F10	2.48	15	
F2/F10	3.09	15	
F2/F14	13.18	15	
F3/F14	29.20	15	
Fabric/Layers			
F2/1L	3.31	15	
F2/2L	4.07	15	
F3/1L	4.21	15	
F3/2L	6.36	15	
F2/4L	10.28	15	
F3/4L	22.69	15	
Apron/Layers			
None/1L	0.88	10	
F10/1L	1.40	10	
None/2L	1.51	10	
F10/2L	1.88	10	
None 4L	2.06	10	
F10/4L	5.09	10	
F14/1L	9.00	10	
F14/2L	12.26	10	
F14/4L	42.31	10	

Means grouped by lines are not significantly different at $p \leq 0.05$

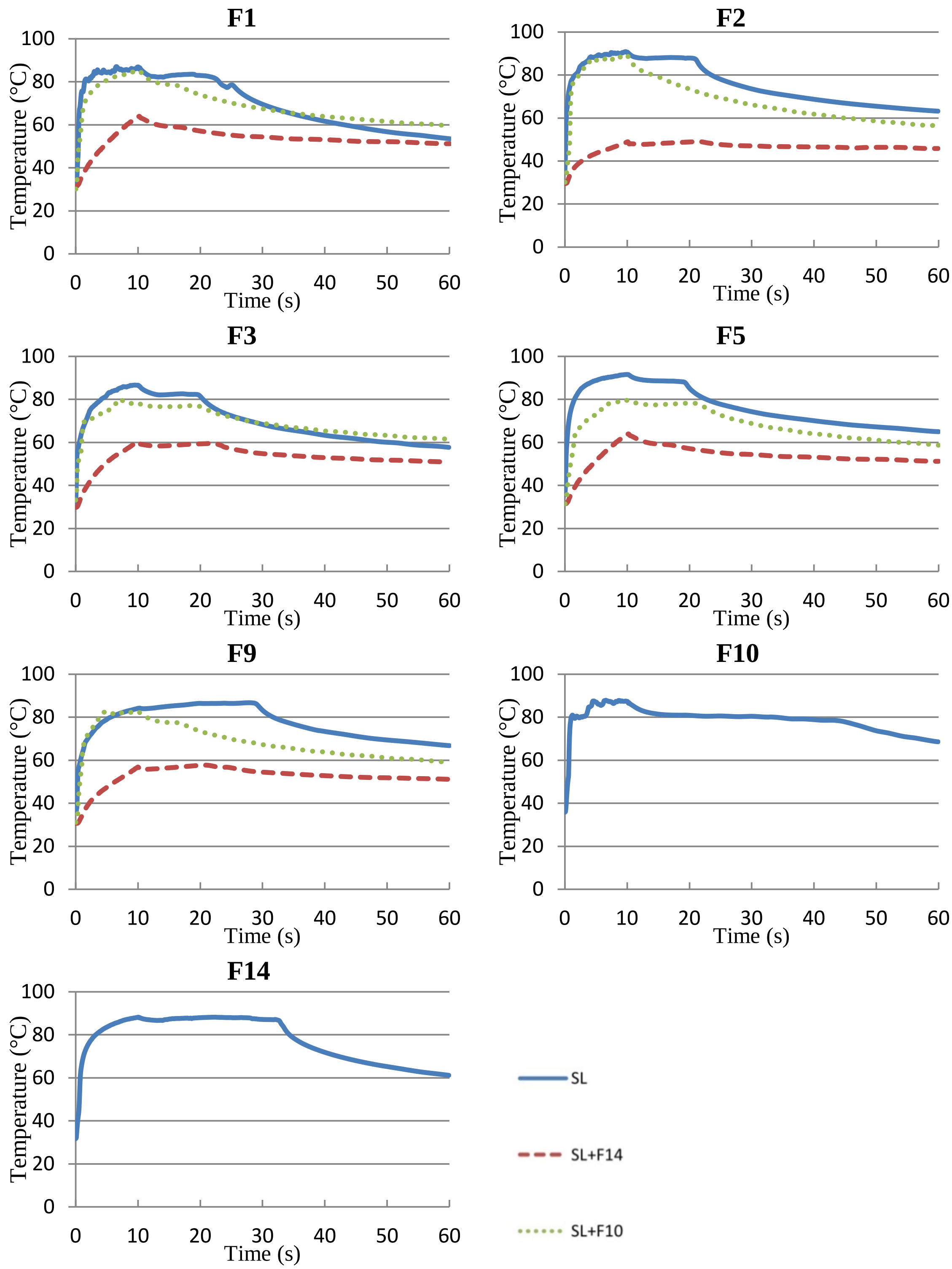


Figure 4.15 Temperature rise over time for single-layered fabrics with and without aprons during steam exposure

Heat flux and absorbed energy over time for single-layered fabrics with and without aprons were calculated according to temperature rise over time and plots showing an initial heat flux rise are depicted in Figure 4.16. The absorbed energy curve of single-layered fabrics and single-layered fabrics covered by F10 were similar. The heat flux of single-layered fabrics covered by F14 increased in a steadier way and slower manner compared to the other two fabric systems. Taking F5 as an example, the curves of single-layered F5 and the F5/F10 fabric system are almost identical. The heat flux increased dramatically once the steam exposure started. However, the heat flux of the F5/F14 fabric system increased more slowly and did not reach such a high peak.

The plots of the temperature rise and absorbed energy/heat flux over time for multiple-layered F2 and F3 fabric systems are shown in Figure 4.17 and Figure 4.18, respectively. Four-layered fabrics covered with F14 presented the smoothest curve of temperature rise over time. A much smaller rise in temperature for four-layered fabric systems could be recognized compared to single-layered fabrics. For example, the temperature of four-layered F3 fabrics increased from 28.64 °C (T0) to 69.25 °C (T_p), while single layered F3 fabrics increase from 30.8 °C (T0) to 85.89 °C (T_p) (Figure 4.17). The peak temperature of four-layered fabric system was much lower and kept plateau after exposure. The overall temperature rise over time in the case of F3 fabric systems was smaller compared to those of F2 (e.g., the T_p of two-layered F2 covered by F10 is 80.57 °C while that of same combination of F3 was 73.19 °C). For all the fabric systems, only the four-layered F3 covered by F14 did not reach second-degree burn following steam exposure.

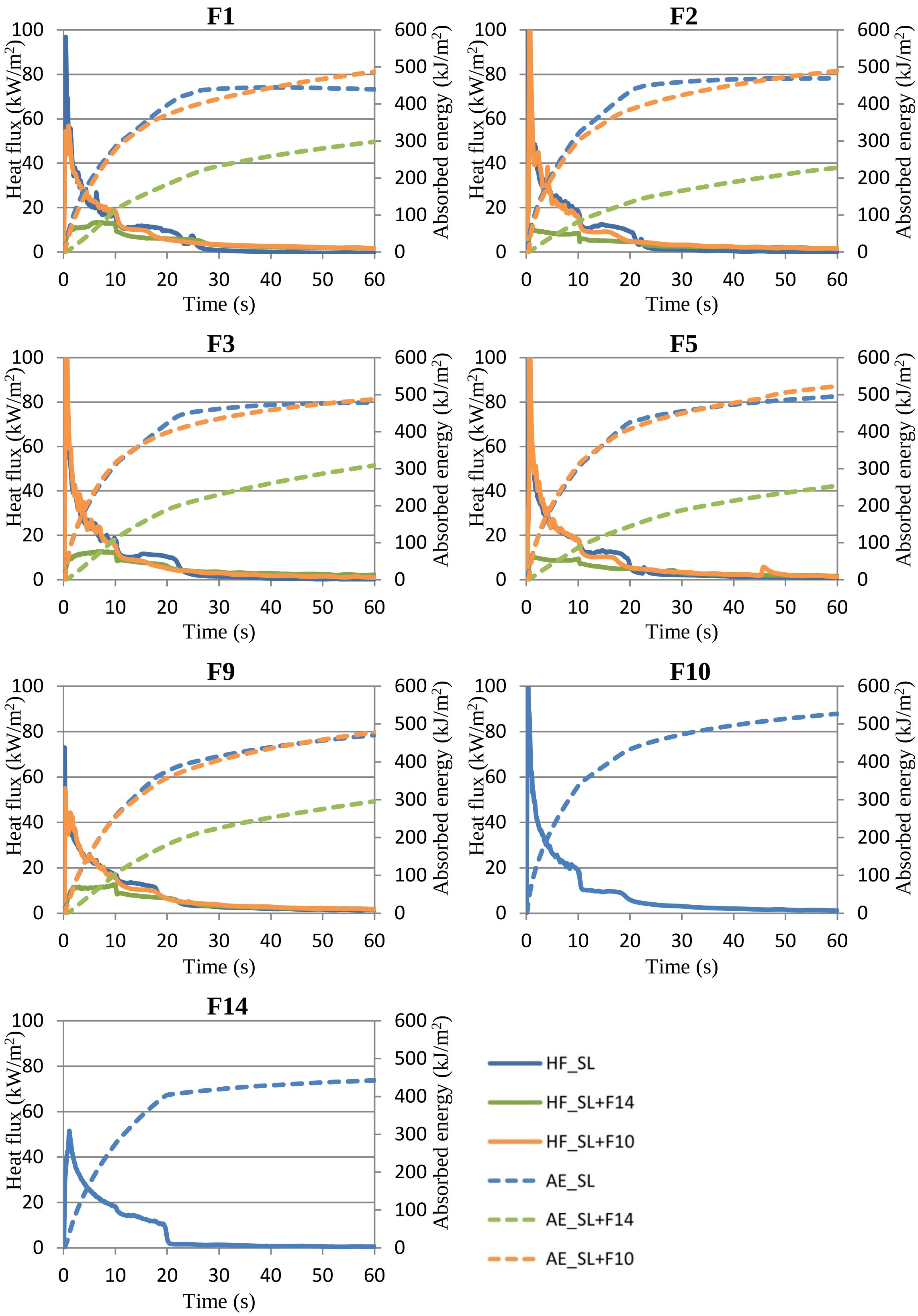


Figure 4.16 Heat flux (HF) and absorbed energy (AE) over time during steam exposure for single layered fabric with and without aprons

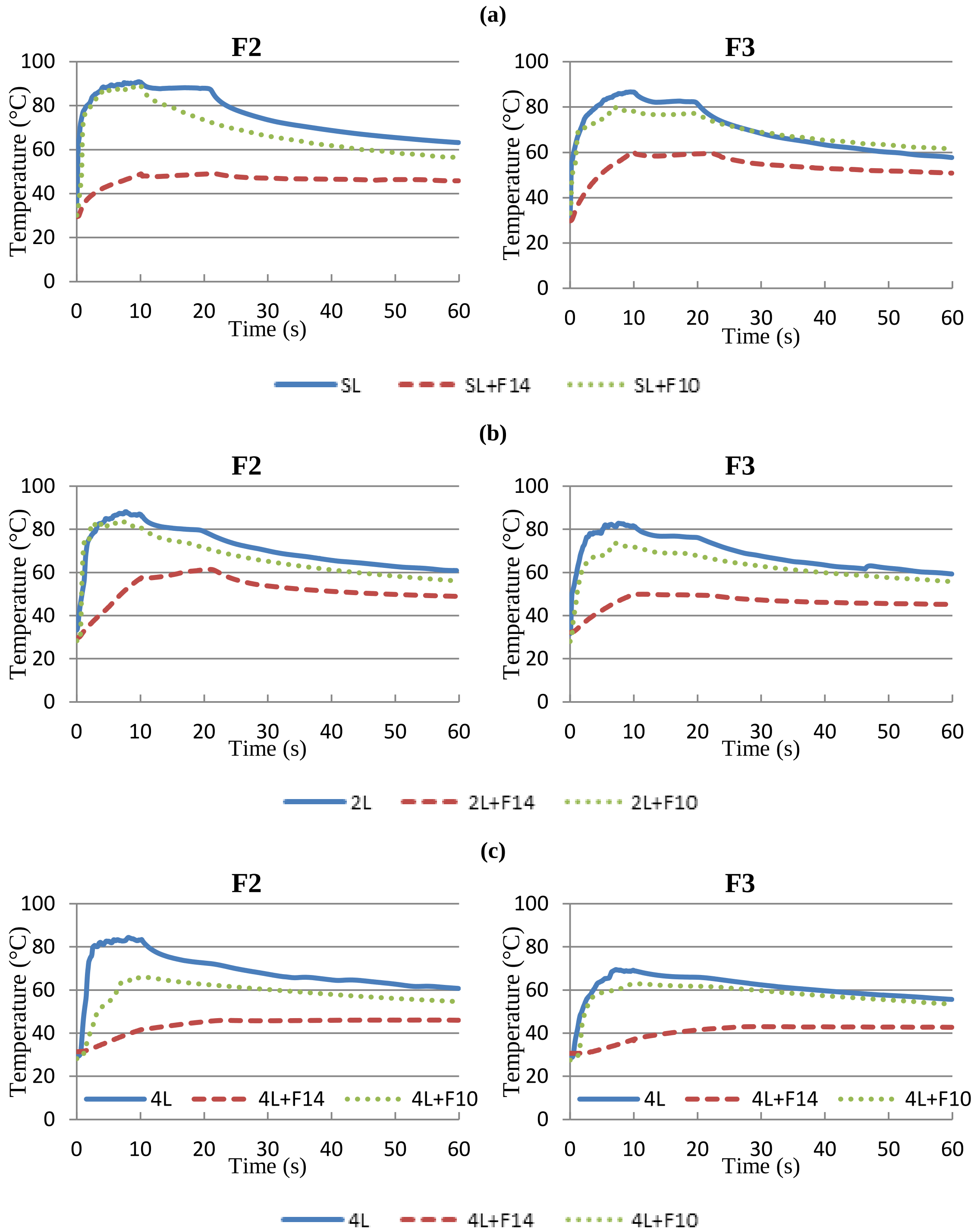


Figure 4.17 Temperature rise over time during steam exposure for F2 and F3 fabric systems a) single layer; b) two layers; c) four layers

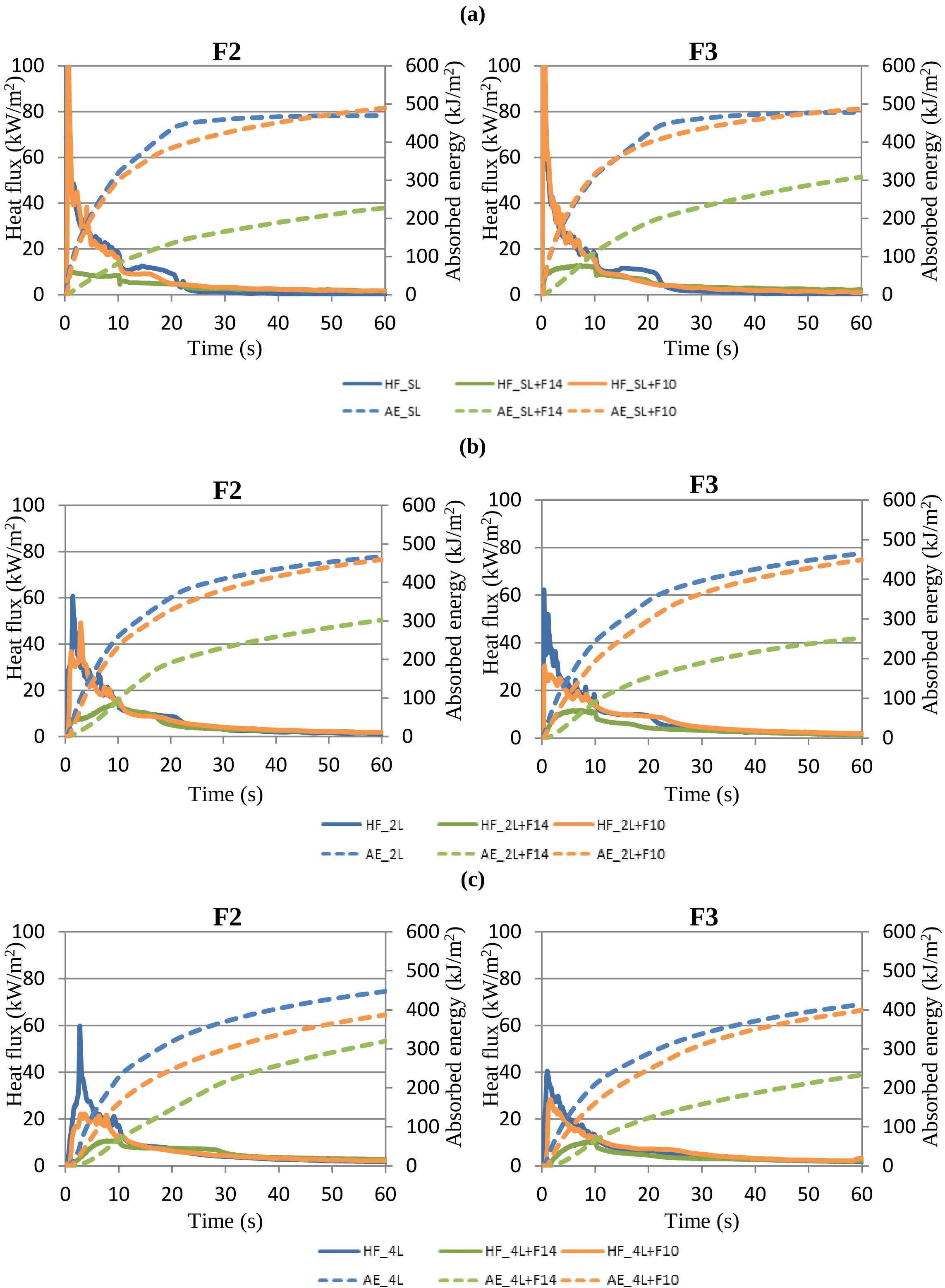


Figure 4.18 Heat flux and absorbed energy over time during steam exposure for multiple-layer fabric system a) single layer; b) two layers; c) four layers

4.2.4 *Thermal protective performance against hot water*

The mean values (±SEM) of absorbed energy and time to second-degree burn for single-layered fabrics against ten seconds of hot water exposure at 85 °C are presented in Figure 4.19. The one-way ANOVAs analyzing the effect of fabric type on absorbed energy and time to second-degree burn against hot water exposure is displayed in Table 4.26. Absorbed energy ranged from 159 kJ/m^2 for F14 to 284 kJ/m^2 for F3, which was slightly higher than that of F9 at 284 kJ/m^2 (Table 4.27). Fabric type had significant effect on absorbed energy ($F_{6,14}$=9.14, p≤0.001) and time to second-degree burn ($F_{6,14}$= 43.50, p≤0.001) (Table 4.26). As the impermeable apron F14 was significantly different from all other fabrics (Table 4.27). Among the other six fabrics, the absorbed energy did not differ, ranging from 251 kJ/m^2 to 284 kJ/m^2; However, F2 took longer to reach second-degree burn (M= 1.67 s) than the other fabrics, although it did not significantly differ from F5 (M=1.34 s).

The comparison of mean values (±SEM) of absorbed energy and time to second-degree burn among single-layered fabrics with and without aprons are presented in Figure 4.20. Generally, the fabrics covered by apron F14 performed the best, exhibiting the lowest absorbed energy and no predicted burn injuries during the 60 seconds of the tests in all cases. Due to the high level of protection offered by the F14 fabric, F14 was not included in the further analysis and a two-way ANOVA was carried out to determine the effect of fabric type and apron (no apron and F10 apron only) (Table 4.28). The effect of the permeable F10 apron was still highly significant on influencing the protectiveness of fabric systems to hot water (AE: $F_{1,20}$=28.99, p≤0.001; second-degree burn: $F_{1,20}$=8.56, p≤0.001) (Table 4.28). The absorbed energy of single-layered fabrics covered by F10 was slightly higher than that of single layers with no apron (e.g., the AE of F2/F10 system was 276 kJ/m^2 while AE of F2 was 254 kJ/m^2) (Figure 4.20 and Table 4.29). The time to

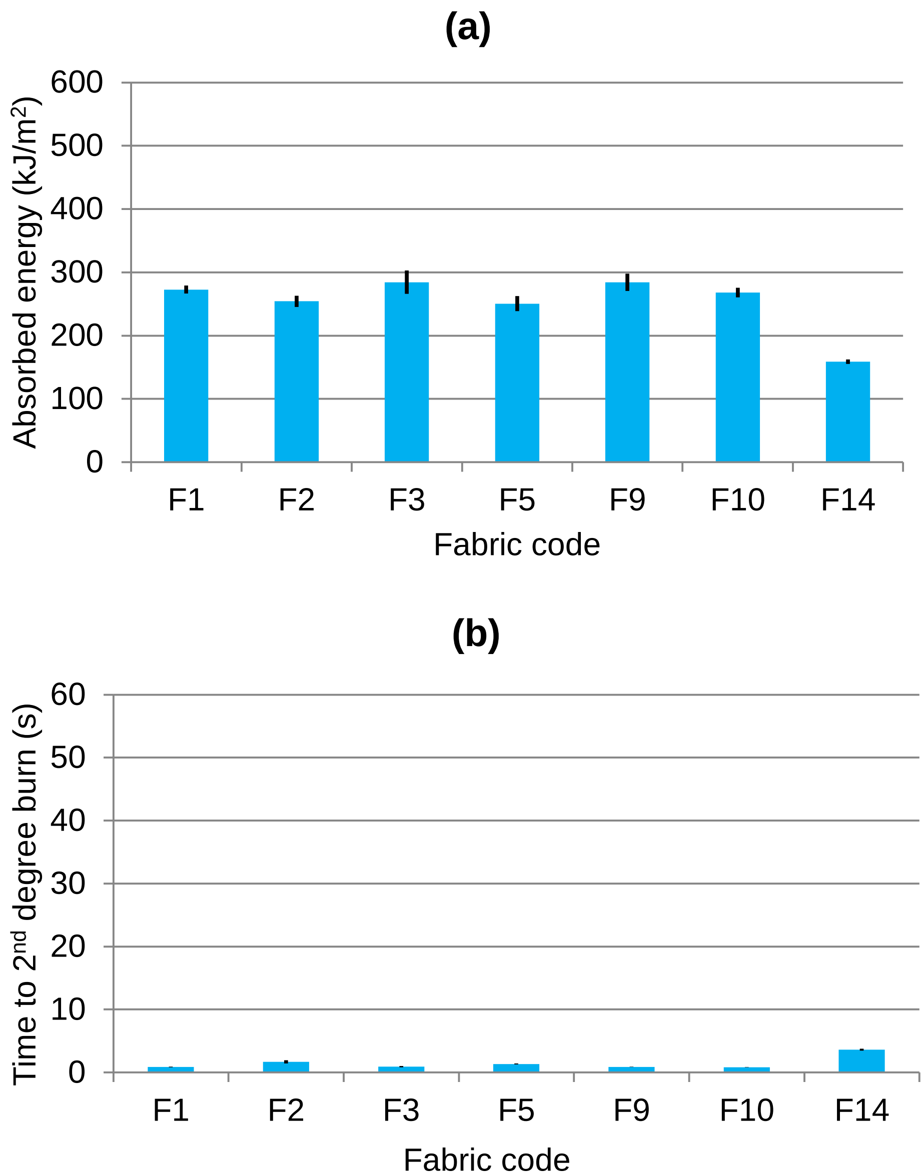


Figure 4.19 Mean (±SEM) of (a) absorbed energy and (b) time to second-degree burn against hot water for single-layered fabrics

Table 4.26 Fabric affecting (a) absorbed energy and (b) time to second-degree burn against hot water - ANOVA

Source		df	SS	MS	F	p≤
(a) absorbed energy						
Fabric	Between groups	6	34345.99	5724.33	9.14	0.001
	Within groups	14	8512.62	608.04		
	Total	20	42858.61			
(b) time to second-degree burn						
Fabric	Between groups	6	18.266	3.04	43.50	0.001
	Within groups	14	0.980	0.07		
	Total	20	19.246			

Table 4.27 Fabric affecting (a) absorbed energy and (b) time to second-degree burn against hot water - Tukey's range test

Interactions	Mean	n	Tukey's groupings
(a) absorbed energy			
Fabric			
F14	158	3	
F5	250	3	
F2	254	3	
F10	268	3	
F1	273	3	
F9	284	3	
F3	284	3	
(b) time to second-degree burn			
Fabric			
F10	0.84	3	
F9	0.88	3	
F1	0.89	3	
F3	0.91	3	
F5	1.34	3	
F2	1.67	3	
F14	3.62	3	

Means grouped by lines are not significantly different at $p \leq 0.05$

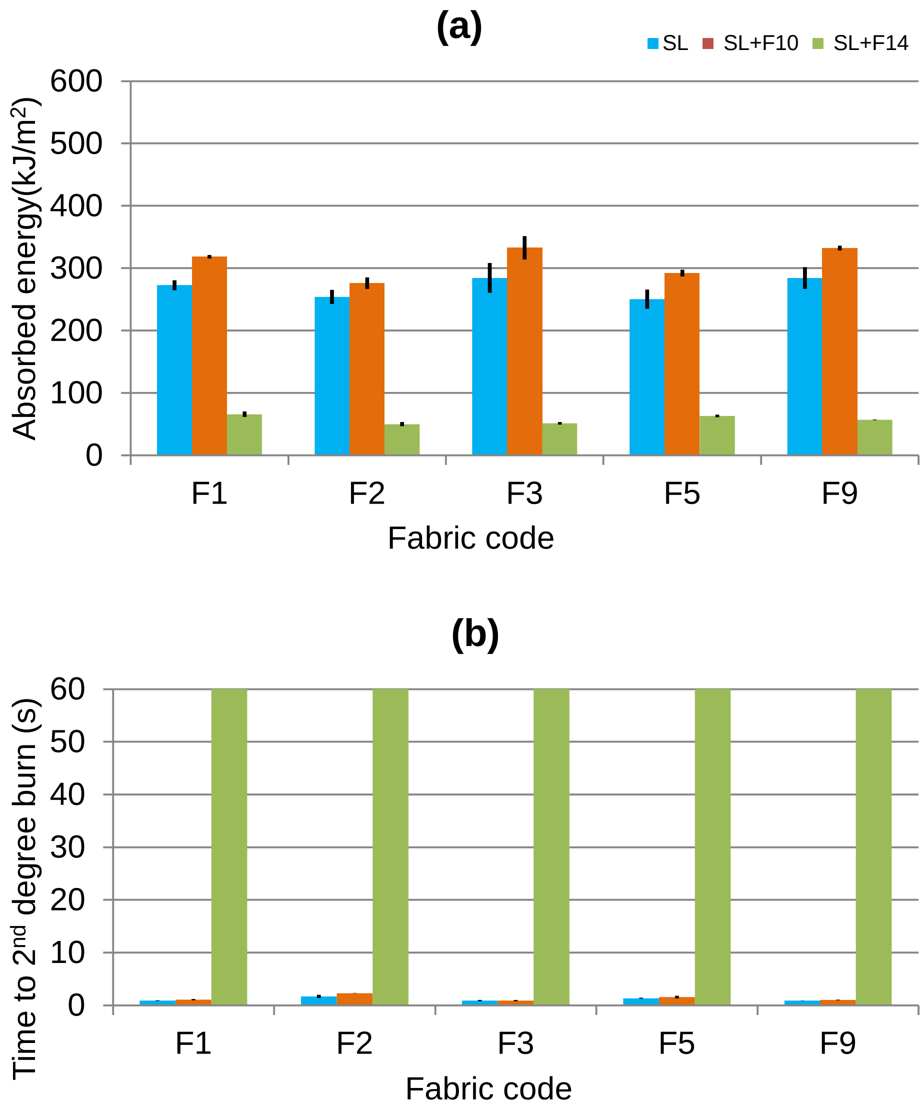


Figure 4.20 Mean (±SEM) of (a) absorbed energy and (b) time to second-degree burn against hot water for single-layered fabrics

Table 4.28 Fabric and apron affecting (a) absorbed energy and (b) time to second-degree burn against hot water – ANOVA

Source	df	SS	MS	F	p≤
(a) absorbed energy					
Fabric	4	9995.30	2498.83	5.68	NS
Apron	1	12743.16	12743.16	28.99	0.001
Fabric/Apron	4	733.20	183.30	0.42	NS
Error	20	8792.45	439.62		
Total	30	2551217.33			
(b) time to second-degree burn					
Fabric	4	5.25	1.31	27.65	0.001
Apron	1	0.41	0.41	8.56	0.001
Fabric/Apron	4	0.36	0.09	1.89	NS
Error	20	0.95	0.05		
Total	30	54.21			

Note: Apron F14 was not included in this data analysis.

Table 4.29 Fabric and apron affecting (a) absorbed energy and (b) time to second-degree burn against hot water -Tukey's range test

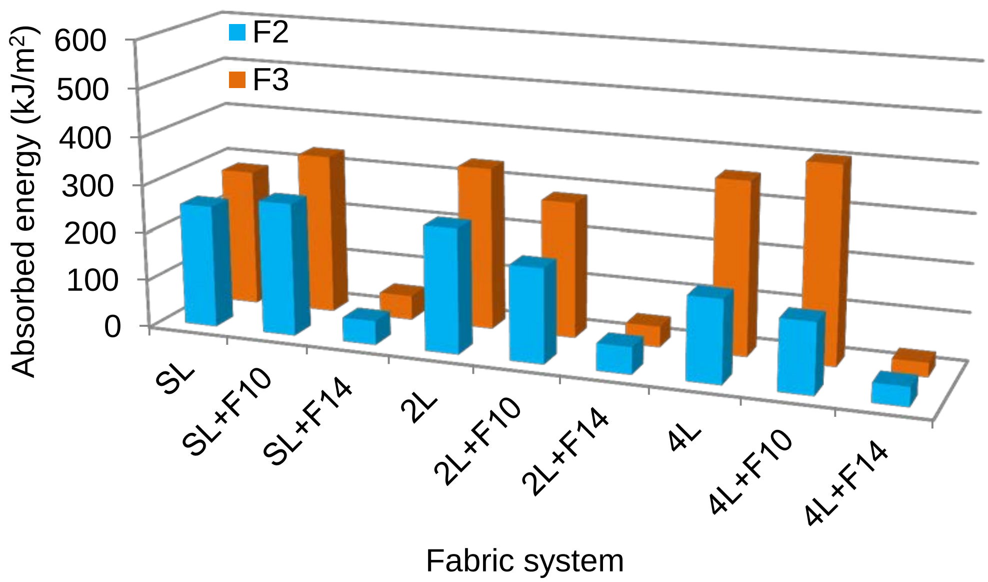
Interactions	Mean	n	Tukey's groupings
(a) absorbed energy			
Apron			
None	274	18	
F10	278	18	
(b) time to second-degree burn			
Fabric			
F3	0.90	6	
F9	0.95	6	
F1	0.98	6	
F5	1.45	6	
F2	1.99	6	
Apron			
None	3.04	18	
F10	4.28	18	

Means grouped by lines are not significantly different at $p \leq 0.05$

second-degree burn of single-layered fabrics covered by F10 (M=4.28 s) was longer than that of single-layered fabrics (M=3.04 s) (Table 4.29).

In Figure 4.21, the comparison of mean values of absorbed energy and time to second-degree burn of multiple-layered F2 and F3 fabric systems, with and without aprons against hot water are presented. The absorbed energy of all F3 combinations was higher than those of F2 combinations (Figure 4.21). It was also noted that with an increasing number of layers, the time to second-degree burn also increased and absorbed energy decreased. Due to the skewing of results by F14, further analysis was carried out on only two apron treatments (i.e., no apron and F10 apron only). Apron F10 covering the fabric system had no effect on protectiveness against burn injury from hot water (AE: $F_{1,24}$=0.67, NS; time to second-degree burn: $F_{1,24}$=5.92) (Table 4.30). However, fabric type significantly influenced absorbed energy and time to second-degree burn (AE: $F_{1,24}$=219.46, time to second-degree burn: $F_{1,24}$=56.68). Overall, the F2 fabrics took longer to reach second-degree burn (M=5.57 s) compared with F3 (M=1.75s) (Table 4.31b). Although the number of fabrics layers had a significant effect on the time to second-degree burn against hot water ($F_{2,24}$=25.74, $p \leq 0.001$), it did not have an effect on absorbed energy ($F_{2,24}$=1.39, NS) (Table 4.30). There was a significant interaction effect between the fabric type and the number of layers for both dependent variables (AE: $F_{2,24}$=36.98, $p \leq 0.001$; second-degree burn: $F_{2,24}$=16.36, $p \leq 0.001$) (Table 4.30).

(a)



(b)

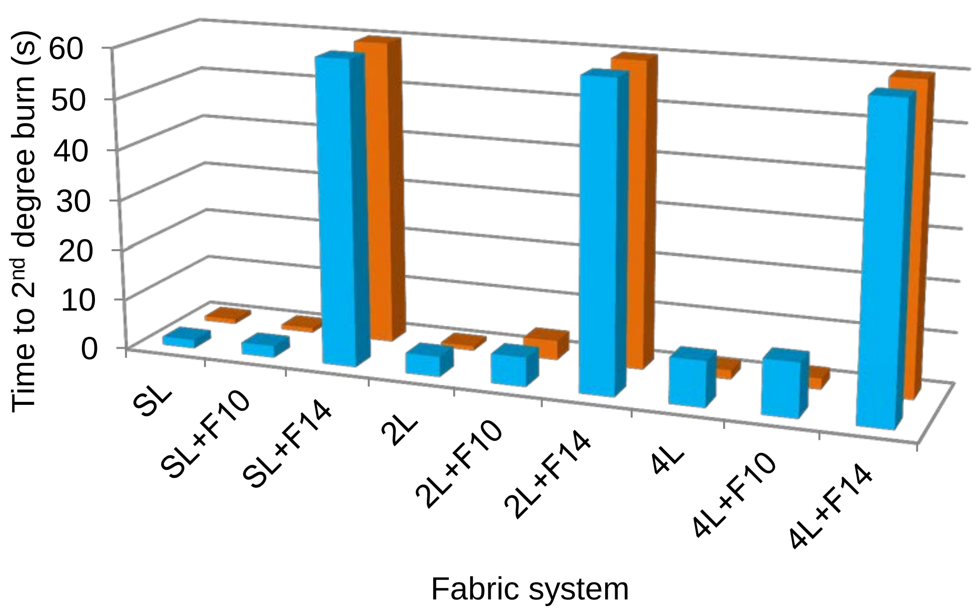


Figure 4.21 Comparison of (a) absorbed energy and (b) time to second-degree burn for multiple-layer fabric systems against hot water

Table 4.30 Significance of fabric, layer and apron on (a) absorbed energy and (b) time to second-degree burn against hot water among multiple-layer fabric systems - ANOVA

Source	df	SS	MS	F	p≤
(a) absorbed energy					
Fabric	1	146310.08	146310.08	219.46	0.001
Apron	1	444.16	444.16	0.67	NS
Layers	2	1856.48	928.24	1.39	NS
Fabric/Apron	1	7535.69	7535.69	11.30	NS
Fabric/Layers	2	49314.30	24657.15	36.98	0.001
Apron/Layers	2	5578.27	2789.14	4.18	NS
Fabric/Apron/Layers	2	1111.96	555.98	0.83	NS
Error	24	16000.77	666.70		
Total	36	3072810.61			
(b) time to second-degree burn					
Fabric	1	131.33	131.33	56.68	0.001
Apron	1	13.71	13.72	5.92	NS
Layers	2	119.28	59.64	25.74	0.001
Fabric/Apron	1	0.16	0.16	0.08	NS
Fabric/Layers	2	75.79	37.90	16.36	0.001
Apron/Layers	2	6.53	3.27	1.41	NS
Fabric/Apron/Layers	2	2.50	1.25	0.54	NS
Error	24	55.61	2.32		
Total	36				

Note: Apron F14 was not included in this data analysis.

Table 4.31 Significance of fabric, layer and apron on (a) absorbed energy and (b) time to second-degree burn against hot water among multiple-layer fabric systems -Tukey's range test

Interactions	Mean	n	Tukey's groupings
(a) absorbed energy			
Fabric			
F2	217	18	
F3	334	18	
Fabric/Layers			
F2/4L	159	6	
F2/2L	228	6	
F2/1L	265	6	
F3/1L	309	6	
F3/2L	343	6	
F3/4L	383	6	
(b) time to second-degree burn			
Fabric			
F2	5.57	18	
F3	1.75	18	
Layers			
1L	1.45	12	
2L	3.63	12	
4L	5.91	12	
Fabric/Layers			
F3/1L	0.91	6	
F3/4L	1.99	6	
F2/1L	1.99	6	
F3/2L	2.26	6	
F2/2L	4.89	6	
F2/4L	9.83	6	

Means grouped by lines are not significantly different at $p \leq 0.05$

Plots of temperature over time data for single-layered fabrics, with and without aprons against hot water are depicted in Figure 4.22. The temperature rose rapidly at the beginning of the test (less than one second) and then kept plateau during the rest of exposure. This occurred for all cases of the single layers and single-layered fabrics with F10 except for apron F14 and single-layered with F2 covered by F10. However, the increase of single-layered fabrics with F14 was much slower and smoother. The peak temperature of single-layered fabrics was much higher than that of single-layered fabrics covered by F14. For example, the peak temperature of single-layered F3 was 82.6 °C and that of F3/F14 was 42.3 °C (Figure 4.22). An evident and quick drop of temperature happened right after the 10 seconds hot water exposure in all cases. During the cooling period, the curve of single-layered fabrics with F10 was slightly higher than that of single-layered fabrics only, which is an indication of slower cooling rate. The curves of single-layered fabrics with F14 during the cooling period were very slow.

Heat flux over time against hot water for single-layered fabrics with and without aprons was calculated based on temperature rise over time and plots showing an initial heat flux are depicted in Figure 4.23. The heat flux increased dramatically in the cases of single-layered fabrics and single-layered fabrics with F10. However, single-layered F5 showed a lower peak compared to other single-layered fabrics (e.g., 63.59 kW/m^2 for F5 compared to 87.29 kW/m^2 for F1).

The plots of the temperature rise and absorbed energy over time for multiple-layered F2 and F3 fabric systems are displayed in Figures 4.24 and 4.25, respectively. An interesting finding between F2 and F3 multi-layer fabric systems was that the overall performance of F2 was much better than that of F3. For example, slope of temperature rise over time of four-layered fabric F3 was larger than that of four-layered F2 (Figure 4.24).

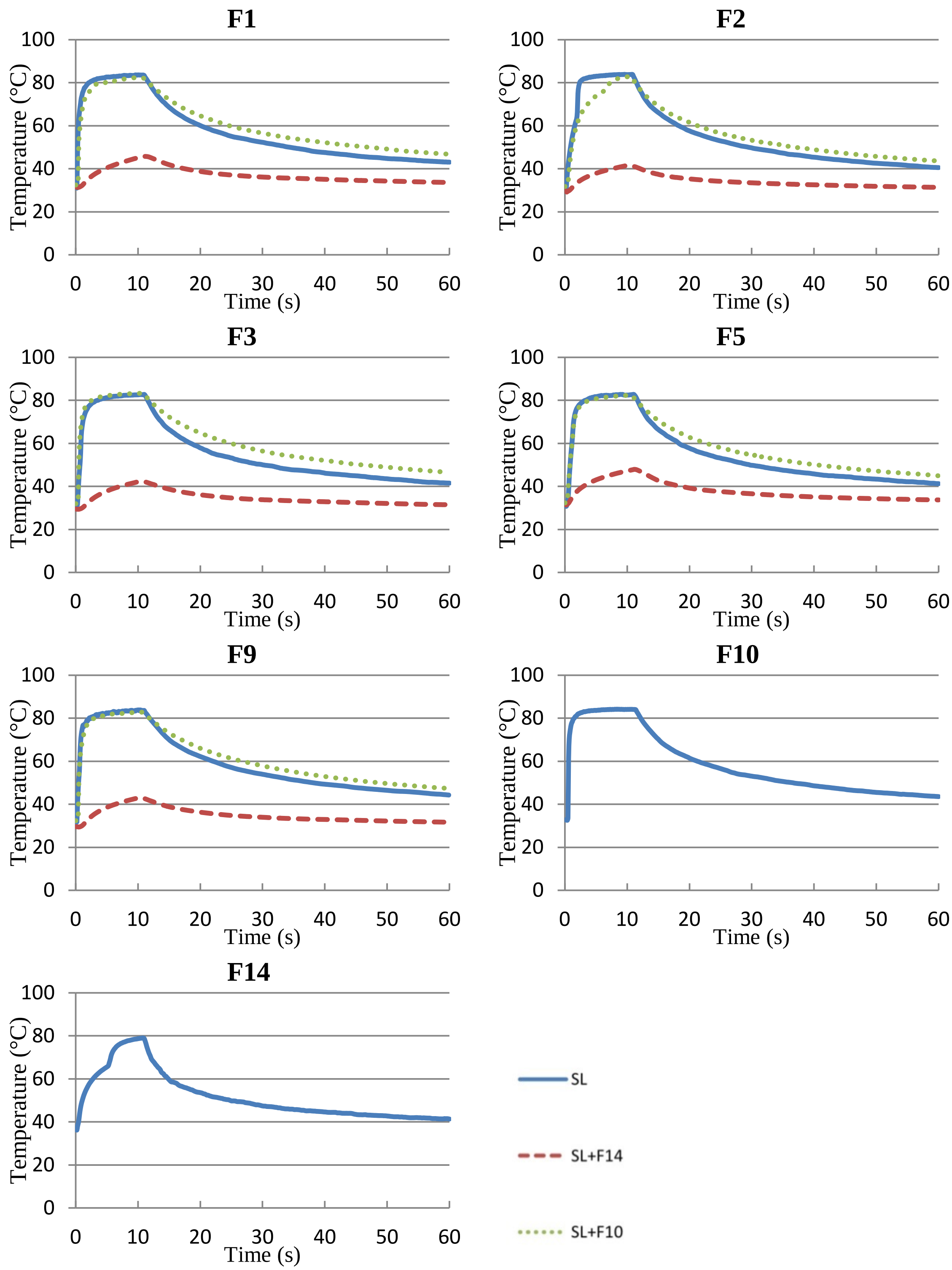


Figure 4.22 Temperature rise over time for single-layered fabrics with and without aprons during hot water tests

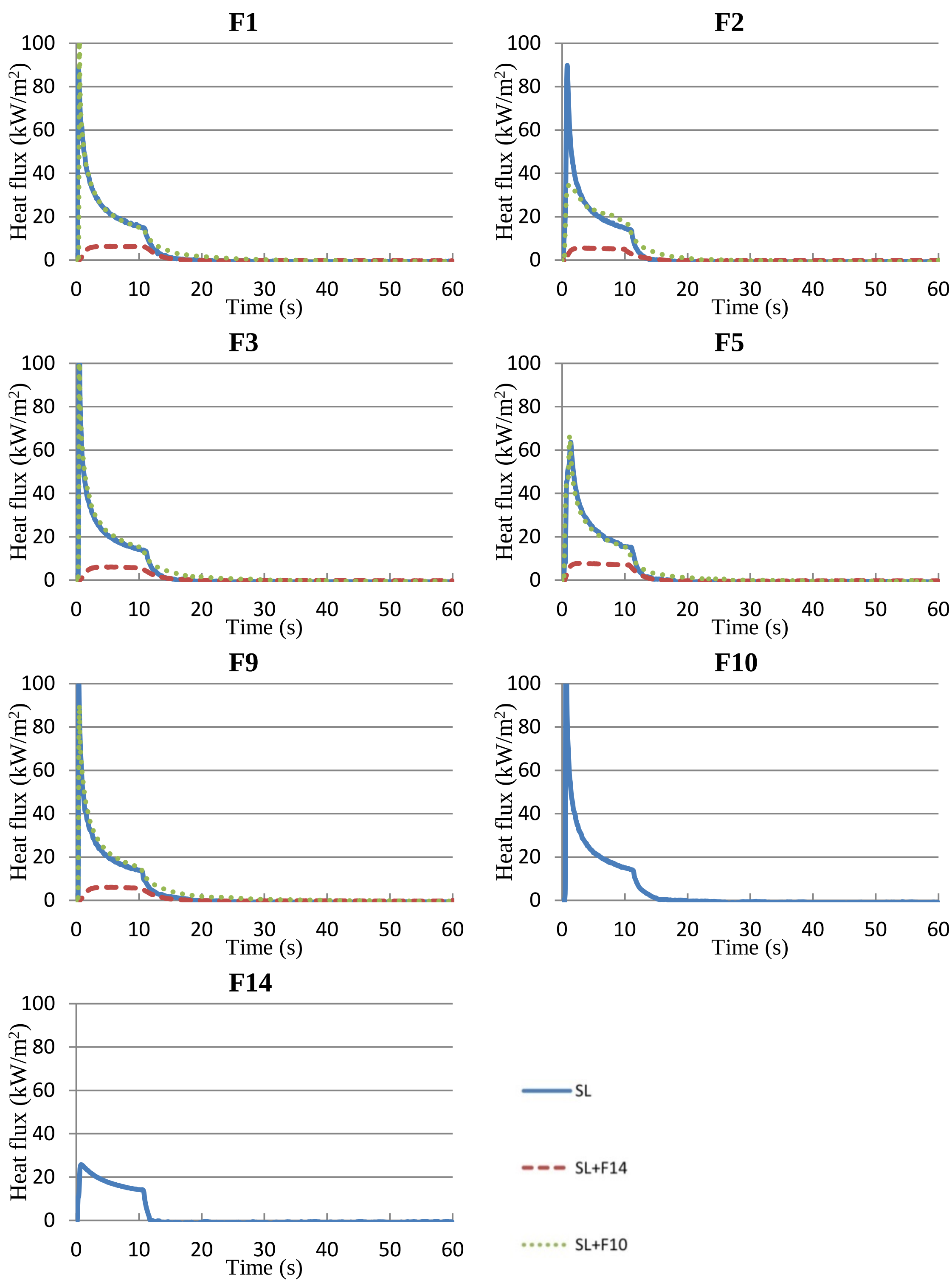


Figure 4.23 Heat flux over time of signle-layered fabrics with and without aprons during hot water test

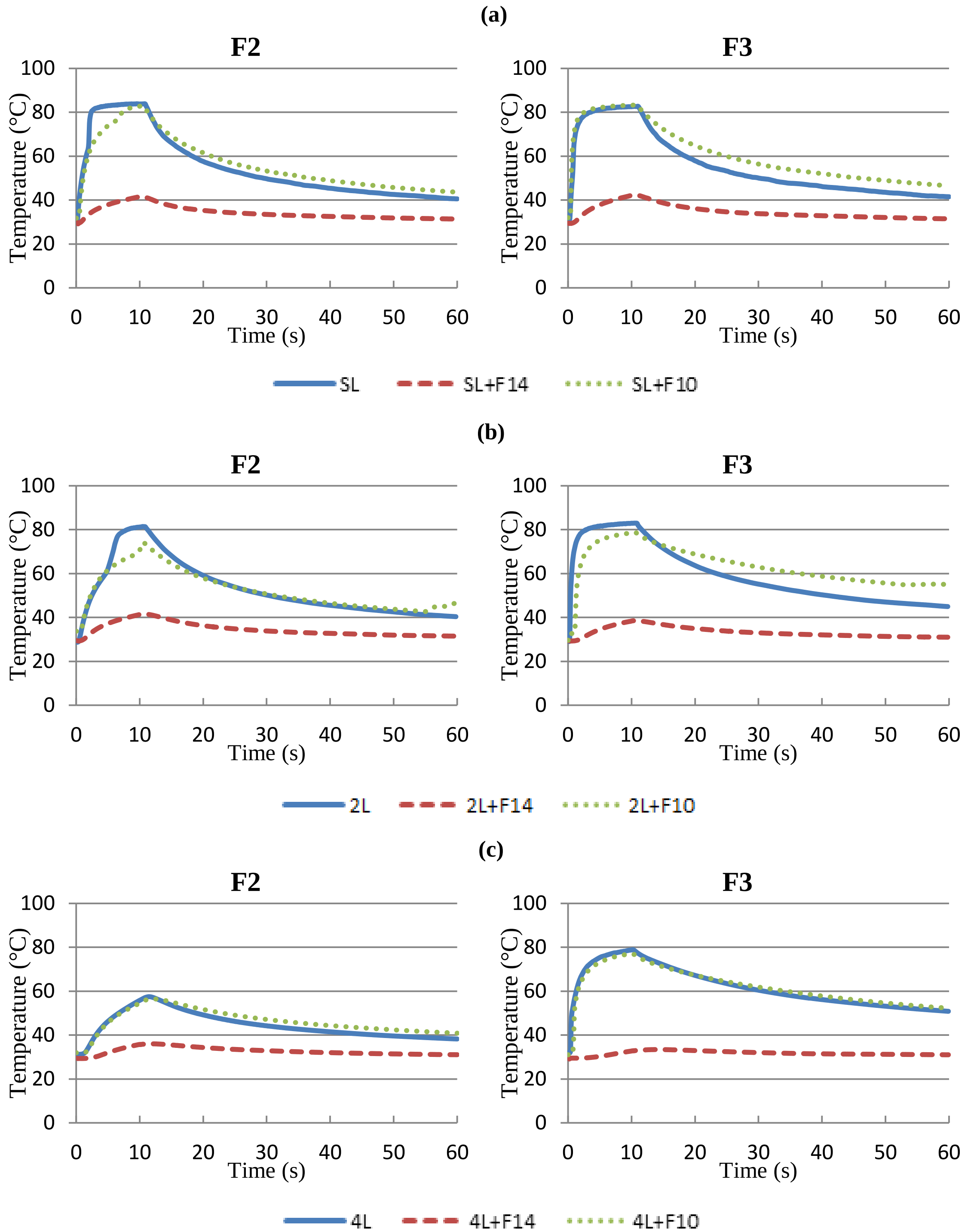


Figure 4.24 Temperature rise over time during hot water for F2 and F3 fabric systems a) single layer; b) two layers; c) four layers

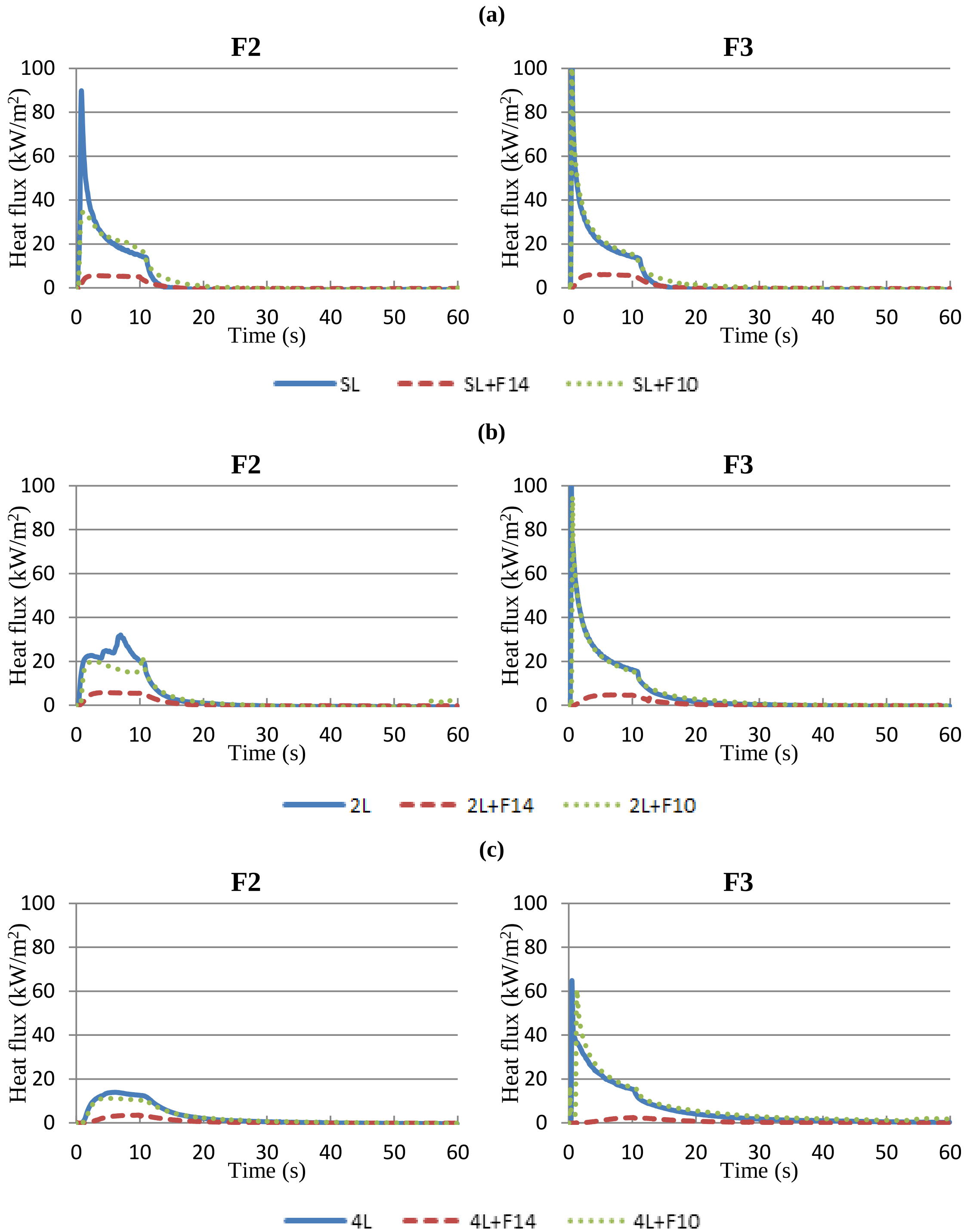


Figure 4.25 Heat flux over time during hot water for F2 and F3 fabric systems a) single layer; b) two layers; c) four layers

At the beginning of the tests, it was also observed that the increase of heat flux of F2 fabric systems was much smaller than that of F3 fabric systems. For example, the peak heat flux of four-layered fabric F3 was 63.80 kW/m^2 and that of four-layered fabric F2 was only 13.93 kW/m^2.

4.2.5 *Thermal protective performance against hot oil*

The mean values (±SEM) of absorbed energy and the time to second-degree burn for single-layered fabrics against ten seconds of hot oil exposure at 85 °C are displayed in Figure 4.26. The level of absorbed energy of F14 ranked the lowest at 199 kJ/m^2 and that of F9 ranked the highest at 236 kJ/m^2. Time to second-degree burn ranged from 3.64 seconds for F2 to 4.89 seconds for F9. Fabric type had a significant effect on absorbed energy ($F_{6,14}=10.19$, $p \leq 0.001$) but not on time to second-degree burn ($F_{6,14}=1.67$, NS). The impermeable apron fabric F14 was significantly different from all other fabrics (Table 4.31 and Table 4.32)

Plots of temperature over time data for single-layered fabrics against hot oil are shown in Figure 4.27 and the shape of the curves are very similar for all fabrics. The increase in temperature after exposure with oil was much smoother than hot water exposure and peak temperature was not as high. For example, the peak temperature of F10 against hot water exposure was 84.2 °C but that of F10 against hot oil at the same temperature is 66.9 °C (Figure 4.27). Heat flux over time for single-layered fabrics against hot oil was calculated according to temperature rise over time and plots are shown in Figure 4.28. In general, the heat flux increased against hot oil exposure to a much smaller extent compared to hot water exposure with the exception of apron F14, which was very similar to each other (Figure 4.23 and Figure 4.28).

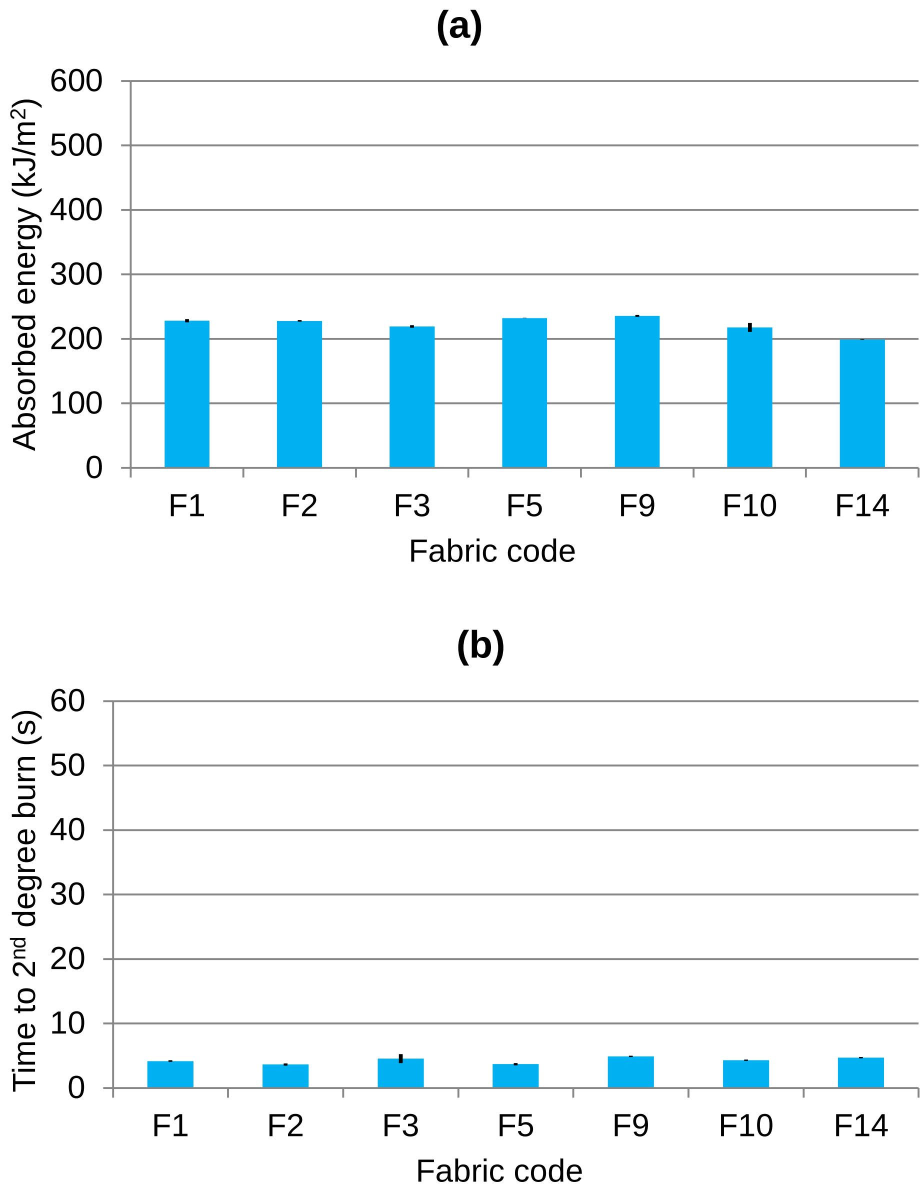


Figure 4.26 Means (±SEM) of (a) absorbed energy and (b) time to second-degree burn against hot oil for single-layered fabrics

Table 4.32 Fabric affecting (a) absorbed energy and (b) time to second-degree burn against hot oil - ANOVA

Source		df	SS	MS	F	p≤
(a) absorbed energy						
Fabric	Between groups	6	2751.95	458.66	10.19	0.001
	Within groups	14	630.34	45.02		
	Total	20	3382.29			
(b) time to second-degree burn						
Fabric	Between groups	6	4.20	0.70	1.67	NS
	Within groups	14	5.88	0.42		
	Total	20	10.07			

Table 4.33 Fabric affecting absorbed energy against hot oil -Tukey's range test

Interactions	Mean	n	Tukey's groupings
Fabric			
F14	199	3	A
F10	218	3	B
F3	219	3	B
F2	228	3	B
F1	228	3	B
F5	232	3	B
F9	236	3	B

Means grouped by lines are not significantly

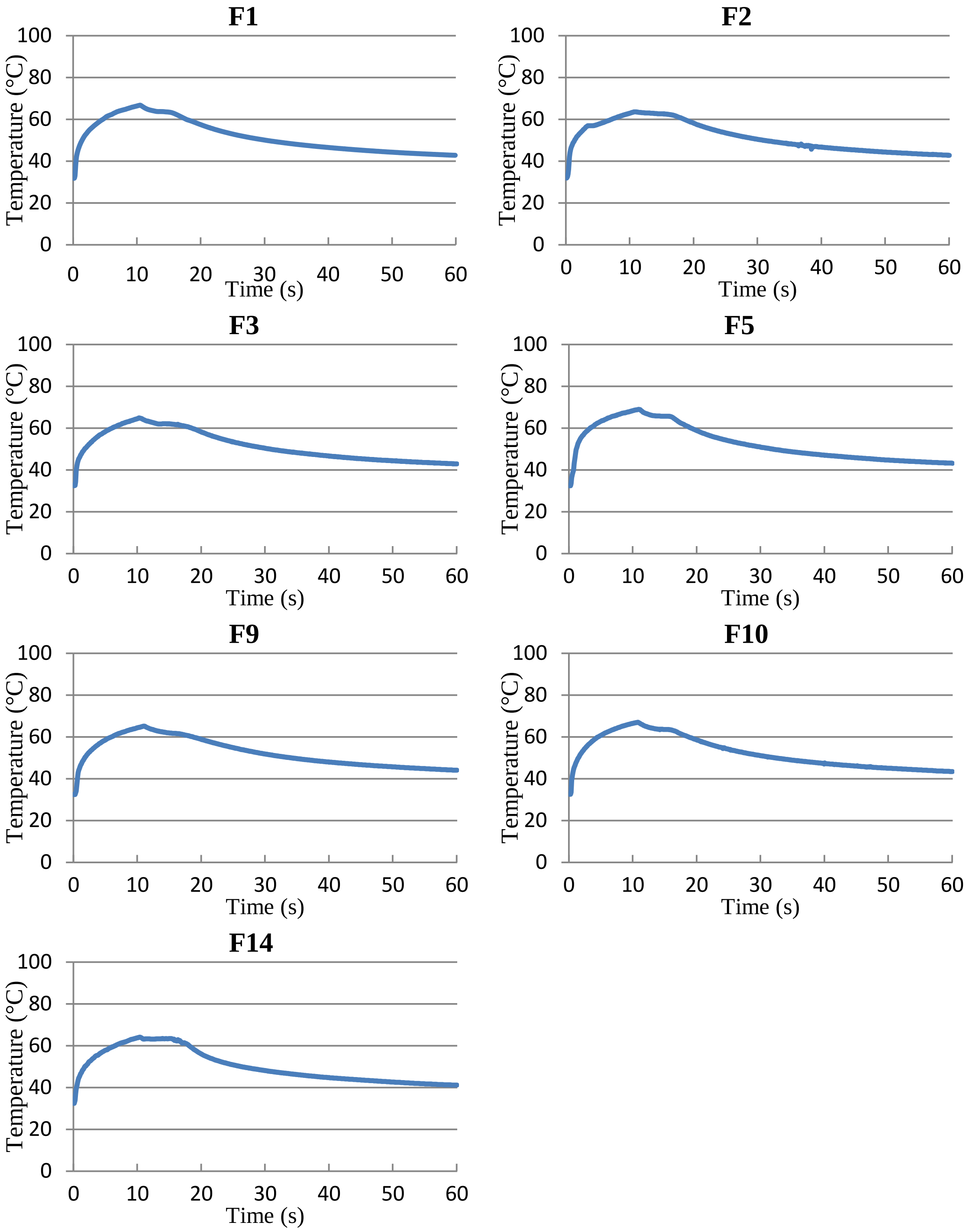


Figure 4.27 Temperature rise over time of single layers during hot oil exposure

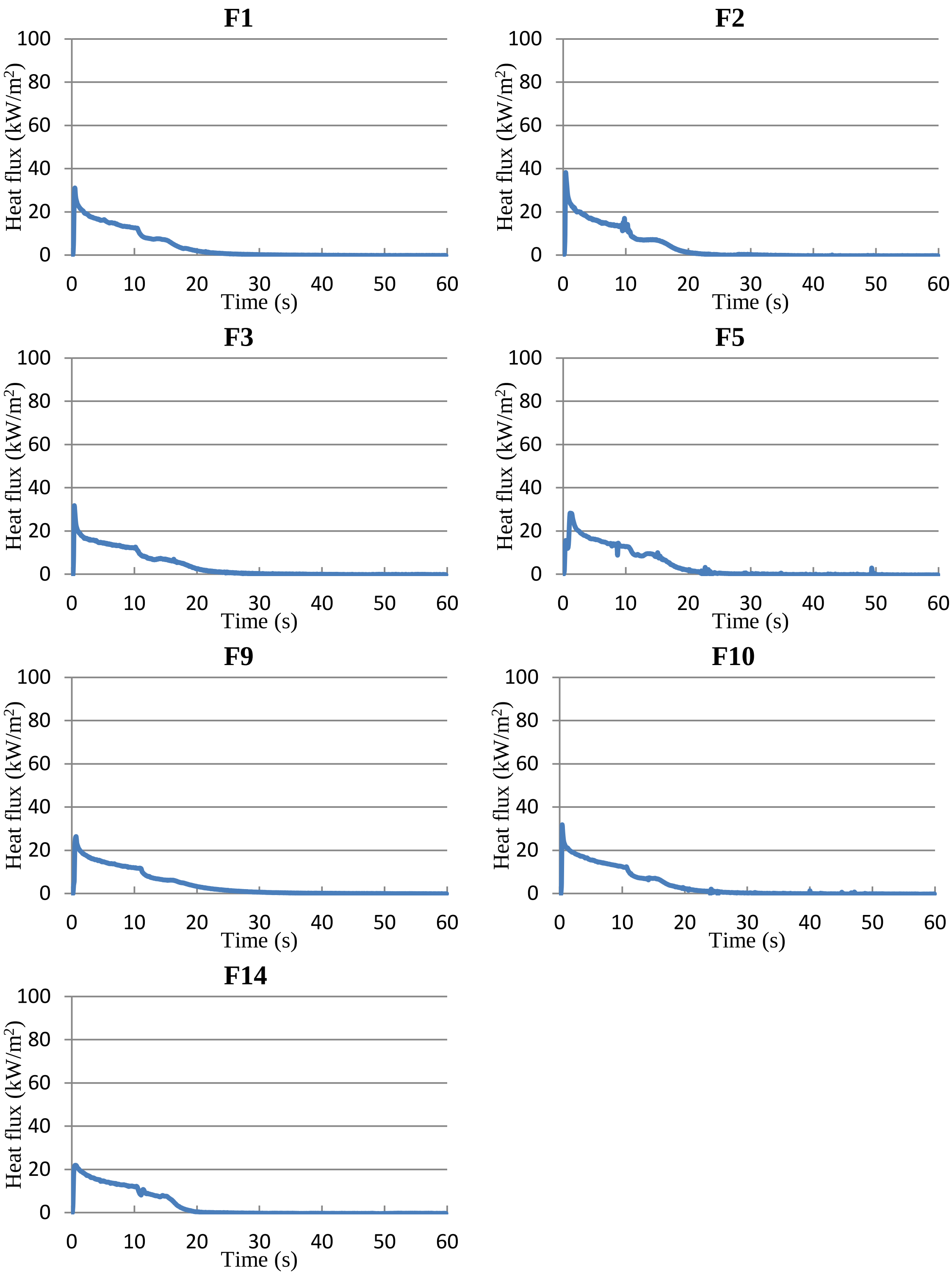


Figure 4.28 Heat flux over time of single layers during hot oil exposure

CHAPTER 5. DISCUSSION

5.1 Thermal comfort properties of fabrics used in chefs' uniforms

Effect of fabric systems on thermal comfort

Many parameters are involved in thermal comfort of fabrics, including air permeability, thermal and water vapour resistance, liquid water transport characteristics, and wicking properties (Gibson, 1993; Rossi, 2005; Xu, McQueen, Strickfaden, Aslund, & Batcheller, 2012; Yoon & Buckley, 1984). In the current research air permeability and thermal resistance of different fabric systems, as well as water vapour diffusion resistance for single-layered fabrics were all measured to characterise the thermal comfort of fabrics used in current chefs' uniforms.

Fabric structure had a considerable influence on air permeability, thermal resistance, and water-vapour resistance. The PU coating on the apron F14 fabric made this fabric impermeable, which resulted in F14 having an air permeability of effectively zero. Although F14 did not differ from the other fabrics in thermal resistance, it did differ significantly in water-vapour resistance due to the PU coating, which made F14 not only impermeable to air but also impeded transmission of water vapour. As a result, F14 would be the least thermally comfortable to wear as it creates a barrier to both water vapour and air. However, since the apron only covers the front of the body it may not noticeably influence perceived thermal comfort during use in a kitchen environment. The apron is most likely intended to protect the wearer's clothing from food-borne soils, but by its impermeable nature may also offer some protection against hot liquid splashes and steam.

It is interesting that the lightweight fabrics used in chefs' garments exhibited lower air permeability than the heavier weight fabrics of the same fibre composition (e.g., F2: 193g/m^2, 6.49 cm^3/cm^2/s compared with F3: 261 g/m^2, 7.81cm^3/cm^2/s. Plots of air permeability against fabric physical properties such as fabric count, mass/unit area, thickness and density are shown in Figure 5.1. The F5 fabric had the highest fabric count (105 yarns/cm) (Figure 5.1a) among all the fabrics as it had the tightest woven structure. This would have contributed to it having the lowest air permeability (2.59 cm^3/cm^2/s) among all the woven non-coated fabrics.

The fibre content of fabrics may also have contributed to differences in air permeability (Havlova, 2013). The air permeability of the two 100% cotton fabrics (F5 and F9) was lower than the 65% polyester/ 35% cotton blend fabrics (F2 and F3) (Figure 5.1). The polyester fibres in the blend fabric may have contributed to smoother, more closely packed fibres and lead to larger pore sizes in-between the yarns (Yoon & Buckley, 1984) resulting in higher air permeability.

All fabric combinations covered by the waterproof F14 apron fabric ended up having an air permeability of effectively zero regardless of the fabric type or number of layers underneath. As previously discussed, this was because the F14 apron blocked the airflow of the fabric systems. Layering with an F10 apron fabric reduced air permeability compared to fabrics without this apron layer as the F10 acted as an extra layer in the fabric system thereby creating more resistance to airflow through the fabric system.

Thermal resistance of fabrics has been found to be mostly determined by the thickness of fabric systems and the stagnant air trapped inside the system (Fourt & Hollies, 1970; Song, 2007; Wen, Song, & Ducan, 2012; Yoon &

Buckley, 1984). Although the fabrics selected for this research differed in fabric thickness from 0.18 mm to 0.79 mm, thermal resistance was not found to differ among any of the fabrics. However, F14 apron had much higher water vapour resistance due to its PU coating. It is also worth noting that F14 enhanced the thermal resistance of single-layered fabrics compared to single-layered fabrics layered with the F10 apron fabric. This may be attributed to 1) the increase in thickness due to layering; and 2) more dead air trapped in between F14 and single layers. As the thickness of F10 (0.74 mm) was much larger than that of F14 (0.18 mm), the second reason would explain the much larger increase in thermal resistance. The dead air trapped between F14 fabric and the underlying fabric is due to the low air permeability of F14 trapping more dead air within the fabric system which provides greater insulating air layers. This finding was supported by the theory from Fourt and Hollies (1970) about thermal resistance and insulation for fabrics.

Fabric layers created more resistance to air passage and hence decreased the air permeability. This is the reason why the four-layered fabric with F10, which was essentially five layers of fabrics, had the lowest air permeability among all permeable fabric combinations. By increasing of the number of layers, the effective thickness of the fabric system increases and the amount of stagnant air increased as well. Therefore, higher levels of thermal resistance were measured.

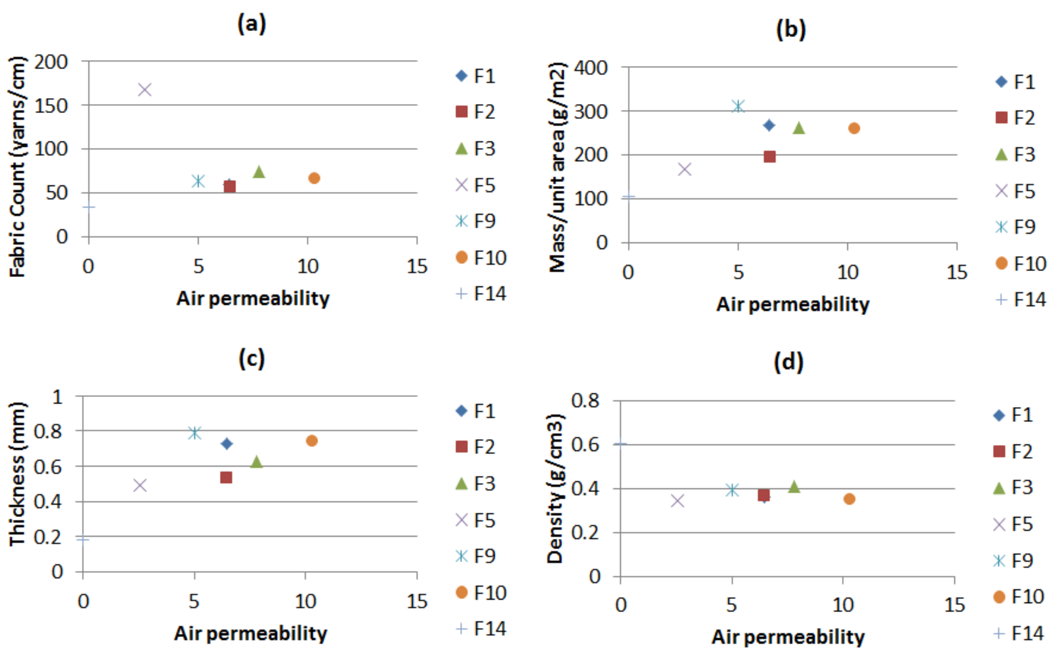


Figure 5.1 Relationship between air permeability and physical properties of fabrics.

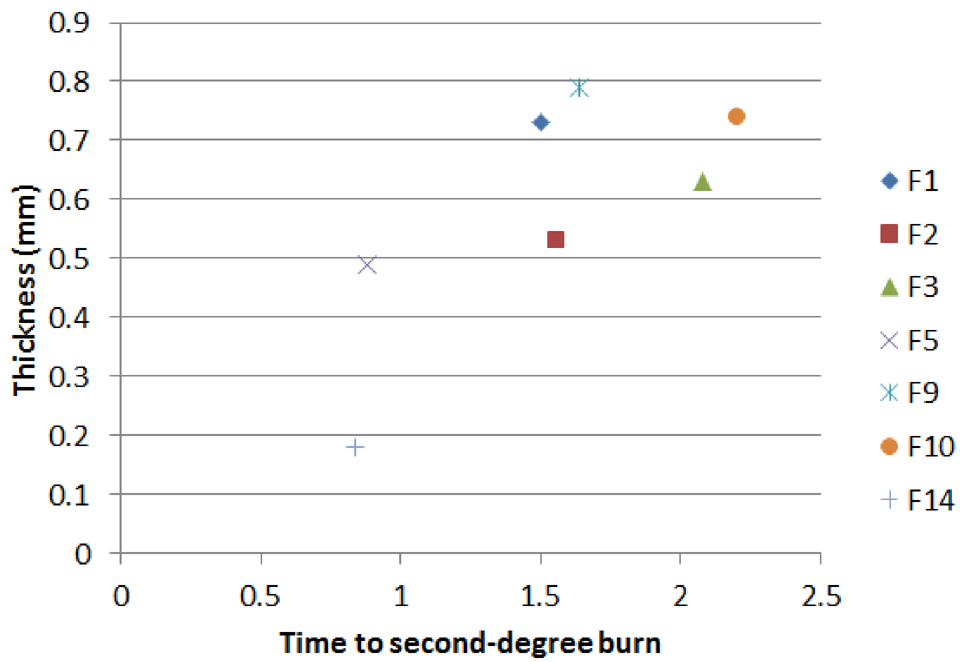


Figure 5.2 Relationship between time to second-degree burn and thickness of fabrics.

5.2 Thermal protection afforded by fabrics used in chefs' uniforms

Effect of fabrics systems on thermal protection

5.2.1 *Ease of ignition*

Ease of ignition is one of the most critical characteristics in determining the flammability of fabrics (Reeves & Hammons, 1980). The density, thermoplasticity, and chemical nature of the fibres from which the fabric is constructed are critical for the burning behaviour of textiles (Backer, Tesoro, Toong, & Moussa, 2003; Collier, Bide, & Tortora, 2009; Health Canada, 2009). The ignition phenomenon involves the complex processes of heat transfer, thermal degradation, fluid mechanics and chemical kinetics (Backer et al., 2003). In the current research, the selected fabrics were exposed to flames approaching from the surface and bottom respectively.

Among single-layered fabrics, 65%/35% polyester/cotton F3 fabric with the thickness of 0.63 mm performed much better, exhibiting a longer time to ignition, than the F2 fabric of the same fibre composition with a lower thickness of 0.53 mm. In addition, for the 100% cotton fabrics the thicker F9 fabric performed much better than the thinner F5 fabric. This indicated a better performance of a thicker fabric, which is in agreement that lighter fabrics, of the same fibre composition and finishing treatment, burn more rapidly than heavier fabrics (Weaver, 1976). Table 3.1 shows that the cotton/polyester blend F3 was denser than F2 and the cotton F9 fabric was denser than F5. A denser fabric is more resistant to ignition than a less dense bulky fabric made of the same material (Health Canada, 2009). This also explains why F3 and F9 fabrics took longer to ignite than F2 and F5 fabrics. The orientation of fabrics against the flame (e.g., surface ignition or bottom edge ignition) significantly influenced the ease of ignition of fabrics. In other research, the fabric surface has been shown to take longer to ignite than the edge of the fabric (Reeves & Hammons, 1980). The results presented in Table 4.14, show this same trend, as the bottom edge of the fabric would ignite more rapidly than the surface. Consequently, flames catching the bottom edge of a garment (e.g., hem and cuff) is much more hazardous than a flame which would be exposed to the surface of the fabric of a garment.

Different fibres react differently towards flames. For example, synthetic fibres such as nylon and polyester are thermoplastic, and melt and curl away from the flame. Because of the lightweight and flammable properties of nylon, the F14 apron fabric ignited rapidly and burned more intensely with dripping and melting occurring. Cellulosic fibres (e.g., cotton and rayon) are not thermoplastic so they do not melt; however, tend to be more susceptible to ignition. Blends of thermoplastic and non-thermoplastic fibres (e.g., cotton/polyester blends) tend to perform more like non-thermoplastics because the non-melting cotton can keep the molten polyester from withdrawing from the flame (Collier et al., 2009). As displayed in Table 4.14, this was not detectable during the ignition of the FR cotton F1 fabric due to its inherent flame retardant property, subsequently, the F1 fabric self-extinguished after being withdrawn from the flame. This is a desirable properties of fabrics used in chefs' uniforms since flammable fabrics pose a potential safety hazard and could turn into a dangerous fire source. As a result, precaution needs to be taken when wearing flammable fabrics in the kitchen and FR cotton F1 is recommended to be used in an environment which presents flame hazards.

The overall performance of simulated cuffs of chefs' uniform against flames approaching from the bottom edge was better than that of single-layered fabrics because the simulated cuffs were made of four layers of fabrics stitched together. This might be attributed to the denser structure of layered fabric systems and which need a longer time to ignite (Backer et al., 2003).

5.2.2 *Hot surface contact*

An important property for fabrics used in chefs' uniform is their ability to insulate against conductive heat transfer, thus providing protection against a burn injury in the case of accidental direct contact with a hot surface (e.g., oven or stove). It was concluded in the research by Barker et al. (1998) that hot surface temperature, contact pressure, fabric properties, and moisture content are all factors that determine the thermal protective performance of fabrics against hot surfaces. The protection time was reduced exponentially with surface temperature. Applied pressure increased the rate of heat transfer by increasing contact between the fabric and hot surface, reducing the effective thickness of compressible fabrics. Heat transfer from hot surfaces to fabrics happens by direct conduction, together with infrared radiation into the pores of the fabric structure. The extent of contribution of individual heat transfer mechanism is highly dependent on fibre composition and fabric construction (Barker et al., 1988).

In the current study, overall results showed that thicker fabrics took longer to reach second-degree burn against a hot surface at 200±3°C than thinner fabrics (Figure 5.2). Fabrics composed of 65% polyester/35% cotton, such as F3 (thickness: 0.63 mm), performed better than F2 (thickness: 0.53 mm); and chefs' uniform fabrics composed of 100% cotton, F9 (thickness: 0.79 mm) performed better than F5 (thickness: 0.49 mm) (Figure 5.2). This is in agreement with other research that protective insulation is directly correlated with thickness (Barker et al., 1988). When comparing F9 and F10 (similar thickness), the fibre component may have made a difference in time to second-degree burn. Under dry conditions, the thermal conductivity of polyester is reported as 0.084 $W \cdot m/m^2 \cdot °C$, which is slightly higher than that of cotton (0.071-0.073 $W \cdot m/m^2 \cdot °C$) (Collier et al., 2009). With the increase of thermal conductivity, thermal insulation decreases. However, the protective insulation against hot surface decreases as the moisture contained by the fabric increases (Barker et al., 1988). Cotton also has a higher moisture regain than polyester (McQueen, Laing, Delahunty, Brooks, & Niven, 2008). This might explain why the polyester/cotton blend F10 fabric exhibited better performance towards hot surface than the 100% cotton F9 fabric. The time to second-degree burn of the FR cotton F1 fabric and 100% cotton F9 fabric were the same. This was in agreement with the result that flame retardant finishing does not influence the performance of fabrics against hot surface according to Barker et al (1998).

The evident shrinkage of F14 fabric might be one of the dominant factors contributing to the immediate second-degree burn within 0.84 seconds. In hot surface contact exposure, shrinkage and degradation have been reported as being detrimental to insulation (Barker et al., 1988). The shrinkage of F14 may have reduced the effective thickness, therefore enhancing the heat transfer by compacting fibre and increasing solid conduction (Barker et al., 1988). Apart from the shrinkage, the thickness of F14 was only 0.18 mm, the thinnest among all the fabrics. Both factors contributed to the poor thermal protective performance against hot surface contact of F14. This will also explain why the increase in time to second-degree burn of single-layered fabrics covered by F10 was more than that of single-layered fabrics covered by F14. Accordingly, apron F10 provided better protection than F14 against hot surface contact in the case of single-layered fabrics with aprons. Among the other single-layered fabrics with differences in fabric thickness and fibre compositions, it is hard to determine which factor dominated the time to second-degree burn. According to Figure 5.2, it was difficult to find the relationship between the thickness and the time to second-degree burn.

In the cases of layering apron F14 and white fabrics (e.g., F3, F5 and F9), evident transferring of black colour from F14 to the other fabrics. This could be an indication of thermal degradation or pyrolysis of F14 (nylon coated PU) or the transferring of dyes on F14 against hot surface at 200°C. As a class, PU does not break down below 246 °C and nylon has a crystalline melting temperature starting at 185 °C (Beyler & Hirschler, 1988). Therefore, there is a good chance that the dye transferred during the hot surface contact exposure.

The temperature for 1% thermal decomposition of cotton is 215 °C (Beyler & Hirschler, 1988). Muralidhara and Sreenivasan (2010) found out by using Differential Thermogravimetric Analysis that the onset of degradation of polyester, cotton and 45% polyester/55% cotton blend fabrics were 410 °C, 310 °C and 365 °C, respectively (Muralidhara & Sreenivasan, 2010). Hence, there was no thermal degradation of the cotton and polyester/cotton blend fabrics in the current research since the exposure temperature was 200 ± 3°C.

As expected, with the increasing of layers, time to second-degree burn increased proportionally. With the same fibre components, four-layered F3 with F10 had the longest time to second-degree burn because of the larger thickness compared to F2 fabric systems. Overall, the results showed that F3 fabric systems performed better than F2 fabric systems, which could also be attributed to the higher thickness of the F3 fabric systems.

5.2.3 *Steam*

The water vapour diffusion and insulation of fabric systems are crucial to thermal protective performance against low pressure steam (Ackerman et al., 2012; Keiser, 2007; Murtaza, 2012; Rossi et al., 2004) During the steam exposure test, specimens were placed in between the PTFE restraint and sensor and support, which were covered by the aluminum cup (Figure 5.3). Therefore, although the interaction between specimens and the steam jet during the tests was not observable, observations were made concerning the physical changes of specimens after the tests and the flow of the steam during the tests. This is very important for understanding the protective performance of fabrics against hot steam exposure.

Except for F14, all the single-layered fabrics were completely soaked by the steam condensation after the tests. As they were constructed with either 100% cotton (i.e., F1, F5 and F9) or 65%/35% polyester/cotton blend (i.e., F2 and F3) they were highly water absorbent. Therefore, due to the permeability and low resistance of the fabrics against pressurized steam, time to second-degree burn and absorbed energy did not differ among the fabrics. The fact that F14 did not end up being soaked by the steam was attributed to the material and construction of this fabric (i.e., nylon coated with PU). Although it was waterproof and had with higher resistance against steam, F14 was not strong enough to resist the penetration of low-pressure steam (10Psi). Hence, the protective performance of the single-layered F14 was not better than that of the other six fabrics. Therefore, single-layered fabrics provided very little thermal protection against low-pressure steam jet.

F14 had a more distinct effect on thermal protection than F10 against low-pressure steam when combined with other fabrics (Figure 4.12). Rossi et al. (2004) concluded that impermeable (waterproof) fabrics normally provide better protection against hot steam compared to permeable or semi-permeable ones. This is in agreement with the findings from the research conducted by Ackerman et al (2011) and Murtaza (2012). In the research herein, single-layered fabrics covered by the apron F14 fabric exhibited much lower absorbed energy (M=305 kJ/m^2) than single-layered fabrics alone and single-layered fabrics covered by F10 (M=471 kJ/m^2) (Figure 4.13). This might be due to the stronger resistance of F14 against steam penetration and the observation that the insulation layer underneath absorbed the condensed water, which penetrated the fabric. Therefore, this fabric system reduced the direct condensation of steam on the skin simulate sensor and as a result the transfer of heat from the steam jet to the sensor was lower. F10 as an apron provided an extra layer of fabric but not necessarily any additional protection because of its high air permeability while allowed the steam to directly penetrate.

For the multiple-layered fabric systems, excluding fabric systems layered with F14, the fabric specimens were wetted to differing extents. For example, four layers of F3 were only soaked on the first layer; the second and third layer were only damp to some extent. The greater thickness of F3, and its ability to absorb more condensed steam with increasing thickness; meant the fourth layer, which was closest to the sensor, was only wet in the center where the steam jet penetrated the layers. Multiple-layered systems impeded the mass transfer and hence contributed to a much lower level of absorbed energy and much longer time to second-degree burn, or even no predicted burn injuries in some cases. When it came to the fabric system combined with F14, most specimens stayed dry except for the central spot penetrated by the steam jet.

The thickness of the fabric system made a difference in the protection against steam. Heat transfer during steam exposure was critically determined by the thickness and the insulation of the certain material systems (Desruelle & Schmid, 2004; Rossi et al., 2004). In the current study, the amount of steam arriving at the skin simulant sensor was reduced tremendously by the resistance of multiple-layers of fabrics against steam penetration. Once the steam came into direct contact with the sensor, there was a sharp increase in the curve showing the temperature rise over time (Figure 4.15). The temperature rise curve of fabric systems of more layers rose more slowly and more smoothly than that of the thinner fabric systems since it required a longer time for steam to travel to the sensor through the layers. However, more layers meant more absorption of hot steam or condensed water and lead to a higher stored energy within the fabric system. The discharged thermal stored energy could also have had a significant influence on the time to second-degree burn and amount of absorbed energy, subsequently slowing down the cooling process after exposure. This explains why during the cooling period, the temperature rise over time curve of multiple-layered fabric systems presented a more gradual decline compared to that of single-layered fabrics.

5.2.4 *Hot liquids*

The ability of a fabric system to resist penetration by liquids is important for thermal protection against hot liquids (Jalbani et al., 2012; Lu, Song, Ackerman, et al., 2012; Murtaza, 2012). In Figure 5.3, heat and mass transfer during hot liquids exposure is depicted. During exposure of permeable fabrics to

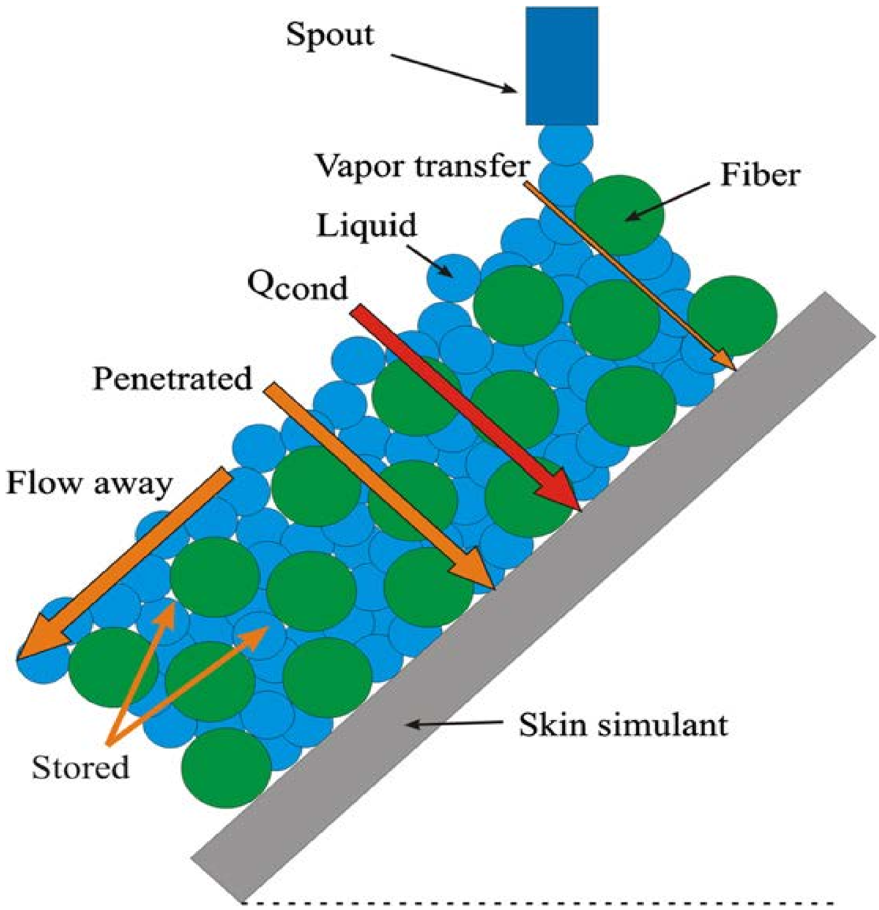


Figure 5.3 Heat and mass transfer in fabric during hot liquid exposure (Lu, Song, Ackerman, et al., 2012)

hot water and hot oil exposure to permeable fabrics, most of the liquid ran off the surface of the fabric and showed a flow pattern related to the fabric surface properties, fabric structure and the properties of the liquids Some of the liquids were absorbed by the fabrics; however, the remain of the liquid penetrated the fabrics to come into contact with skin simulant sensor. Resistance to liquids is related to several physical properties of fabric systems, such as fabric construction, air permeability, and water vapour diffusion, surface properties (Jalbani et al., 2012; Lu, Song, & Li, 2012). As an impermeable fabric, F14 blocked the penetration of water and oil. Consequently, for F14 fabrics following exposure to hot liquids no water or oil came into direct contact with the sensor board. Therefore, in the absence of liquid penetration, conduction was the major mode of heat transfer. This contributed to the F14 fabric exhibiting the lowest absorbed energy and longest time to second-degree burn during both oil and water exposure among all the single layered fabrics. While among the other six fabrics, the mass transfer occurred directly through the permeable fabric structure, leading to more transfer of heat to the sensor.

All the single-layered fabrics, except for F14 and F2 fabrics quickly became saturated with soaked by water during ten seconds of water exposure as the water wicked very rapidly through the fabrics. As plain woven fabric structures have been found to contribute to poorer wicking rates when compared to twill fabrics (Babu, Ramakrishnan, Subramanian, & Kantha, 2012), the plain weave structure may account for the single-layered F2 fabric not becoming saturated during the ten seconds of hot water exposure. However, this did not give F2 fabric better performance compared to other single-layered fabrics since penetration through the fabric occurred where the hot water flowed and contribute to the heat transfer to the sensor. In the case of oil exposure, the saturated area of all fabrics was confined to the flow pattern of the oil, since oil did not wick beyond the contact area or spread out on the fabrics.

Testing with hot water produced more rapid second-degree burn prediction than hot oil. This may be attributed to: 1) the specific heat of water (4.17 kJ/(kg·K)) is higher than that of oil (2.35 kJ/(kg·K)) (Table 3.2). The ability of water to store energy is approximately one and half times higher than that of oil per unit mass; 2) the thermal conductivity of oil (0.23 W/(m·K)) is lower than that of water (0.67 W/(m·K)); and 3) the lower viscosity of water, which made it much easier for water to penetrate the fabrics compared to oil (Lu, Song, Ackerman, et al., 2012). Therefore, even with the same experimental settings (temperature at 85 °C and flow rate at 100 mL/s) on single-layered fabrics, the heat transferred from the water to the sensor through the fabric systems was greater than for oil. This explained why single layered fabrics took a shorter time to reach a second-degree burn and presented a higher level of absorbed energy during hot water tests than oil splash tests.

It was expected that the absorbed energy of single-layered fabric covered by F10 would be higher than that of single-layered fabrics without F10. The reason for this was that the two layers of fabric could absorb more hot water and store more energy compared to single-layered fabrics (Gholamreza & Song, 2013; Lu, Song, & Li, 2012; Murtaza, 2012). However, single-layered fabrics took a shorter time to reach the second-degree burn criteria since it was easier for hot water to penetrate one layer of fabric than two.

With the presence of F14 in the fabric systems, during hot water exposure conduction was the dominate mode of heat transfer since it blocked the water penetration and therefore eliminated mass transfer. With a layer of insulation underneath the apron F14 fabric, the level of absorbed energy was significantly reduced and did not cause any second-degree burns during the 60 seconds recording time. This shows why thickness and thermal conductivity of fabrics are important for improved thermal protective performance of fabric systems against hot water when the fabric system is covered by a water resistant barrier (Jalbani et al., 2012; Murtaza, 2012).

As mentioned previously, because of the poor wicking property of F2, by increasing the number of layers, the water transmission through the layers was much slower compared to F3. Consequently, at the end of the test, the layered F3 fabric system absorbed considerably more hot water than F2. As it has been pointed out that wet garments present significantly higher heat transfer rates compared to dry garments (Mell & Lawson, 2000) and also the rate of heat transfer increases with the presence of water in multiple-layered fabric systems thereby influencing the overall thermal conductivity and heat capacity of the fabric system Keiser (2008). It is therefore likely that while cooling, the heat dissipation of the F3 fabric system was not as efficient as that of F2. As a result, it kept transmitting heat to the sensor, contributing to a higher absorbed energy level eventually. This might possibly explain why all the multiple-layered F2 fabrics with and without F10 apron performed better than the F3 fabric systems, despite the fact that F2 was lower in weight and thickness than F3. It was unexpected that F2 was more protective than F3 considering that a heavier weight and thicker fabric should be more protective.

5.3 Recommendations for improved protection by fabrics used in chefs' uniforms

The majority of kitchen workers are exposed to various kinds of thermal hazards. Therefore, the chefs' uniform is supposed to be treated as a PPE. A chefs' uniform should be designed primarily to prevent skin burn injuries. Based on the findings from this research, recommendations for improving the thermal comfort and thermal protective performance of fabrics used in current chefs' uniforms against thermal hazards are:

Flame resistance is a desirable property for chefs' uniforms. Therefore, applying flame retardant fabrics in certain parts of the uniform (e.g., cuff and hem) is recommended. However, as the FR fabric evaluated in the current study was protective only against flame ignition but not against steam or hot water; therefore, it is recommended that protection against hot water and steam will be improved by incorporating impermeable or semipermeable layers at vulnerable spots (e.g., arms and breast areas).

In the current study the impermeable F14 apron fabric provided an excellent level of protection towards hot water and steam but exhibited a high level of flammability. Modified fabrics could utilize flame retardant cotton or lightweight Nomex® with waterproof coatings, providing protection against both flames and hot liquid splashes at the same time. Alternatively, the concept of a two-level protection design used in protective clothing in the oil and gas industry (Crown & Dale, 2005) could be adopted in protective clothing used within kitchens. When the chefs are handling hot equipment or standing by a deep fryer, a separate coverall besides chefs' jackets could be used. This coverall ideally should possess the properties of flame retardancy, be water resistant and provide moisture management.

Thermal comfort issues are equally important due to the incidents of heat stroke and heat exhaustion within the kitchen environment. Using thinner fabrics which have moisture management properties for chefs' uniforms would minimize the thermal stress encountered by kitchen workers is highly recommended to enhance thermal comfort.

It is important to note that as all the fabrics evaluated in the research herein are fabrics used in current chefs' uniforms, the values obtained for air permeability, thermal resistance, and water-vapour resistance should provide the baseline for newly developed fabrics incorporating protective properties. Therefore, a garment which provides protection against hot liquid should not add thermo-physiological burdens more than the current chefs' uniforms.

CHAPTER 6. SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS FOR FUTURE WORK

6.1 Summary

Workers in the culinary industry are commonly exposed to thermal hazards including high heat and humidity, flames, hot surfaces, steam and hot liquids. Whether the current chefs' uniforms could provide an adequate level of protection against these thermal hazards is questionable. The first purpose of this research was to evaluate the thermal comfort of fabrics used in chefs' uniforms by assessing air permeability, thermal resistance and water vapour resistance. The second purpose was to evaluate the thermal protective performance of the fabrics used in chefs' uniform, such as examining the flammability of the chefs' uniform fabrics, determining time to second-degree burn injury and absorbed energy of different fabric systems when exposed to hot surfaces, hot liquid splashes and steam.

Among single-layered fabrics used in chefs' jackets, the FR cotton (F1) provided excellent resistance to ignition from flame approaching from both the surface and bottom edge of the fabric, however, it did not perform differently from the other fabrics for hot surface contact, steam and liquids. The waterproof apron (F14) provided adequate protection against hot liquids and steam while exhibiting high flammability and poor performance towards hot surface contact. The polyester/cotton blend apron could provide one extra layer of protection to hot surface contact but not necessarily provide effective protection against hot water. Overall, with the increased number of layers in the fabric system, the thermal protection level increased but the thermo-physiological burden increased as well.

6.2 Conclusions

The conclusions drawn from the current research apply only to the particular fabrics or similar fabrics used in chefs' uniforms and test conditions used in the current research. The following conclusions can be made:

1. Among single-layered fabrics used in chefs' uniforms, the thermal resistance and water-vapour resistance were maintained at the same level regardless of the differences in fabric construction and physical properties.

2. With the increase in the number of layers, thermal resistance of the fabric systems increased proportionally. However, this would therefore contribute to a higher thermo-physiological burden on workers within commercial kitchen.

3. The inclusion of the waterproof apron F14 in the fabric systems with single-layered fabrics contributed to higher thermal resistance. However, F14 would be the least thermally comfortable to wear as it creates a barrier for water vapour transmission and does not allow any air to pass through. However, since the apron only covers the front of the body it may not noticeably influence perceived thermal comfort during use in the kitchen environment.

4. 100% cotton fabrics react differently than polyester/cotton blend fabrics towards flames but the time to ignite is similar among single-layered fabrics used in chefs' jackets. Apron F14 constructed of PU coated nylon was the most rapid to catch fire and therefore could pose a potential fire risk source. Chefs' uniforms without flame resistant properties could be

potential combustibles when exposed to different types of heat sources within kitchens. The overall performance of simulated cuffs of chefs' uniform against flames approaching from the bottom edge was better than that of single-layered fabrics.

5. This research provides insight into the relationship between fabric properties and conductive insulation of fabric at 200 °C. Consistent with research in this field the thickness of the fabric system is a critical factor regarding the thermal protective performance against hot surface exposure. With the increasing of the layers, the effective thickness of the fabric system increased and then thermal protection increased.

6. Fabric systems with aprons could provide better protection under the condition of steam exposure at 10 Psi, 108±5 °C than a fabric system without aprons. The waterproof apron F14, as a liquid barrier, provided better protection than the permeable F10 apron against steam and hot water in all cases. Better protection was provided by fabric systems with more layers against steam exposure. This is in agreement with previous research in steam and hot water protection

7. Oil at 85 °C did not pose as much of a hazard as water at 85 °C due to its physical properties and behaviour when in contact with fabrics. There was some indication that fabric structure may play a role in thermal protection against hot water. With the same fibre composition, plain woven fabrics may exhibit better thermal protection against hot water than twill fabrics due to poorer wicking ability.

6.3 Recommendations for future work

The following recommendations for future work are made based on the findings and limitations in the current study:

1. A modification to the hot liquid apparatus may be considered in order to simulate oil temperatures ranging from 175-190°C which is more typical in commercial kitchens. Canola oil at 85 °C did not pose as great a hazard compared to hot water at 85 °C and it could not differentiate among different fabric systems at such a low temperature. The improvement of the hot liquid tester could be done through changing some elements on the tester which are not heat resistant, such as the plastic container and the circulating pipe. If this is achievable, different fabric systems used in the research design for the hot water test could be adopted to evaluate the thermal protective performance against hot oil at a higher temperature.

2. The results and indications from the current research are confined to bench scale tests only at the fabric level. Full scale tests using the hot liquids spray manikin developed by researchers at the University of Alberta could be used to further study the thermal protective performance of current chefs' uniform against large amount of water splashes.

3. Body mapping which is currently in use in exercise and sportswear could be used in the garment design of chefs' uniforms. Based on the conclusions from this research, fabrics incorporating flame retardancy, steam and water resistance should be applied to vulnerable parts of the body, such as the arms and chest area. Moisture management fabrics

should be applied to the back and axillary area of the body to optimize the heat and sweat dissipation in the hot and humid kitchen environment.

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