University of Alberta

Development of a Test Device and Procedure to Measure Heat Transfer through Fabrics when Exposed to Pressurized Steam.

by

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ABSTRACT

Extensive use of pressurized steam in oil and gas sectors has led to incidents where workers were seriously injured. In this study a test device and procedure to measure heat transfer through fabrics during steam exposure were developed. Several factors were considered while designing the test device to simulate the work site conditions. Fabrics were exposed to steam at two distances (50mm and 100mm) and two pressures (207 kPa and 69 kPa). Theoretical considerations included heat and mass transfer, fabric structure and relationships to performance properties of fabrics.

The test device and procedure differentiated well among fabrics and between conditions. Maximum heat transfer was observed at 30 psi and 50mm distance in all fabrics. It was found that laminated and coated fabrics performed better than fabrics without such treatment. Hence, fabrics with high water permeability showed poor resistance to heat and moisture transfer compared to semi permeable and impermeable ones.

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Chapter 1

INTRODUCTION

Within many industrial sectors worker safety issues have risen for individuals working in high-risk environments, especially those with the potential of exposure to thermal hazards. The oil and gas sector is one with potential danger from thermal hazards. Although workers in these industries wear flame resistant (FR) protective clothing to prevent skin burn injuries from fire breakouts, steam is another substantial hazard to which workers are vulnerable. This element can pose hazards in those industries where steam is a source of power generation or is used for several different applications. At Imperial Oil Resources' facility in Cold Lake, Alberta, high-pressure steam is pumped into the ground to heat the oil and make it less viscous as the nature of oil present underground in those areas is "heavy" (in other words, too thick and viscous to flow on its own). Thus, steam injection makes the oil more mobile and enables it to flow into wells where it can be produced.

Steam is widely used in industrial applications in the oil and gas industries. Incidents have been documented in which workers were seriously injured by steam and/or hot water condensate (Fennel, 2003). Even though government agencies such as Alberta Occupational Health and Safety and standard developers such as the Canadian General Standards Board (CGSB), the American Society for Testing and Materials (ASTM) and the International Standards Organisation (ISO) work to create safe environments for those working in hazardous, high-risk environments in industry, there is no performance standard or standard test method for evaluating FR protective clothing against the hazards of steam. This has brought into consideration questions regarding the level of protection the existing flame resistant clothing can provide against steam, the need for materials specifically designed to protect against steam, and appropriate methods to evaluate materials intended for this application.

Statement of the Problem

The potential danger posed by steam is illustrated in the following comment:

> "The steam that drives turbines in electrical power generating plants is an invisible gas that can be four times as hot and exert several hundred times force [compared to steam coming out of a tea kettle]. It can come out with a wail, not a whistle, if its escape hole is the right size and shape. But usually, its victims don't know it's there until it hits them. And when it hits it can kill." (Dupont Magazine, 1995).

This article refers to a steam pressure of 5700 kPa (825 psi) and a temperature of 500° C. Workers in the oil and gas industries may be exposed to steam-line bursts and leaks while repairing those lines or during routine service. The pressure in the lines is not as high as 5700 kPa, but it certainly can be hazardous. Since these workers are working in a high-risk environment, and because they come in direct contact with steam and hot water condensate, determining the performance of garment systems under similar conditions is of paramount importance. Steam has higher energy content per gram than hot water at the same temperature; this energy can easily penetrate the clothing system and seriously damage skin tissue. Skin burn injury and heat tolerance in humans depend on complex interaction of physical heat exchange processes and other physiological and psychological factors involved during the interactions.

Purpose and Justification

The overall purpose of this study was to develop a test device and procedure to measure heat transfer through fabric systems exposed to steam and to validate these by evaluating the performance of some existing FR fabrics. The objectives of this study were accomplished in two phases. In the first phase, a test device and procedure to evaluate the performance of fabrics against the hazards of steam was developed. In the second phase the test device was utilized to evaluate selected flame resistant fabrics. Physical properties of fabrics were also measured and related to the steam performance in phase II.

There is no existing performance standard for evaluating FR protective clothing against steam. Existing FR protective fabrics are not effective in preventing steam penetration as revealed through both field experience and preliminary experimentation. This is especially true for fabric systems without a vapour barrier. Understanding steam penetration in a garment system is of extreme importance particularly for those who are working in industries where steam is used in several different applications. There have been incidents documented by the Canadian Petroleum Safety Council (now merged into ENFORM) where workers have been injured due to steam exposure, including one fatality (CPSC, 2004). By examining the rate of heat and moisture transfer through fabrics, and by understanding the mechanisms of heat and moisture transfer during steam exposure, differences among FR clothing materials can be evaluated and improved clothing systems can be developed. Thus, this study will help protect individual workers from the hazards of steam and will help to better understand different factors influencing steam permeability of fabrics.

Objectives and Hypotheses

The specific objectives of this study were:

1. To develop a test device to measure heat transfer through a fabric while exposing it to steam under the conditions that are typical in the oil and gas industry.
2. To validate the test device and procedure by evaluating the relative protective performance of some existing FR fabrics against steam.
3. To determine if steam protection is related to:
    a. Fabric characteristics like thickness, mass and fabric structure, or
    b. Other performance properties of the fabrics such as water vapour permeability, air permeability, thermal insulation and total heat loss.

To meet objective 2, the following null hypotheses were tested:

H_o1 - There are no significant differences among fabrics in heat transfer through the fabrics when subjected to steam exposure.

H_o2 - The distance between the nozzle and fabric surface has no significant effect on heat transfer through fabrics when exposed to steam.

H_o3 - Steam pressure has no significant effect on the rate of heat transfer through fabrics.

Limitations and Delimitations

Limitations of this research include:

1. During the experiments maximum steam pressure achievable was around 350 kPa (50 psi) in the main steam pipeline; the pressure was maintained at 207 kPa (30 psi) at the steam outlet (nozzle).

2. Steam and hot water condensate were used, as dry steam was not available.

3. Because there was no controlled environment where pressurized steam was available, the atmospheric conditions of the test room were recorded rather than controlled during the experiments.

The delimitations of this research include:

1. This study was limited to FR fabrics. Only three fabrics were evaluated in the main experiment. This factor contributed to difficulties in fulfilling objective 3, as determining meaningful relationships between heat transfer and fabric properties was unlikely.

2. Although data from all sensors are provided in heat transfer plots, only data from the main sensor are discussed in detail.

Definitions

Heat Transfer

Heat transfer refers to the transfer of energy from one environment/object to another in response to a temperature difference. There will be exchange of energy between the two environments until they reach an equilibrium state. Heat always flows from a high temperature zone to a low temperature zone. Energy in the form of heat can be transmitted in three ways: by conduction, convection and radiation.

Heat Flux. The thermal intensity indicated by the amount of energy transmitted per unit area per unit time. Heat flux is expressed in kW/m^2 (CGSB, 2001, p.2).

Thermal Inertia. Thermal inertia represents resistance of a material to temperature change and it shows the ability of a material to conduct and store heat. It is defined as $(kc\rho)^{1/2} = c\rho\,(\alpha)^{1/2}$. The term α, related to conductivity k, is known as *thermal diffusivity*, and has units of cm^2/sec; this parameter governs the rate of temperature change within a material.

It measures the ability of material to conduct thermal energy relative to its ability to store thermal energy (Incropera, 2002).

Thermal Transmittance. Time rate of unidirectional heat transfer per unit area, in the steady state, between parallel planes, per unit difference of temperature of the planes. It is also called thermal conductance and the heat transfer coefficient. It is expressed in W/m^2-K (ASTM, 1998).

Total Thermal Resistance (Rct). Reciprocal of total thermal transmittance, expressed in K-m^2/W (ASTM, 1998).

Moisture Transfer

Moisture transfer is a physical phenomenon involving movement of water in liquid or vapour form that affects thermal properties of the fabrics. The concept of moisture transfer is similar to heat transfer as the transfer is generally from a higher humidity zone to an area of lower humidity.

Evapourative heat transmission. Time rate of unidirectional evapourative heat transfer per unit area, in the steady state condition between parallel planes, per unit difference of water vapour pressure of the planes. It is expressed in W/m^2-kPa (ASTM, 1998).

Total Evapourative Resistance (Ret). Reciprocal of total evapourative heat transmittance expressed in kPa-m^2/W (ASTM, 1998).

Total Heat Loss. The amount of heat transferred through a material or a composite by the combined dry and evapourative heat exchanges under specified conditions expressed in W/m^2(ASTM, 1998).

Condensation. Condensation occurs when a vapour molecule becomes slow enough (i.e. loses energy or has lower temperature) that it can become bound to other (liquid) molecules. When this happens, the average kinetic energy of the remaining vapour molecules is slightly higher than before, so the vapour temperature has increased. In this way, condensation is a warming process. When 1 gram of water vapour condenses, about 25 kJ of energy will be released to the environment. In simple terms "condensation occurs whenever the local vapour pressure reaches saturation vapour pressure at local temperature" (Ren & Ruckman, 1999).

Chapter 2

REVIEW OF LITERATURE

In the following review, mechanisms of skin burn injuries and skin stimulant sensors will first be discussed, followed by steam penetration through fabrics, theories of heat and moisture transfer in fabrics, including the effect of condensation on heat transfer. Research addressing the effect of fabric structure and performance properties on heat and moisture transfer will be also be reviewed.

Skin Burn Injury

Human skin is highly sensitive to high heat flux situations. One of the primary objectives in the design of industrial clothing is the prevention of thermal damage to the skin. To develop new test methods for the evaluation of these kinds of fabrics one must have an understanding of the effects of thermal exposure on the skin. Stoll and Chianta (1969) reported that the rate at which injury proceeds increases logarithmically with a linear increase in skin temperature. The normal human skin temperature at the surface is 32.5°C, and thermal damage will begin when the temperature at the base of the epidermis, approximately 80 μm below the surface, is increased above 44°C. Damage to the skin is a nonlinear function of the skin temperature, and the period of time when the temperature of basal layer is greater than 44°C (Stoll & Chianta, Parsons, 1993). For example, at 50°C, the damage proceeds at 100 times the rate it would at 45°C. Stoll and Chianta further determined that at 72°C, the damage to the skin is irreparable.

Steam can be defined as the hot vapour into which water is converted when heated. Steam may condense in the air into a mist of minute liquid droplets. Steam injuries are worse than those from hot water at the same temperature, since there is additional heat generation from the steam going from a gas phase to a liquid phase.

Skin Simulant Sensors

As tests cannot be conducted directly on human skin, materials which have thermal physical properties similar to human skin are used to measure the energy absorbed. The skin simulant sensors used in this research respond to heat transfer as closely as possible to the way the human skin does. Heat transfer from a short duration high heat exposure onto the surface of the skin simulant sensor can be modeled as that for a semi-infinite solid, with constant initial temperature and thermal physical properties subjected to a constant heat flux on its surface. Temperature difference at any point can be derived analytically and has been shown as (Incropera and Dewitt, 2002):

$$T(x,t) - T_i = \frac{q}{k}\left[2\sqrt{\frac{\alpha t}{\pi}}\, e^{-\frac{x^2}{4\alpha t}} - x\,erfc\left(\frac{x}{2\sqrt{\alpha t}}\right)\right] \text{............ Eq. 1}$$

Where:

T = temperature in Kelvin

Ti = initial temperature of semi-finite solid in Kelvin

q = heat flux in W/m^2

k = thermal conductivity in W/m-K

α = thermal diffusivity (k/ ρc) in m^2/s

ρ = density in kg/m^3

c = specific heat in J/kg-C

t = time in seconds

e = 2.7183

x = distance/depth of the solid in meters

erfc = error function

Measurement at depth x=0, reduces the equation to

$$T(x,t) - T_i = \frac{2q\sqrt{t}}{\sqrt{\pi k \rho c}} \text{..............Eq. 2}$$

Thus, for a skin simulant sensor to closely simulate skin it is important that the thermal inertia (kρc) and its square root are close to that of skin. Dale, Crown, Ackerman, Leung and Rigakis (1992) described skin stimulant sensors made from "colorceran" material. The thermal physical properties of this material closely simulate human skin for the short duration of heat transfer from a flash fire.

Steam Penetration through Fabrics

Steam can easily penetrate most single layered fabrics, as there are enough spaces to allow the transfer of hot vapour. Rossi, Indelicato and Bolli (2004) analysed the transfer of steam through different types of textile layers to a sweating body, considering the relationships to specimen parameters like thickness and water vapour permeability. To simulate a sweating human arm they used a cylinder that released defined amounts of moisture and exposed it to direct steam. A laboratory apparatus was designed to assess the hot steam transfer for flat and cylindrical samples. A defined amount of water was poured into conical flask and was brought to boiling. The conical flask was closed with a cork containing two apertures. One aperture was used as a steam source and the other to avoid high-pressure generation in the flask. The steam utilized in this experiment was not under high pressure. The authors assessed the influence of different sweating rates on the heat and mass transfer using copper calorimeter sensors. A steam transfer index, the time to reach a temperature increase of 12°C (STI-12) was measured. The authors concluded that the materials which are impermeable to vapour provided better protection to hot steam than the semi-permeable ones. Transfer of energy was dependent on the water vapour permeability as well as on the thickness and thermal insulation of the specimens. The results indicated that for flat specimens, the thicker the lining material and spacer (air gap) was, the higher the STI-12 values of the specimens. For specimens tested on a cylindrical shaped body, the heat flux was measured on three different locations of the cylinder (i.e top, middle and bottom). The time to reach an increase of 12°C was much higher for the cylindrical tests as compared to the flat specimens, although this was attributed to the higher mass of the cylinder. The steam protection time was reduced for wetted samples because their thermal conductivity was higher.

Le and Ly (1994) studied the heat and mass transfer in a condensing flow of steam through an absorbing fibrous medium. The fibrous medium, a packed bed consisting of layers of textile fabric, was subjected to a flow of steam from one side to the other. This was carried out in a vertical cylinder sealed at the bottom and open to atmospheric pressure at the top. The fabric was stacked one layer on another on a perforated plate sitting just above the steam inlet; another perforated plate was placed on the top of the fabric assembly to constrain the volume of the fabric bed. Saturated steam at 100°C and 104kPa (15 psi) was utilised during the experiment. The pressure difference between the two sides of the fabric bed causes the steam to flow from bottom towards the top. Le and Ly considered convection the only mechanism to transfer heat and mass, and considered the heat transfer by radiation and conduction between fibers to be negligible. The reason convection was considered the most important mechanism of heat and mass transfer was the physical nature of the fibrous assembly, which is mainly porous. Porous assemblies such as fabrics have high air and water vapour permeability and hence the heat transfer due to conduction and radiation was ignored.

The applications of the two studies reviewed above are very different. Rossi *et al*'s study focused on firefighter's clothing and the affect of steam on their clothing systems. On the other hand, Le and Ly's study applies where textile layers (especially wool) are subjected to steaming processes at a relatively high temperature and pressure, as in pressure-decatizing of wool fabric. However, both studies are of interest as they measure heat and mass transfer through textile layers when exposed to steam and they both agreed that porous textiles facilitate heat and mass transfer.

Theories of Heat and Moisture Transfer in Fabrics

In understanding the mechanisms of steam penetration through textile materials, both heat and moisture transfer through fabrics and their coupled effect need to be understood. Although little reference was found in the literature to studies on the steam permeability of thermal protective clothing and its effects on the thermal protective properties of fabrics and fabric systems, there is a relevant body of literature in the area of comfort that will be applied to study the steam transfer phenomenon in fabrics. However, in most cases the direction of heat and moisture transfer discussed in that literature is from skin to the environment through clothing systems. Several studies of heat and mass transfer in firefighter's clothing were also reviewed and applied to this research to help understand the mechanisms of heat and moisture transfer through fabrics.

Heat transfer in porous textiles includes transfer of heat by conduction by the intervening air (fibers), convection and radiation. Liquid water and vapour transfer mechanisms include vapour diffusion in void space, moisture absorption by fibers, evapouration, and capillary effects (Li, 2001).

The transport of one constituent from a region of higher concentration to that of lower concentration is called mass transfer. When a system contains one or more components whose concentration varies from point to point, there is a natural tendency for mass to be transferred, minimizing the concentration differences within the system. The mechanism of mass transfer can be understood by drawing an analogy to heat transfer. Just as energy (heat) is transferred towards the lower temperature decreasing the temperature gradient, mass is transferred towards the lower concentration decreasing the concentration gradient. Likewise, energy (heat) transfer ceases when there is no longer a temperature difference, and mass transfer ceases when the concentration gradient is reduced to zero. Lastly, the rates of both heat and mass transfer depend on a driving potential and a resistance.

Moisture transfer in textiles encompasses both mass diffusion on a molecular level and bulk mass transport basically through the process of convection. These two distinct modes of transport, molecular mass transfer and bulk mass transfer are analogous to conduction heat transfer and convective heat transfer. The diffusion rate is given by Fick's first law of diffusion which states that the mass flux of an element per unit area is proportional to the concentration gradient (Morton & Hearle, 1975). Therefore,

$$m/A = -D\, dC/dx \text{ ....Eq. 3}$$

Where,

m/A is the mass flow per unit time per unit area ($kg/hr\text{-}m^2$)

A is the area through which mass is flowing

D is the diffusion coefficient in m^2/hr

C is the mass concentration of the component in kg/m^3

dC/dx is the spatial concentration gradient.

Heat in the form of energy is transferred between a surface and air when there is a difference in temperature or a temperature gradient. Heat is initially transferred into the air by conduction as air molecules collide with those of the surface. As the air warms, it circulates upwards via convection. Thus the transfer of heat is accomplished in a two-stage process. Air is a poor conductor of heat; it is convection that is the most efficient way of transferring energy into the air. This mechanism basically applies in understanding heat transfer from the body towards the environment.

When heat is transferred from environment towards the body through clothing, and the air gap between clothing and the body is very small, the heat transfer is basically governed by conduction. Several authors investigated the influence of air gaps on bench-top thermal protective performance tests of flame resistant fabrics. Torvi, Dale & Faulkner (1999) found that at smaller air gaps, before the natural convection is initiated, transfer is actually by thermal conduction rather than convection. Kim, Lee, Li, Corner & Paquette (2002) also investigated air gaps entrapped in protective clothing systems. Their study demonstrated that the presence of air gaps in a clothing system can prevent serious burn injuries.

Heat transfer through “moist” fabrics takes place primarily through three modes, conduction, radiation and the process of distillation (Schnieder, Hoschke & Goldsmid, 1992). Heat transfer due to radiation, although not very significant, contributes slightly to the total heat transfer. Fiber sorption properties determine the evapouration process and therefore the heat and mass transfer by vapourization of water, diffusion of water vapour, and condensation. Generally heat transfer increases with increasing fiber regain. Fohr, Couton & Treguier (2002) proposed a model to determine the occurrence of liquid in certain places in textile layers. They comment that fabrics have interfiber and interyarn pores generated by the manufacturing process; the diffusion properties of heat and water in the liquid and vapour form are determined from this network. During a dynamic process the vapour would diffuse through larger pores.

Mell and Lawson (2000) cited the NISTIR 5804 report stating that wet garments may exhibit significantly higher heat-transfer rates than dry garments, that heating and evapouration of moisture trapped in protective clothing may result in scald or steam burns, and that moisture may help to store heat energy in protective clothing. Lawson, Crown, Ackerman, & Dale (2004) investigated the effects of moisture on heat transfer through layered materials comprising clothing systems worn by wildland firefighters. They concluded that when moisture is a factor, heat transfer through thermal protective textiles differs among conditions of moisture application and among layered fabric systems. They determined that for high heat flux exposures (60 seconds), moisture in external layers decreased heat transfer through fabric systems while moisture in internal layers tended to increase it. Under low heat flux radiant exposure (100 seconds), internal moisture decreased heat transfer through the fabric systems, while the effects of external moisture were inconclusive.

Torvi and Dale (1998) modeled the thermal protective performance of several single layer FR fabrics with moisture content varying between 0% and 100%. They predicted that as the amount of moisture in fabrics increased, heat transfer would increase. When the moisture regain was close to saturation, the thermal protection was reduced. This was attributed to increased thermal conductivity of saturated fabrics. They suggested evaluating the thermal performance of clothing systems before and after exposure to a heat source. In the current study, when the heat source (steam) is taken away, the energy transfer (in the form of vapour) between the heated clothing system and the underlying skin continues and may cause (second degree) burns. Stull (2000) observed that the effect of moisture on thermal insulation varies with the kind of heat transfer, the water content of the fabric, the type of material used in construction of the fabric, and both the intensity and duration of thermal exposure.

To understand coupled heat and moisture transfer in a clothing system, Wang and Yasuda (1991) conduted mathematical simulations to predict the performance of different waterproof and breathable fabrics used in the clothing systems. Li (2001) echo's Wang and Yashuda's views that "heat and moisture transfer are two highly coupled processes". Li states that the heat transfer process is coupled with the moisture transfer processes, with phase changes such as moisture sorption/desorption and evapouration/condensation.

Mechanisms of heat transfer include conduction through the solid material of the fibers and the intervening air, radiation and convection. Liquid and vapour transfer mechanisms include vapour diffusion in the void space, moisture sorption by the fibers, evapouration and capillary effects. Water vapour moves through textiles as a result of a vapour concentration gradient and fibers absorb water due to their internal chemical compositions and structures. The flow of liquid moisture through the textiles is caused by fiber-liquid molecular attraction at the surface of the fibers, which is determined mainly by surface tension and the effective capillary pore distribution and pathways (Wang and

Yashuda). Evapouration and/or condensation take place depending on the temperature and moisture distributions. Wang and Yasuda's simulations demonstrated the significant influences of waterproof fabrics on complex interactions among the processes of heat and moisture transfer in the clothing system.

Gibson (2000) studied the degree to which water vapour transport properties of several different polymer membranes and membrane/textile laminates are affected by temperature. Tests were carried out in a Dynamic Moisture Permeation Cell (DMPC), an automated device that can test the mass transport properties of very small pieces of fabrics, membranes, and foams at a variable temperature range from –15°C to 50°C. Gibson explained that, in nonporous samples transport of water vapour proceeds by pure diffusion, driven by vapour concentration differences. In the case of porous materials, if a pressure difference across the sample exists, convective gas flow through the sample carries water vapour along with the flow, and depending on the direction of the convective flow the diffusive flux will be high or low. It is notable from his findings that the water vapour flux increased at an exponential rate with the rise in temperature.

Effect of condensation on water vapour transfer through waterproof breathable fabrics

The rate of water vapour transfer through "waterproof breathable" fabric is affected by the amount of condensation on the surface of the fabric as liquid droplets cannot escape through the fabric pores due to the presence of a moisture barrier. Ren and Ruckman (1999) demonstrated that condensation increased the rate of water vapour transfer under isothermal conditions. They concluded that non-isothermal conditions are also subject to the same relationship between condensation and vapour transfer, except that when the level of condensation increases to a certain limit, the vapour rate decreases. According to Incropera & Dewitt (2002), the resistance to water vapour transfer increases with the condensate thickness and thus the condensate provides a resistance to heat transfer between vapour and surface.

Porous fabrics allow steam to carry through the fabric, but for non-porous fabrics steam will condense on the surface of the fabric. There will always be fresh condensate formation on the surface of the fabric, because the velocity of the steam will constantly disperse the condensate as it is formed on the surface of the fabric until the steam is shut off. If the condensate tends to completely wet the surface and thereby forms a liquid film, the process of condensation is known as film condensation (Incropera and Dewitt, 2002). In dropwise condensation the condensate does not tend to wet the surface but rather forms droplets on the surface. Both types of condensation occur on textile materials and may occur simultaneously. In filmwise condensation, the heat from the vapour is transferred to the cooling medium through the film of the condensate formed on the surface, whereas in the dropwise condensation process only a part of the surface is covered with condensate. Very high heat transfer rates are reported in the dropwise process due to the good contact between vapour and the surface.

Effect of fabric structure and related properties on steam transfer phenomenon

The thermal properties of a clothing system are determined by both its resistance to heat transfer and its resistance to moisture transfer. Morton and Hearle (1974) suggested that textile materials take a long time to come into equilibrium with their surroundings. They reported that the rate depends on a variety of factors such as temperature, air humidity, wind velocity and structural factors such as thickness of material, density of material and fibre type. Breckenbridge (1977), who studied the effect of body motion on convective and evapourative heat exchanges of clothing, suggested that the thermal insulation of clothing is dependent on a number of structural factors like thickness, number of layers, fiber density, flexibility of layers, fit, drape and adequacy of closures in a garment system. These factors are important in the study of heat and mass transfer. Kong, Li, Gao & Wong (2001) discuss the effect of fiber geometry and porosity on the heat and moisture transfer in textiles, combining both theoretical and computational methods to analyze the heat and mass transfer within fibers. Kong *et al* commented, “in accordance with the geometry and porosity, fibers can be classified into three main categories, hollow fibers, solid fibers and multilayer fiber configurations”. They also showed that these different fiber types differ on the rate of heat and vapour transfer. Hollow fibers are very good for moisture absorption (e.g. cotton fiber) and are excellent for preventing heat loss (e.g. synthetic hollow fibers). Solid fibers are generally stiffer and harder to absorb water and moisture compared to hollow fibers. Multilayer fiber configurations are a mix of hollow and solid fibers and are composed of a number of layers of different properties.

All the researchers above highlighted that fibre, yarn and fabric structure influence heat and moisture transfer through the fabric. Several other authors have emphasised the influence of fabric parameters on heat and moisture transfer. Their views and findings are presented in the following section where several textile characteristics and properties, and their influence on the heat and moisture transfer phenomenon are described. These factors include thickness, fabric structure (tightness of the fabric), air permeability, water vapour diffusion and fabric finish (waterproof breathable fabrics)

Thickness. The thickness of a fabric determines its thermal insulation capacity to a great extent. Thickness can be expressed as the product of the fiber proportion and the mass of the specimen divided by the product of fiber density and the packing factor of the specimen. Li, Zhu & Yeung (2002) investigated the influence of thickness and porosity on the coupled heat and moisture transfer in porous textiles. They carried out a series of computations with systematic variations of fabric thickness and porosity to reveal the interaction between heat and moisture transfer. They concluded that the heat transfer process, which is influenced by fabric thickness and porosity, has a significant impact on moisture transport process. Krasney (1986) considered thickness as a first approximation related to thermal resistance, but also suggested that for a given thickness, the lower the density, the greater the resistance. Even in short durations of steam exposure, the intensity of exposure is very high. He suggested that thermal inertia is a factor in reducing heat flux through garments [fabrics] when the exposure is of high intensity and short duration.

Tightness and porosity. The pores or the interstices within a fabric are influential factors in moisture and air transfer. Porosity is the ratio of air space to the volume of fabric, expressed as a percentage. As the fabric gets more densely woven (decreasing the porosity) two situations can be predicted: one, convective heat loss decreases due to a decrease in air circulation through the fabric; two, conductive heat loss increases due to increased conductivity (less air entrapped in the fabric, and more fibre contact). For any given fabric design, the natural and forced convection heat transfer coefficients decrease with the increase in fabric tightness due to less air permeability (Seyam & El-Shiekh, 1994). Thus, it may be said that when the fabric tightness for any fabric structure increases, heat loss due to air circulation (convective heat loss) becomes less important than conductive heat loss. Since most FR fabrics fall within the range of medium or high fabric tightness, the conductive heat loss/transfer through FR fabric can be more important than that of convective heat transfer.

Air permeability. The air permeability of a textile fabric is the degree to which the material is penetrable by air. Gibson (1993) examined the influence of air permeability on heat and water vapour transport through woven and non-woven fabrics, and concluded that a fabric's air permeability becomes particularly important in the situation where there is an air space between the fabric and a sweating skin-simulating surface. Textile materials with high air permeability allow the external air to penetrate through them and in the process can enhance the rate of heat and moisture transfer. Air penetration is related to factors such as pore diameter, material thickness, and tortuosity of the passages through the material. Gibson (p.758) states that when airflow through fabric occurs, the measured heat and water vapour transfer both increase greatly.

Water vapour permeability. Fohr et al (2002) proposed a model to determine the occurrence of liquid in certain places in fabric layers. They comment that fabrics have two scales of pores generated by the manufacturing process- interfiber and interyarn pores and that the diffusion properties of heat and water in liquid and vapour form are determined from this network. Water vapour can diffuse through the air spaces between fibers and yarns. Diffusion is more likely to occur in fabrics that have large interstices, or open spaces within the structure (Colliers & Epps , 1999). Interstices, or pores, which are effective in diffusion, include fabric interstices (between yarns) and yarn interstices (spaces between fibers within yarns). The factors on which the size and number of fabric interstices depend include fabric count, yarn linear density, and yarn twist and the type of weave. Colliers & Epps further comment that if yarn linear density and yarn twist are kept constant and yarn count is lowered, fabric interstices decrease in number but increase in size. Similarly if yarn twist is increased, size of fabric interstices will also increase. Steam can easily penetrate open weave fabrics due to their low resistance to water vapour diffusion.

Although not considered by Fohr et al (2001) fibers also absorb water vapour due to their internal chemical composition and structures. The flow of liquid moisture through textiles is caused by fiber-liquid molecular attraction at the surface of the fiber materials, which is determined mainly by surface tension and effective capillary pore distribution and pathways. Woo, Shalev & Barker (1994) concentrated on fabric structure when considering vapour diffusivity and heat transfer through fabrics. They reported that moisture absorption into textiles may be affected by both fiber morphology and the structure of the yarn and fabric. Fibers with a flat cross section increase the fabric cover and hence restrict the moisture vapour transport, as compared to fibers with round cross section.

Fabric Finish. Existing waterproof breathable fabrics can be categorised into the following: high-density fabrics, laminated and coated (Kramar, 1998). High density fabrics are woven so tightly that no interstices are seen between the yarns. Microfibers less than 1 decitex per fiber are generally used to manufacture high density fabrics. Water resistance can be increased by applying chemical finishes on the surface of such fabrics.

In laminated/coated fabrics a film/coating is adhered or applied to the fabric surface. The film/coating could be microporous, hydrophilic or a combination of both. The pores in either microporous films or microporous coating material are large enough for vapour to pass through but too small for liquid water to pass. A hydrophilic film or coating moves water vapour through physical chemistry. The charges in long polymer chains draw water vapour molecules which have a negative charge near the oxygen molecule, to the positive side of the film or coating.

Summary

The current research is concerned with heat and moisture transfer through fabrics during steam exposure. In the current research a laboratory test device and procedure was developed to measure heat transfer through fabrics during steam exposure. After considering the literature reviewed, little reference was found to studies on the steam permeability of thermal protective clothing, its effects on FR properties of fabrics, or consequences for the wearer. Rossi *et al* (2004) concluded that generally impermeable materials offer better protection against hot steam than semi permeable ones. Heat and vapour transfer are two highly coupled processes. Most of the literature on heat and moisture transfer through clothing referred to transfer from skin towards the environment and the research was conducted at a relatively lower temperature as compared to this study where the temperature during the test was expected to be 100 °C. Besides temperature, the heat and moisture transferred through clothing was measured for a longer duration of time and the diffusion of moisture through clothing was mostly at a molecular level. In this research this is not the case as the heat and moisture transfer is considered from outside toward the body through clothing and steam is at high pressure and temperature. Gibson (2000) showed that temperature has a significant influence on the water vapour transfer through fabrics. Fabric characteristics and performance properties also influence the rate of heat transfer during steam exposure. Some of the important characteristics include fabric thickness, finish and structure. Air permeability, water vapour permeability, thermal insulation (both dry and wet) and total heat loss of fabrics should also contribute to the steam protection properties.

Chapter 3

METHODS

This study was accomplished in two phases. Phase I comprised development of a laboratory test device and procedure to measure heat transfer through fabrics when exposed to steam, preliminary experimentation and subsequent refinements of the test device. Phase II comprised a set of experiments that focused on measuring the heat transfer through a series of fabrics when exposed to steam under varying conditions. Another set of tests were conducted as part of phase II to determine the fabric's structural characteristics and performance properties and to consider the relationship of such, if any, to heat transfer during steam exposure. Methods for each phase are described in this chapter.

Phase I: Development of Test Device

To achieve objective 1, a laboratory test device was designed to measure heat transfer through fabric when exposed to steam. Several factors were taken into consideration while designing the test device. These factors include (a) the shape of fabric mounting surface on the test device, (b) type of temperature measuring devices (sensors), (c) high pressure steam source and regulator, (d) exposure time, (e) proximity between the hazard and subject, (f) type of nozzle and (g) use of a spacer providing an air gap between fabric inner surface and skin.

First, steam transfer through a fabric specimen tightly clamped on a square frame was observed to determine if there was significant steam transfer. A cylinder measuring 23 cms diameter and 46 cms in height was built with fibreglass and polyester resin, and was fixed onto a steel frame. Body filler was applied to smoothen the surface of the cylinder. Skin stimulant sensors were mounted on the surface of the cylinder to measure heat transfer through fabrics. These sensors are connected to a data-acquisition device that records the temperature as a function of time. Sensors are evenly distributed over the front face of the cylinder. Figure 1 and 2 shows various elements of the test device.

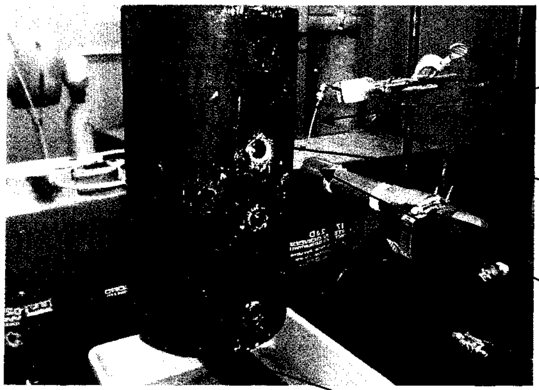


Figure 1.Cylinder with sensors on the test device

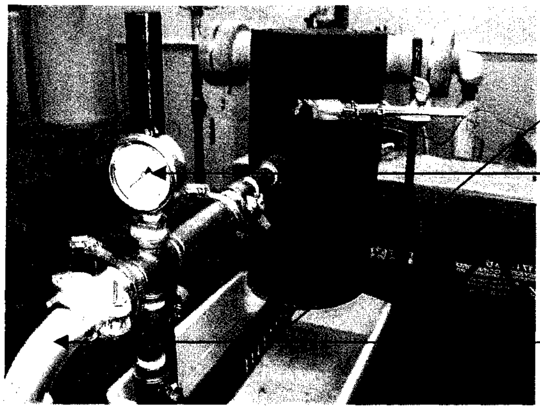


Figure 2. Fabric mounted on the cylinder

Two sets of preliminary experiments were conducted during which each of the factors stated above were considered. In the first set of preliminary experiments five FR fabrics typically used in the oil industry were tested. Two of the five fabrics did not have a moisture barrier and were plain weave designs; the other fabrics had a polyurethane laminate moisture barrier. The pressure during these initial tests was 35 kPa (5 psi), the steam was discharged for 10 seconds and temperature/time data were collected for 20-25sec. Tests were performed with the steam nozzle at 50mm, 100mm and 180mm from the fabric surface. The results of these preliminary tests are found in Appendix 2 and are incorporated into the discussion of design factors below.

In the second set of preliminary experiments the dependent variables were peak heat flux and total energy. The independent variables were fabric, distance and pressure. Two fabrics were chosen for conducting these preliminary experiments based on their water vapour permeability. Table 1 provides the characteristics and the diffusion resistance (Dm) of the two fabrics.

Table 1. Characteristics and resistance to water vapour diffusion of fabrics - preliminary experiment.

Fabric	Finish	Mass[1]	Thickness[2]	Dm[3]
Aramid	Polyurethane laminate	260	0.66	22.53
Carbon/Silicon	Silicone coated	1000	1.31	>150

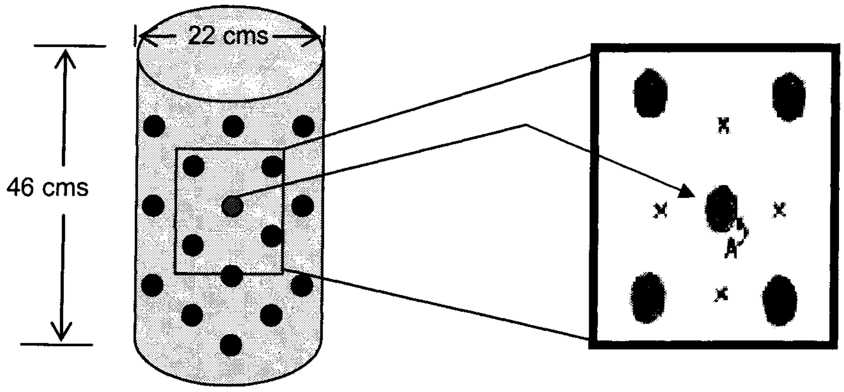
[1] *measured in grams/m^2, according to CAN/CGSB-4.2 No.5.1-M90.*
[2] *measured in mm, according to CAN/CGSB-4.2 No.37-2002.*
[3] *measured in equivalent mm still air, according to CAN/CGSB-4.2 No. 49-99.*

To optimise the flow of steam coming out of the nozzle, two different nozzles were developed. A nozzle with a 20mm opening was designed to achieve low pressure at the nozzle exit. To achieve higher steam pressure at the nozzle outlet, a nozzle with 6mm orifice was utilized. Three distances between the nozzle and fabric specimen were selected to determine the extent to which such distances affected heat transfer. Results from this set of experiments are found in Appendices 3 to 5 and are incorporated into the discussion in the following section.

Considerations and recommendations for final design of test device

Each factor considered in the design of the test device/procedure is discussed below followed by a description of the final device.

Shape of fabric mounting surface and location of sensors on the test device. There is a significant difference in the energy distribution for a flat surface compared to a curved surface while that surface is exposed to forced convection, such as occurs during steam exposure. For a flat surface the steam will concentrate on a localized area rather than surround the surface as may be observed for curved surfaces. Thus, larger surface areas are likely to be exposed for curved surfaces compared to flat surfaces. Since the human body is cylindrical in geometry, a cylindrical shape was selected to simulate a human torso. During the preliminary experiments it was observed that not all 16 sensors (Figure 3a) were affected when the steam was discharged on the cylinder. It was recommended that those sensors unaffected during the test should be excluded. To obtain a better temperature distribution four more sensors (marked x) were placed around the main sensor “A” (Figure 3b).



(a) (b)

Figure 3. Cylinder with (a) original sensor placement and (b) revised sensor placement

Type of temperature measuring devices on the fabric mounting surface. To measure the heat transfer through fabrics, nine skin simulant sensors were located on the front surface of the cylinder. The sensor used was based on that developed by Dale et al (1992). Figure 4 illustrates a skin simulant sensor with a 30 gauge copper constantan thermocouple mounted on the surface adhered by glue. No changes were made to sensors following preliminary experiments.

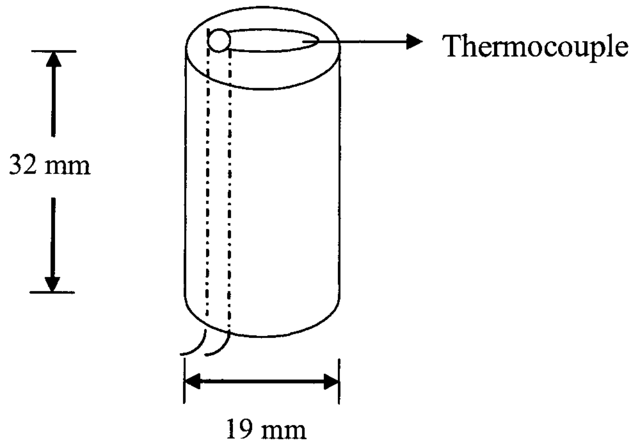


Figure 4. Skin simulant sensor

High pressure steam source and regulator. To perform the tests under the conditions that are typical in the oil and gas industry a high pressure steam source was required. During the initial series of tests, maximum pressure achieved in the main line was 35 kPa. This pressure is too low to identify potential significant differences among fabrics at realistic higher pressures therefore the test device was moved to a different lab where the pressure in the main line was more than 350 kPa. However, to obtain a uniform pressure through out the tests a uniform supply of steam was desired and hence a pressure regulator was deployed in the system. To facilitate observation of the pressure in the steam inlet pipe a pressure gauge was also installed directly upstream of the nozzle.

Exposure time (the total time during which the fabric is exposed to steam). In a real scenario, a person coming in direct contact with steam would try to get away from it almost instantly as the body's physiological response will come into play. In some situations where the person is bewildered due to the sudden outbreak or is trapped, the exposure time may increase. Based on a probable worst case scenario, the exposure time was set at 10 sec during all experiments.

Proximity between the hazard and subject. To simulate a hazard it is important to identify the distance between the steam source and the subject. A person might be exposed to steam at varying distances; some might be very close to the hazard, some may not. Two distances (50mm and 100mm) were recommended for the main experiments. A larger distance used earlier (180mm) was not considered because it did not show significant differences among fabrics in the preliminary experiments (Appendices 3 and 4).

Nozzle Design. There are different ways the steam can escape the system. It is important to know the geometry of the source where the steam is escaping. From this geometry a pattern of steam distribution can be predicted. Several nozzles were tried before deciding on the final design. From the preliminary experiment results it was peculiar to observe higher peak heat flux values and total energy transferred at lower pressure than at higher pressure (Appendix 5). This was attributed to the size of the nozzle, as a bigger nozzle would release more mass compared to a smaller nozzle. Thus, a rapid heat transfer rate was observed with the bigger size (Appendix 3). A vertical slit would best simulate a real life hazard (e.g. a piece of gasket blown off between the two flanges) and also facilitate obtaining a high enough pressure.

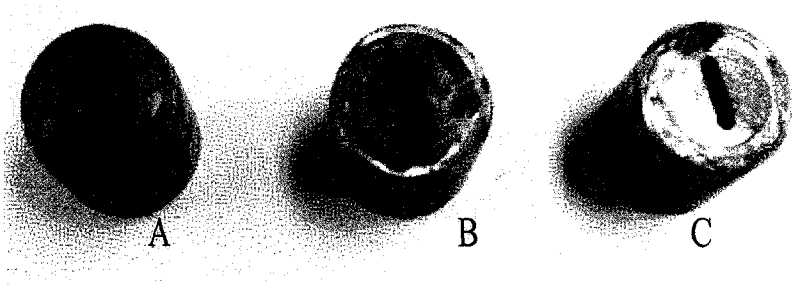


Figure 5. Nozzle designs

Three different nozzles were designed (Figure 5) and several tests were conducted to see the pressure drop for each. To achieve a uniform spray on the cylinder surface nozzle A was designed; nozzles B and C were designed to simulate the real life hazard. However with bigger nozzles (nozzle A and B) more mass loss was observed. Therefore, to maintain a high pressure at the nozzle outlet and to closely simulate the hazard, nozzle C was selected.

Spacer. A spacer was utilized in the initial experiments to create a gap between the fabric inner surface and cylinder. The spacer was constructed with a 6mm iron bar to fit on the face of the cylinder. In the first set of preliminary experiments, some tests were conducted with the spacer mounted to the cylinder. The temperature curves (Appendix 1) showed little differences between fabrics in temperature rise of the main sensor, with and without spacer because the force of high pressure steam pushed the fabric towards the sensors even at low pressures. Hence the use of spacer was discontinued for further experiments at higher pressures.

Phase II: Main Experiments

A laboratory experiment with three independent variables (fabric, steam pressure, and the distance between nozzle and cylinder surface) and four dependent variables (peak temperature, peak heat flux, time to reach peak heat flux and total energy) was conducted to determine heat transfer through different FR fabrics when exposed to steam. Only two replications of the experiment were conducted because preliminary experiment results were quite consistent and after two replications in the final experiments their consistency suggested no need for a third replication.

Independent Variables

Fabrics. Three fabrics were chosen based on their rankings for water vapour diffusion resistance. Table 2 provides physical characteristics of these fabrics. Fabric A was permeable to liquid water and vapour. The second fabric, Fabric B was impermeable to liquid water but permeable to vapour, and Fabric C was impermeable to both liquid and vapour.

Table 2. Characteristics of fabrics – Main experiment

Fabric	Description	Mass[1]	Thickness[2]
A	Meta Aramid Plain weave, Comfort finish	194	0.56
B	Meta Aramid Plain weave Polyurethene Laminated	237	0.64
C	Meta Aramid Plain weave Tri-Chloroprene Coated	520	0.34

[1] *measured in grams/m^2, according to CAN/CGSB-4.2 No.5.1-M90.*
[2] *measured in mm, according to CAN/CGSB-4.2 No.37-2002.*

Distance between the nozzle and cylinder. The distance between the steam jet nozzle and cylinder was to simulate real life situations. Two distances (50mm and 100mm) were chosen for conducting the experiments.

*Pressure**. The test was performed under two different pressures, 69 kPa (10 psi) and 207 kPa (30 psi).

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* Actual test were performed at 10 and 30 psi. In this report these values are stated as 69 kPa and 207 kPa.

Test Procedure

Fabric specimens (45cm x 45cm) were conditioned in a standard atmosphere of 20°C and 65 % R.H. Fabric specimens were taken in a sealed poly bag from conditioning room to the lab where the tests were performed. Each specimen was removed from the sealed bag and clamped onto the cylinder within 60 seconds of their removal from the bag. Steam was discharged on the test specimen for 10 seconds. Sensors connected to data loggers measured temperature as a function of time. Total recorded time was 90 seconds, including 10 seconds exposure time. Relative humidity of the environment during the test was recorded, as was the steam temperature at the nozzle outlet. Because the skin simulant sensors take a long time to cool down, air was applied to cool the sensors after every test. Figure 6 show the test device in operation.

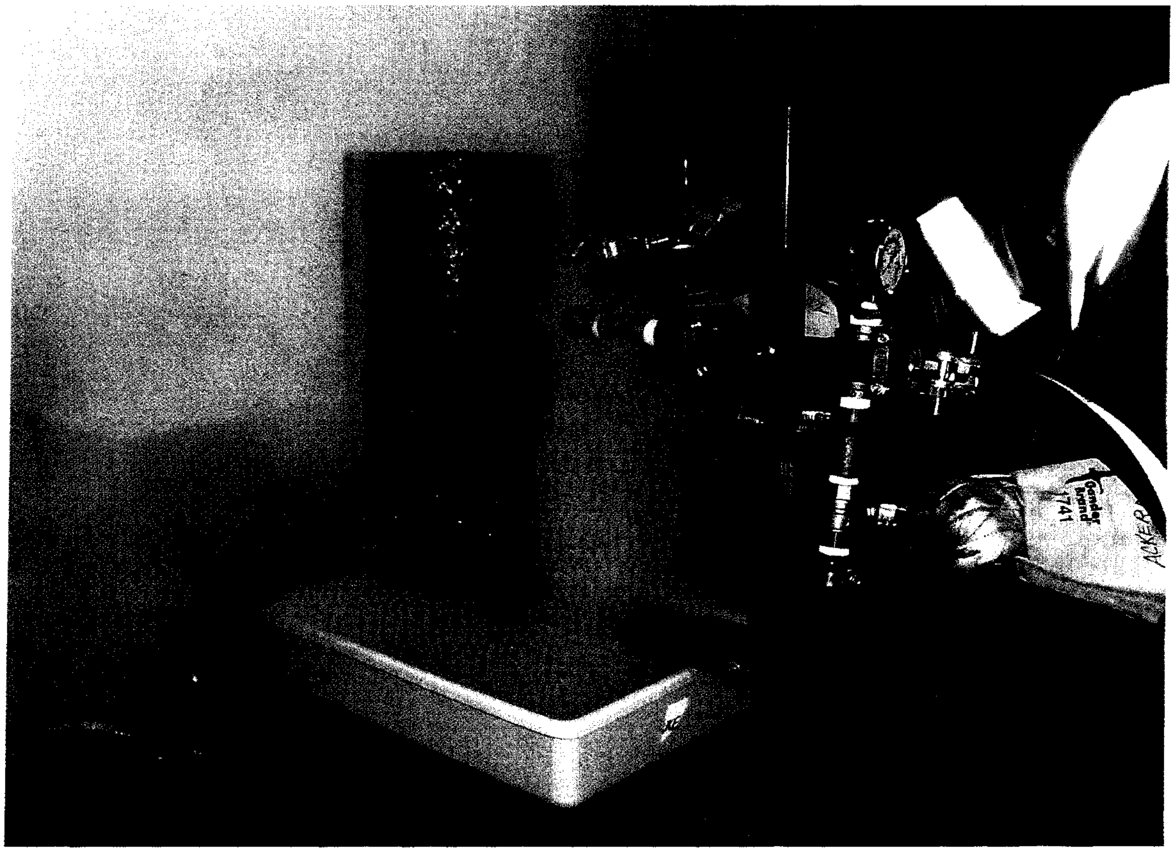


Figure 6. Fabric exposed to high pressure steam

Calculation of Dependent Variables

Peak Temperature: the highest temperature reached was obtained from each temperature/time plot.

Peak heat flux through fabric: the temperature data obtained from skin simulant sensors were inversely transformed to obtain the heat flux using equation 2 (p. 9). Heat flux was calculated over 90 seconds, and the highest value was obtained from each curve.

Time to reach peak heat flux: was obtained from each heat flux versus time curve.

Total Energy: the integrated value of the area under the heat flux/time curve over 90 seconds.

Statistical Analysis

Statistical analyses were performed using the Statistical package for Social Sciences (SPSS) Version 11, and Microsoft Excel, with a significance level of $p < .05$ set for hypothesis testing. Descriptive statistics (means and standard deviations) were calculated for all four dependent variables (peak temperature, peak heat flux, time to reach peak heat flux and total energy) for each fabric at two distances and two pressures. A full factorial design using SPSS was utilized to conduct 3-way analyses of variance. Each replication was analysed separately and a combination of data from the two replications (referred as "total" in this report) was also analysed. Main effects for independent variables and two-way and three-way interaction effects among the main effects were determined. To identify differences among fabrics, Duncans post hoc test was conducted.

Evaluation of fabric properties

Evaluation and measurement of fabric characteristics and properties was carried out under standard conditions of 65% RH and 20°C (CGSB, 1988), following CGSB and ASTM standard test methods. The following fabric characteristics and physical properties of fabrics were determined.

Fabric characteristics (See Table 2, p.31):

Mass. The conditioned mass of each fabric was determined according to CAN/CGSB – 4.2 No. 5.1 – M90. The mass is calculated in grams per unit area (g/m^2) (CGSB, 1987).

Thickness. The thickness of each fabric was determined according to CAN/CGSB – 4.2 No. 37-M87 and is reported in mm (CGSB, 2002).

Physical properties of the fabrics:

Water Vapour Diffusion. The water vapour diffusion resistance of each fabric was measured according to CAN/CGSB-4.2 No. 49-99, method C, and is reported in mm equivalent still air (CGSB, 1999).

Air Permeability. The air permeability of each fabric was determined using a Frazier High-Pressure Differential Air Permeability Apparatus according to CAN/CGSB-4.2 No.36-M89, and was reported in $cm^3/cm^2/sec$ (CGSB, 1997).

Thermal Insulation. The thermal resistance of each fabric was determined according to ASTM F 1868- 98, Part C and recorded in $m^2 K/W$. Thermal resistance is expressed as the temperature difference (Kelvin) in relation to thermal flux (Watts) per surface area (square meter) of the test specimen. Both dry thermal resistance (Rct) and evapourative resistance (Ret) were measured and Rcf and Ref were calculated by subtracting the bare plate value from the Rct and Ret (ASTM, 1998).

Total Heat Loss. From Rcf and Ref, Total heat loss was calculated from the equation given below: (ASTM, 1998)

$$Qt = \frac{10°C}{Rcf + .04} + \frac{3.57\ kPa}{\mathrm{Re}f^{a} + .0035} \quad \text{.........Eq. 4}$$

Where,

Qt = total heat loss (W/m^2)

Rcf = average intrinsic thermal resistance of the sample ($K\text{-}m^2/W$)

Ref^{a} = average apparent intrinsic evapourative resistance of the sample ($kPa\text{-}m^2/W$)

The fabric properties outlined above were used to help explain differences among fabrics in their performance against steam.

Chapter 4

RESULTS AND DISCUSSIONS

Three way analyses of variance (ANOVA) were conducted to determine significant differences in each dependent variable (peak temperature, peak heat flux, time to reach peak heat flux and total energy) for each of the independent variables (fabric, pressure and distance) as well as their interaction effects. In this chapter, three-way and two-way interactions are first presented, followed by a discussion of the differences among fabrics for each dependent variable. Temperature, heat flux and energy curves are presented and discussed. The chapter ends with a discussion of results relative to the study's objectives.

Analyses of Variance

Analyses of variance results are summarized in Table 3. Most three-way interaction effects (fabric by distance by pressure) were not significant. On the other hand, many two way interaction effects for fabric by distance were significant ($p< .001$), suggesting that the differences found among fabrics depended on the conditions of the test (distance). However, most of the fabric by pressure interactions were not significant, suggesting that pressure has less influence on differences among fabrics. Significant distance x pressure interaction effect suggests that for peak temperature and total energy the effect of one parameter may be dependent on the other.

The main effects for pressure were highly significant for all dependent variables, except for time to reach peak heat flux. Main effects for distance were found to be significant for peak temperature, peak heat flux and total energy in replication 1, 2 and total but were insignificant for time to reach peak heat flux in replications 1 and total. For both the replications and their total, the main effect for fabric was highly significant (p < 0.001) for all four dependent variables suggesting that the test device was able to differentiate well among the three fabrics.

Table 3. Three way analysis of variance: Significance of interaction and main effects

Interactions	Peak temperature	Peak heat flux	Time to reach peak heat flux	Total energy
3 way Interaction effects				
Fabric x Pressure x Distance				
Replication 1	NS	NS	NS	NS
Replication 2	*	NS	NS	NS
Total	NS	NS	NS	NS
2 way interaction effects				
Fabric x Distance				
Replication 1	*	***	NS	***
Replication 2	NS	***	NS	***
Total	**	***	NS	***
Fabric x Pressure				
Replication 1	*	NS	NS	*
Replication 2	NS	NS	NS	NS
Total	NS	NS	NS	**
Distance x Pressure				
Replication 1	***	NS	NS	**
Replication 2	NS	NS	NS	NS
Total	**	NS	*	*
Main effects				
Fabric				
Replication 1	***	***	***	***
Replication 2	***	***	***	***
Total	***	***	***	***
Distance				
Replication 1	***	***	NS	***
Replication 2	***	***	*	***
Total	***	***	NS	***
Pressure				
Replication 1	***	***	NS	***
Replication 2	***	***	*	***
Total	***	***	*	***

NS: Not statistically significant (p value>.05)
$^{*}p<.05$, $^{**}p<.01$, $^{***}p<.001$

Results of Duncan's post-hoc tests of differences among fabrics (Table 4) confirm significant differences for all four dependent variables. These analyses are based on data for both replications. Separate analyses for replications 1 and 2 are provided in Appendix 5. All three fabrics differ significantly from each other for peak temperature, peak heat flux and total energy, but there is no significant difference between fabric B and C for time to reach peak heat flux. The differentiation between different test conditions referred to earlier can also be seen in Table 4. Higher values were reported at 50mm than at 100mm for peak temperature, peak heat flux, total energy, with no significant difference for time to reach peak heat flux. Similarly higher values for peak temperature, peak heat flux, total energy were observed for high pressure than at a lower low pressure.

Table 4. Heat Transfer through fabric A, B and C.*

Fabric		**Peak Temperature** (in °C)				**Peak Heat Flux** (in kW/m^2)				**Time to reach Peak Heat Flux** (in seconds)				**Total Transferred Energy** (in Joules)			
	Pressure (in kPa)	69		207		69		207		69		207		69		207	
	Distance (in mm)	50	100	50	100	50	100	50	100	50	100	50	100	50	100	50	100
A	Mean	97^a	80^a	104^a	86^a	91^a	60^a	97^a	67^a	1.2^a	1.1^a	1.2^a	1.2^a	321^a	241^a	368^a	275^a
	Std Dev	2.2	3.4	6.3	7.1	14	10	10	7	0.3	0.3	0.2	0.2	9	24	15	36
B	Mean	48^b	39^b	60^b	46^b	9.8^b	6^b	17^b	11^b	2.5^b	2.5^b	2.5^b	2.0^b	82^b	58^b	110^b	84^b
	Std Dev	2.6	0.6	7.7	1.9	1.4	0.3	3.7	1.8	0.5	0.7	2.5	0.6	11	5	11	17
C	Mean	67^c	57^c	78^c	59^c	21.5^c	17^c	31^c	20^c	2.3^b	2.6^b	2.3^b	1.9^b	144^c	119^c	171^c	120^c
	Std Dev	2.4	1.2	3	8	2.3	0.7	2.2	5.3	0.3	0.5	0.3	0.3	13	11	17	23

* *Means and standard deviations are for the total data. For replications 1 and 2, refer Appendix 5.*

[a,b,c] *For each condition (column) fabric means with different superscripts differ significantly from each other.*

Before discussing the temperature, heat flux and energy plots it is important to discuss the fabric characteristics and properties which largely influence the rate of heat and water vapour transfer. Table 5 provides mean data on several physical properties such as water vapour diffusion resistance (Dm), air permeability, dry thermal insulation

(Rct), evapourative resistance (Ret) and total heat loss. Mass and thickness data are provided earlier in Table 2. Of the three fabrics tested, fabric A has the highest air permeability and very low resistance to water vapour diffusion, making it vulnerable to permeation of steam at high temperature and pressure. Steam easily penetrated through the fabric and instantaneously increased the temperature of the fabric and of the skin simulant sensors behind the fabric. This phenomenon was observed on the surface of the cylinder which was completely wetted during steam exposure and could be examined when the specimen was removed from the cylinder surface. Fabric B with very low air permeability and moderate Dm offered better resistance to evapourative heat transfer than Fabric A. Although the water vapour resistance for Fabric C is highest (Dm = >150), it is thinner and more dense than Fabric B (Table 3), likely contributing to a higher rate of heat transfer, mainly by conduction.

Table 5. Physical performance properties of fabrics- Main experiment

Fabric		Dm[1]	Air permeability[2]	Rct[3]	Rcf[3]	Ret[4]	Ref[4]	Total Heat Loss[5]
A	**Mean**	1.05	56.90	0.08	0.02	7.56	3.00	692.00
	Std. Dev	0.01	0.53	0.00	0.00	0.06	0.00	5.40
B	**Mean**	19.80	0.08	0.08	0.02	18.35	14.00	363.00
	Std. Dev	1.01	0.00	0.00	0.00	1.15	0.00	12.00
C	**Mean**	>150	0.00	0.07	0.01	175.43	171.00	227.00
	Std. Dev	0.00	0.00	0.00	0.00	44.93	45.00	11.00

[1] *measured in mm still air, according to CAN/CGSB-4.2 No. 49-99.*
[2] *measured in $cm^3/cm^2/sec$, according to CAN/CGSB-4.2 No.36-2002.*
[3] *measured in $K\text{-}m^2/W$, according to ASTM F 1868- 98, part C.*
[4] *measured in $Pa\text{-}m^2/W$, according to ASTM F 1868- 98, part C.*
[5] *measured in W/m^2, according to ASTM F 1868- 98, part C.*

In an attempt to demonstrate such relationships between fabric parameters and heat transfer, means were plotted for the three dependent variables against fabric parameters: thickness, thermal insulation (Rct), resistance to water vapour (Dm) and total heat loss. Each plot in Figure 7 shows the data points for the three fabrics for each condition of pressure and distance. The patterns among fabrics are very similar for thickness and thermal insulation (Rcf) (Figure 7a and 7b) related to each of peak temperature, peak heat flux and total energy indicating that these two factors affect the heat transfer in a similar fashion. Likewise, similar but inverse patterns among the fabrics are seen for relationships between resistance to water vapour diffusion and heat transfer variables (Figure 7c) and between total heat loss and heat transfer variables (Figure 7d).

For Fabric A, which is air and vapour permeable, most of the heat and moisture transport is by convection and bulk moisture transport through the interstices of the fabrics. Gibson (1993) has stated that when airflow through fabric occurs, the measured heat and water vapour transfer both increase greatly. Fabric B, was expected to show higher rates of heat transfer than Fabric C due to its moderate resistance to water vapour permeability, but actually performed well compared to Fabric C. For Fabric C the heat transfer is through conduction only where thickness and thermal insulation (Rcf) are the key factors effecting steam related heat transfer. Thus the overall plots do not suggest any obvious linear relationships between fabric parameters and steam related heat transfer indicators, suggesting that the effects of fabric parameters may need to be considered together rather than individually. Developing such a model, however, is outside the scope of this thesis.

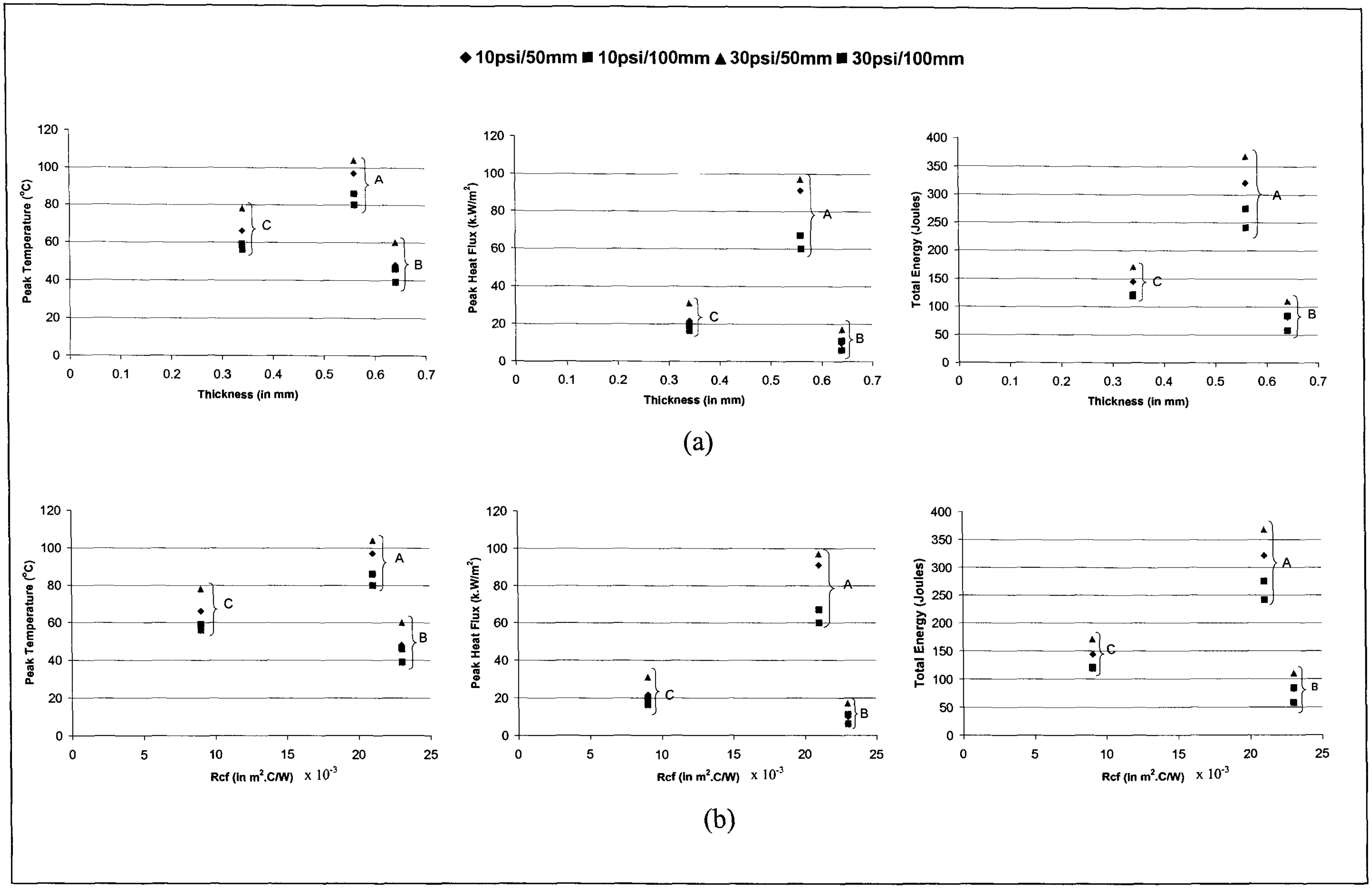
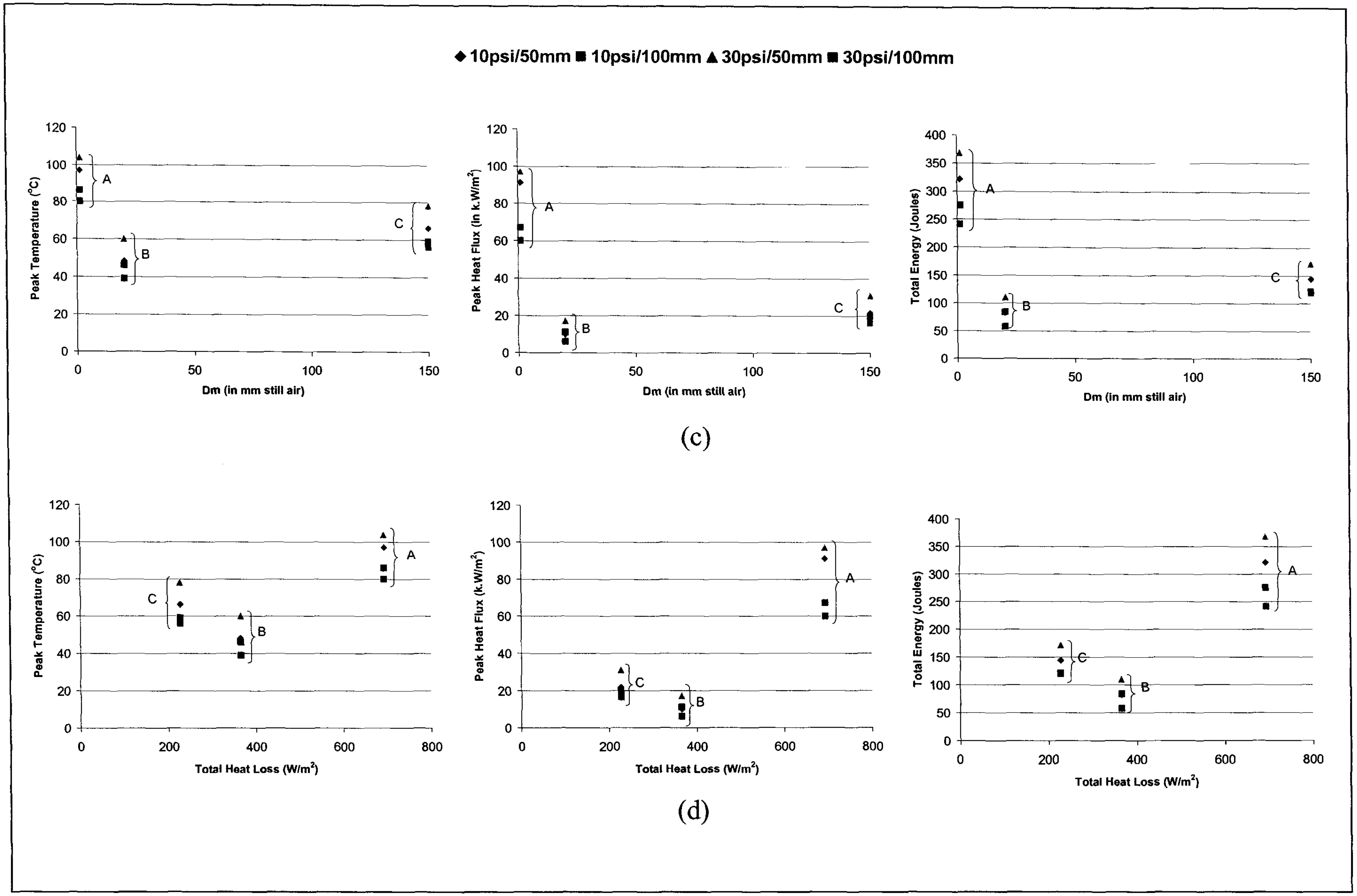


Figure 7. Relationship between fabric parameters and dependent variables.



(c)

(d)

Figure 7 (continued) . Relationship between fabric parameters and dependent variables.

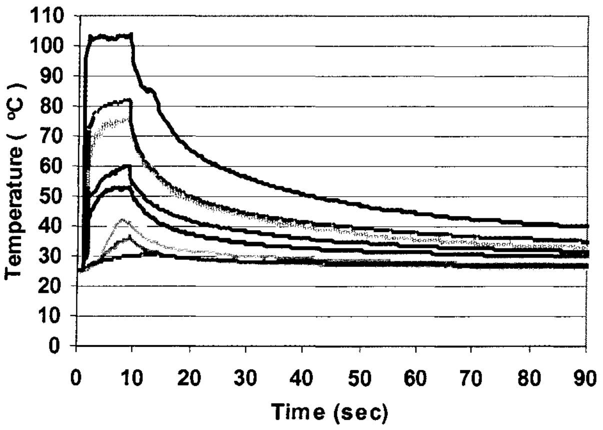
Temperature, Heat Flux and Energy Plots

In the following section, curves representing temperature, heat flux and total energy as a function of time will be examined. For each condition of pressure (69 kPa and 207 kPa) and distance (50mm and 100mm), temperature, heat flux and energy curves were plotted for each sensor for each specimen. The plots in Figures 8 to 15 are those of a typical specimen of each fabric sample.

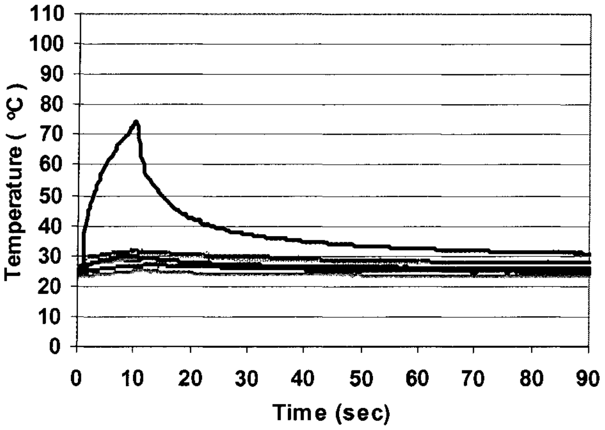
Temperature vs Time plots

Figures 8 to 11 show temperature vs time plots for a duration of 90 seconds. These plots are placed in order of the severity of exposure. All the plots show a similar pattern but peak temperature reached differentiates one exposure condition from other. For the severest condition (Figure 8) at 207 kPa and 50mm distance, temperature rise is very sharp in fabric A. Several other sensors close to the main sensor are also affected. For fabric B, the peak temperature reaches almost 75°C by 10 seconds but falls sharply when the heat source is removed at 10 seconds. For fabric C, the temperature rises very rapidly and reaches a peak above 80°C after the heat source is removed.

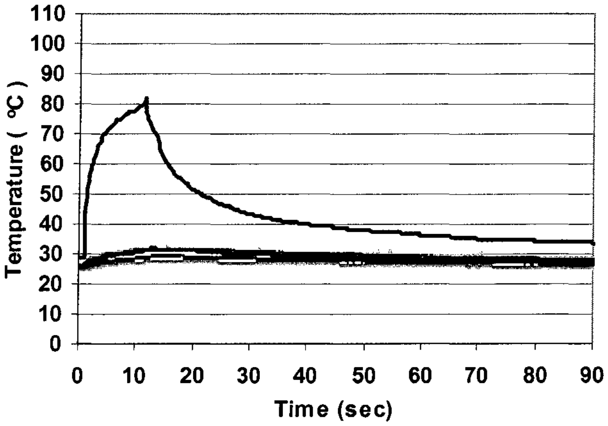
In figure 9, at 69 kPa and 50mm distance, the temperature rise for fabric A is abrupt for some of the sensors and stays constant for the duration of exposure (10sec) during which steam is discharged. For fabrics B and C, only the main sensor is greatly affected during the steam exposure. The temperature rise is not as sudden for Fabrics B and C as it was found for fabric A. Also fabric C reaches a higher temperature than fabric B but falls rapidly when the heat source is removed.



Fabric A

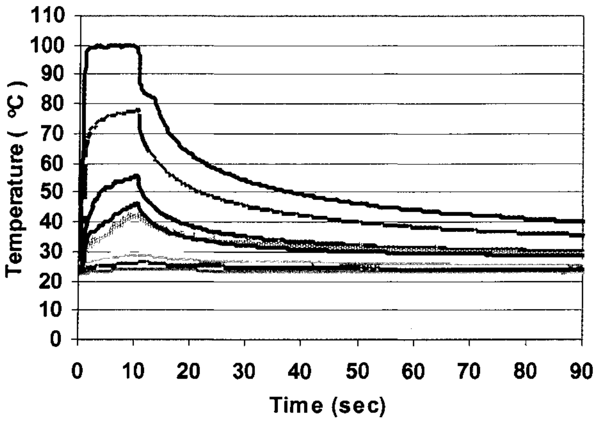


Fabric B

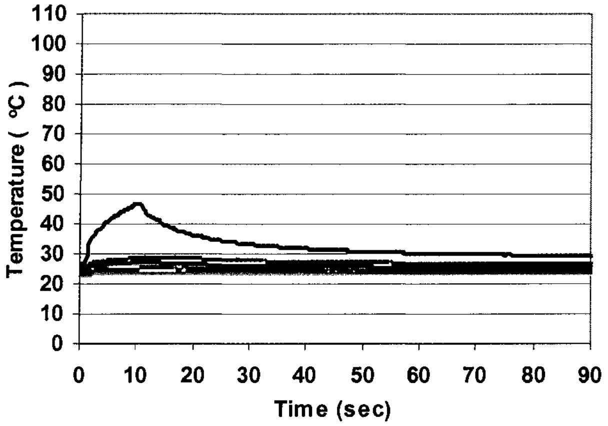


Fabric C

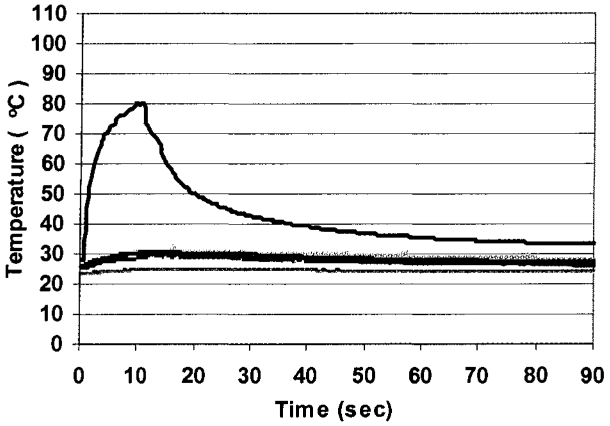
Figure 8. Temperature vs Time - 207 kPa and 50mm



Fabric A



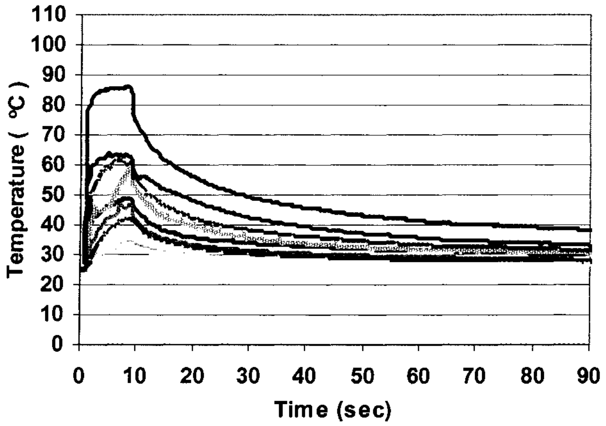
Fabric B



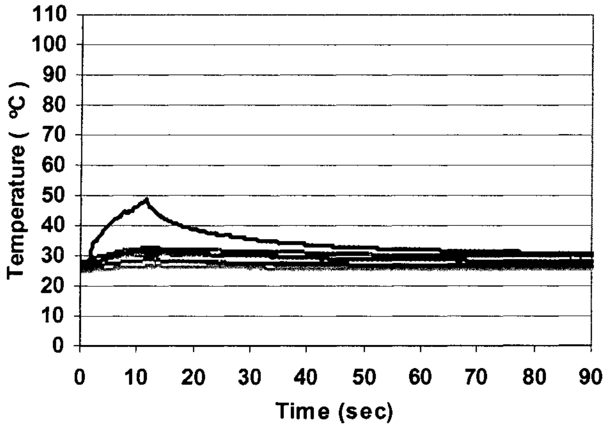
Fabric C

Figure 9. Temperature vs Time - 69 kPa and 50mm

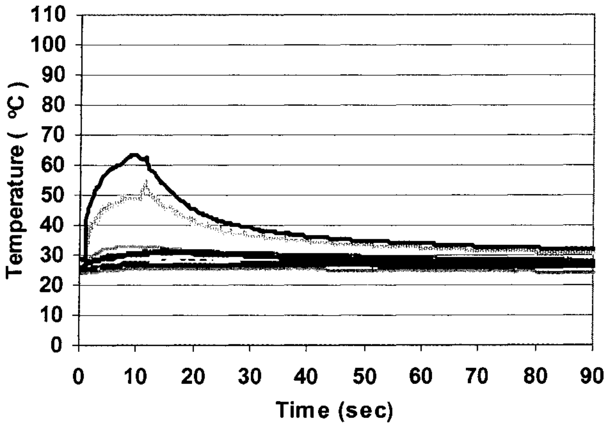
Figures 10 and 11 are for conditions where the distance in both is 100mm. For 207 kPa and 100mm (figure 10) the temperature rise is slightly higher compared to 69 kPa and 100mm (figure 11) indicating that at 100mm, pressure influences heat transfer to an extent. On the other hand when keeping the distance constant at 50mm (figures 8 and 9) there is significant difference between pressures only for fabric B. These results suggest that influence of distance is greater than that of pressure and also confirms the significant interaction between fabric and distance presented in Table 3. The dominant effect of distance can also be explained theoretically by taking a look at the nozzle. The steam coming out of the nozzle grows due to entrainment with surrounding air, the more the distance the more the expansion of jet resulting in a rapid pressure drop. Hence, for a greater distance the pressure drop is higher at the fabric surface compared to a shorter distance were the steam jet expansion is restricted due to less space between nozzle and fabric surface.



Fabric A

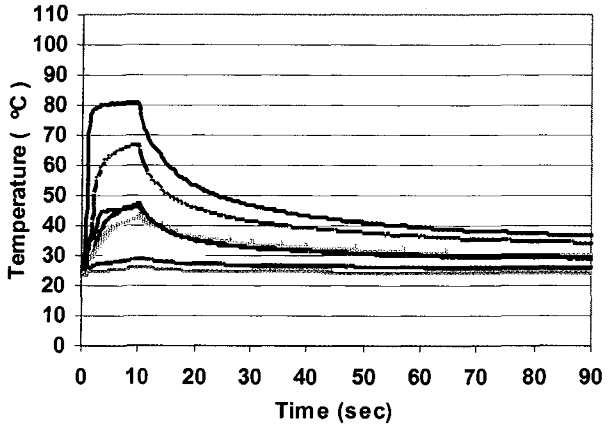


Fabric B

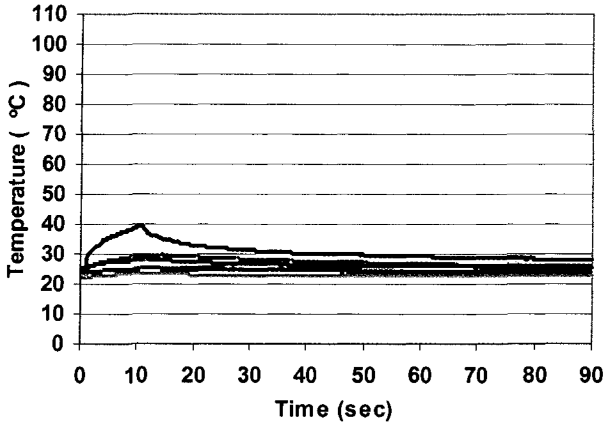


Fabric C

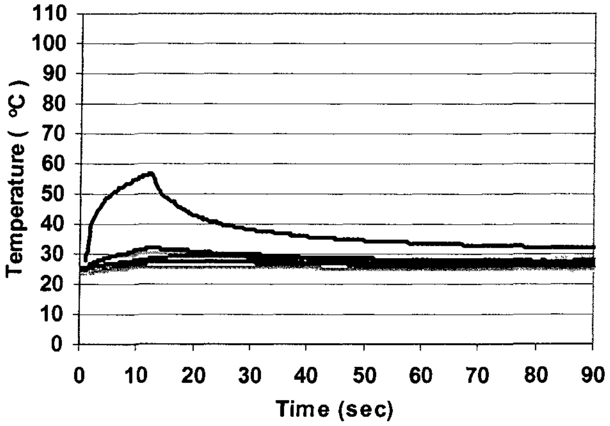
Figure 10 . Temperature vs Time - 207 kPa and 100mm



Fabric A



Fabric B



Fabric C

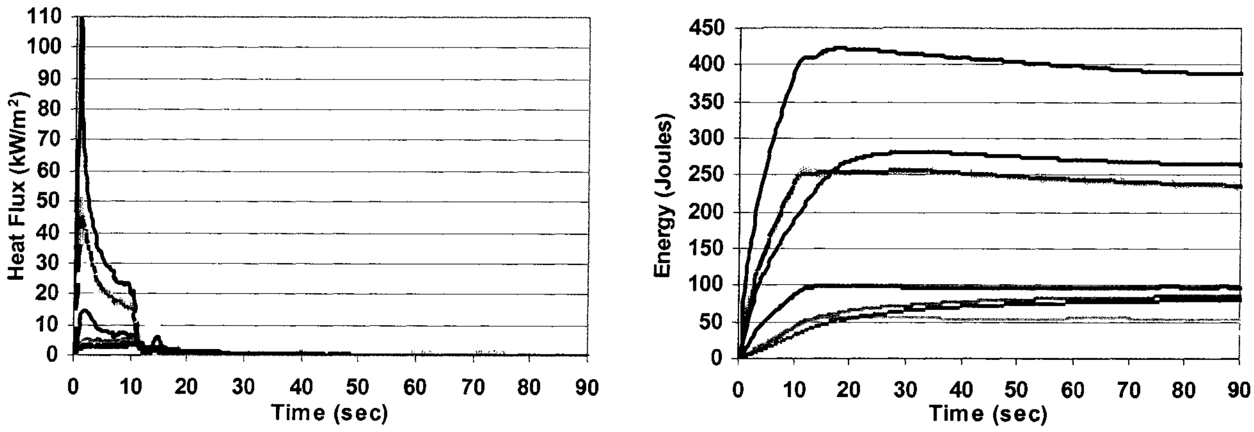
Figure 11 . Temperature vs Time - 69 kPa and 100mm

Heat flux and Energy plots

Figures 12-15 show that heat flux and total energy transferred were highest for fabric A in all the conditions. The peak heat flux for the worst case scenario, 207 kPa/50mm (figure 12) was above 110 kW/m^2 and the lowest peak heat flux was found in conditions where the distance was 100 mm at either pressure (Figures 14 and 15). The peak heat flux reached close to 90 kW/m^2 at 69 kPa and 50mm condition (Figure.13).

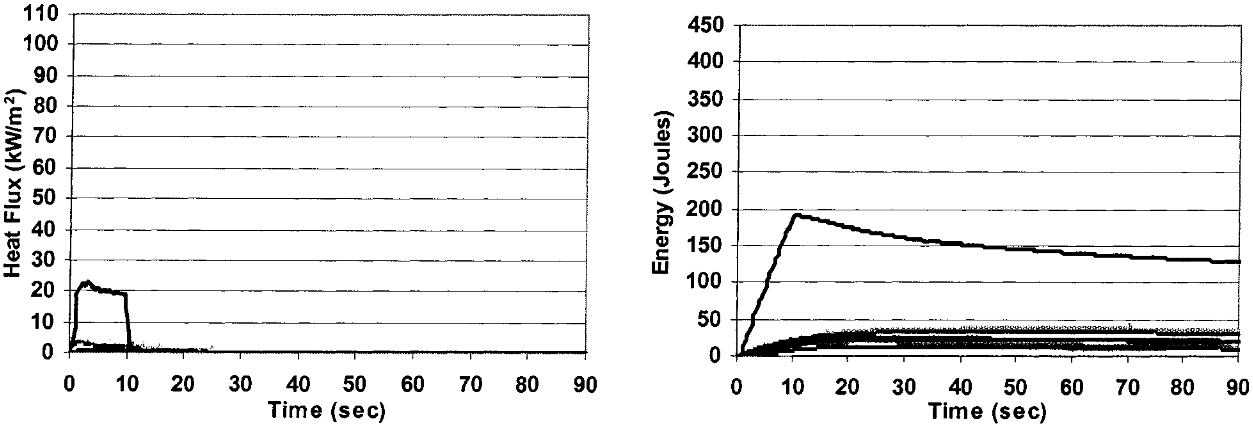
For fabric A under all conditions the heat flux rapidly rises to a peak as long as there exists a gradient between steam temperature and sensor temperature, but drops sharply, even during the exposure period, once the steam and the sensor temperature reach an equilibrium condition and there exists no temperature gradient. For all conditions several sensors were affected during the steam exposure. Fabric B had the lowest heat flux and energy transfer under all the conditions in comparison with the other two fabrics, but there is a distinct rise in the heat flux for higher pressure and shorter distance condition (figure 12). Fabric C showed higher heat flux and energy transfer in the conditions where the distance was shorter (Figures 12 and 13) than for the larger distance (Figures 14 and 15)

In most of the Energy plots (figure 12-15) the curve declines slightly because once the steam is shut off the sensor tends to give up the heat to the surrounding atmosphere. Temperature of the fabric starts falling as soon as steam is shut off, and while the fabric is in contact with the sensors it drives the heat from the sensor toward the cooler fabric.



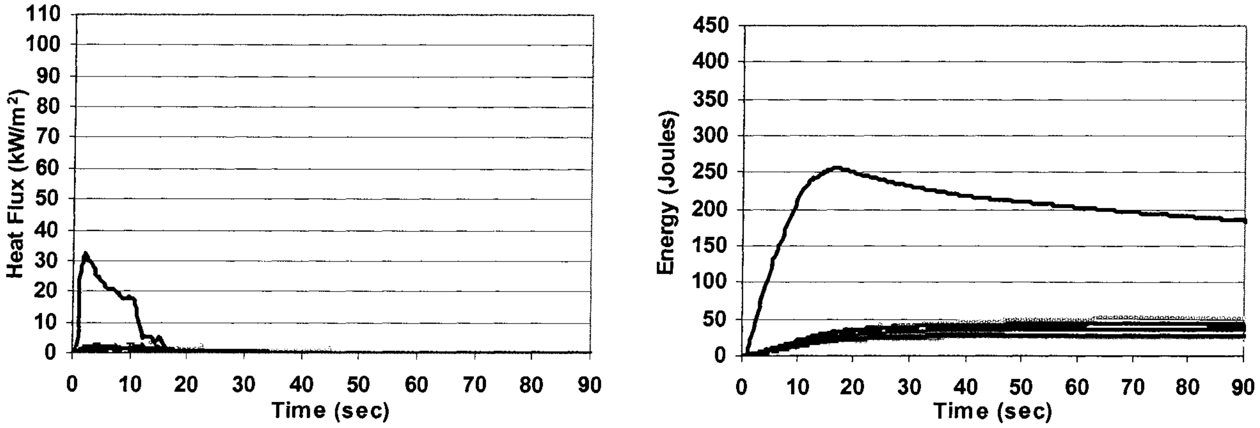
(a) *(b)*

Fabric A



(a) *(b)*

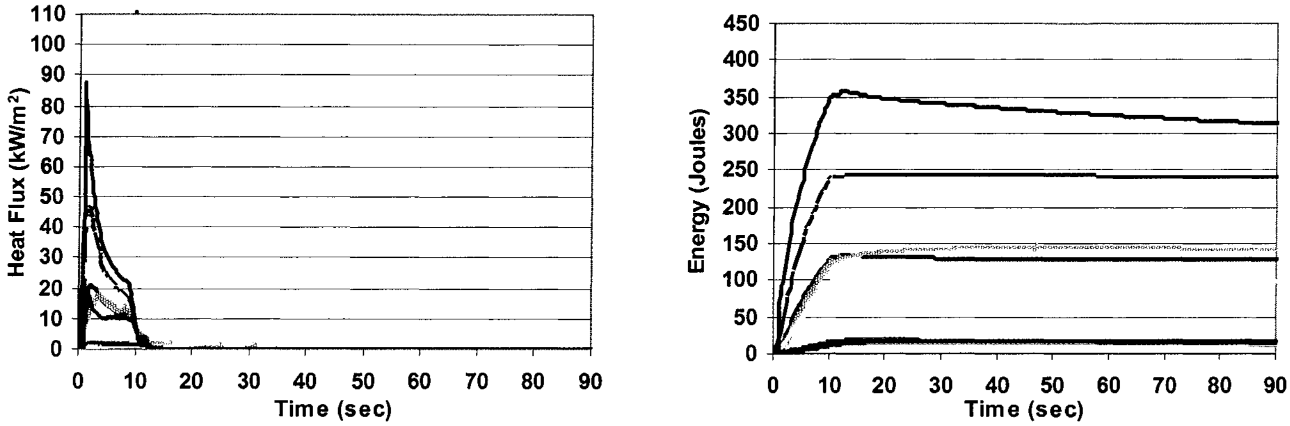
Fabric B



(a) *(b)*

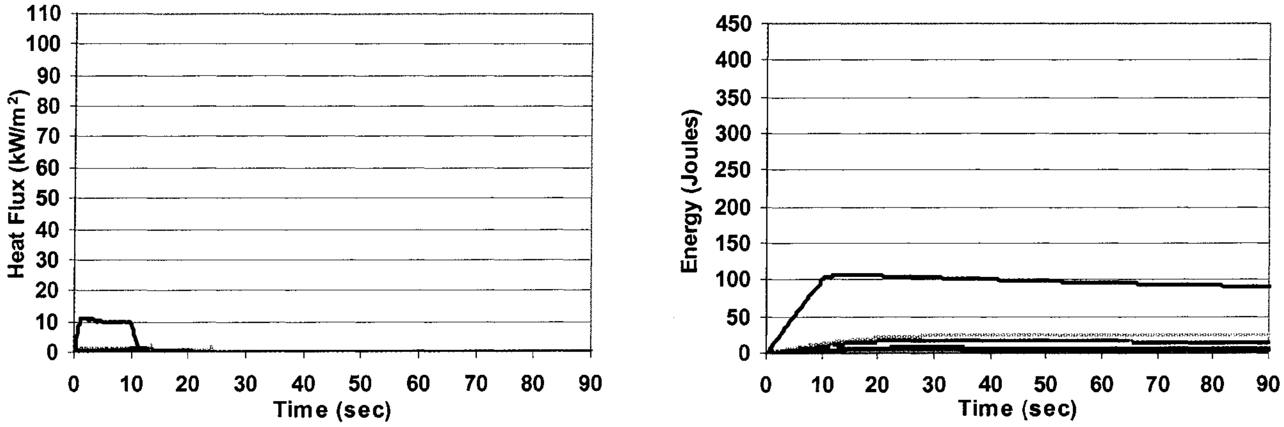
Fabric C

Figure 12. (a) Heat Flux (b) Energy Transferred - 207 kPa/50mm



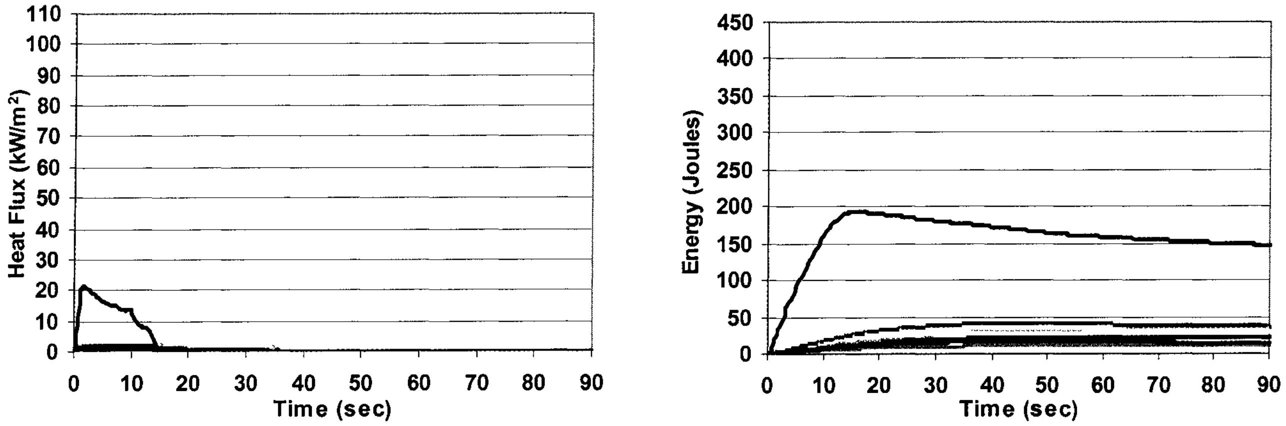
(a) *(b)*

Fabric A



(a) *(b)*

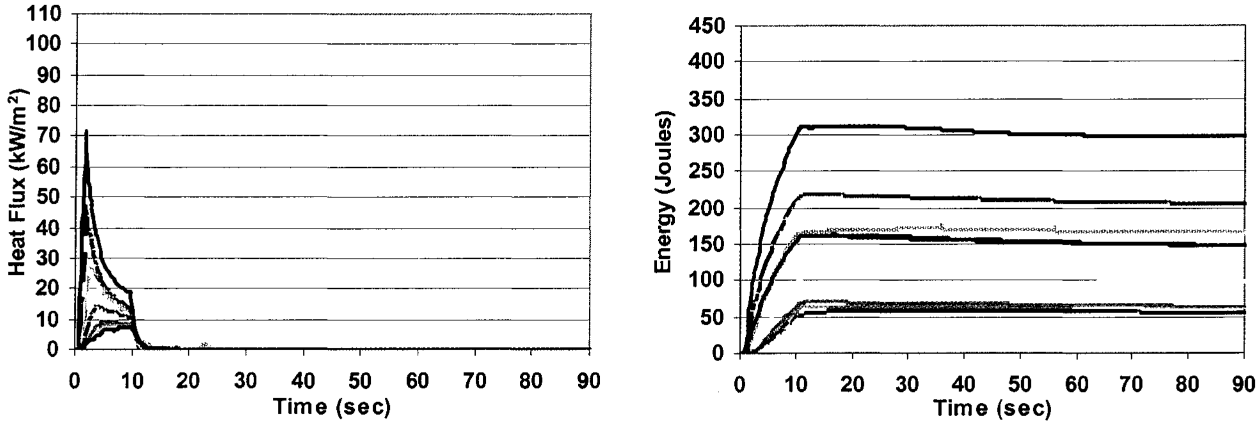
Fabric B



(a) *(b)*

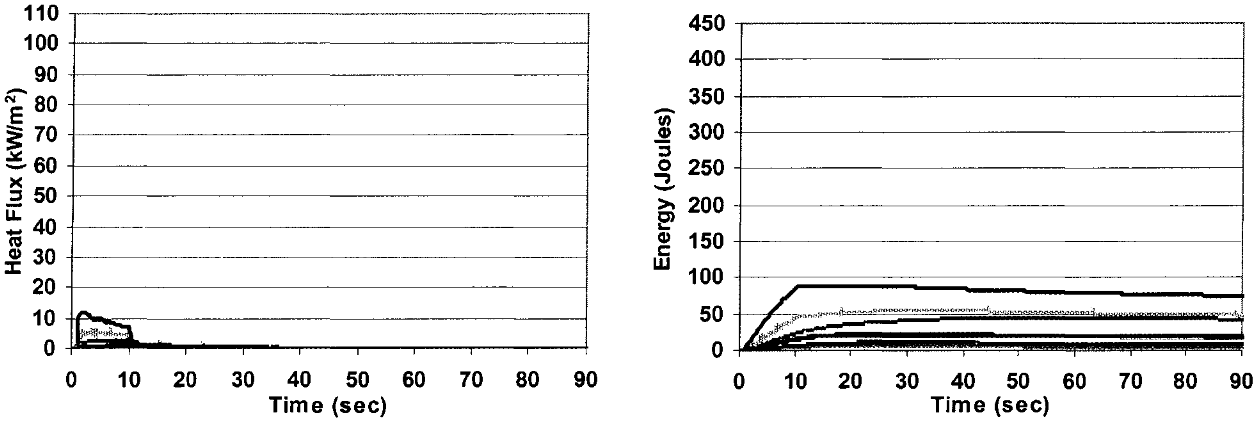
Fabric C

Figure 13. (a) Heat Flux (b) Energy Transferred - 69 kPa/50mm



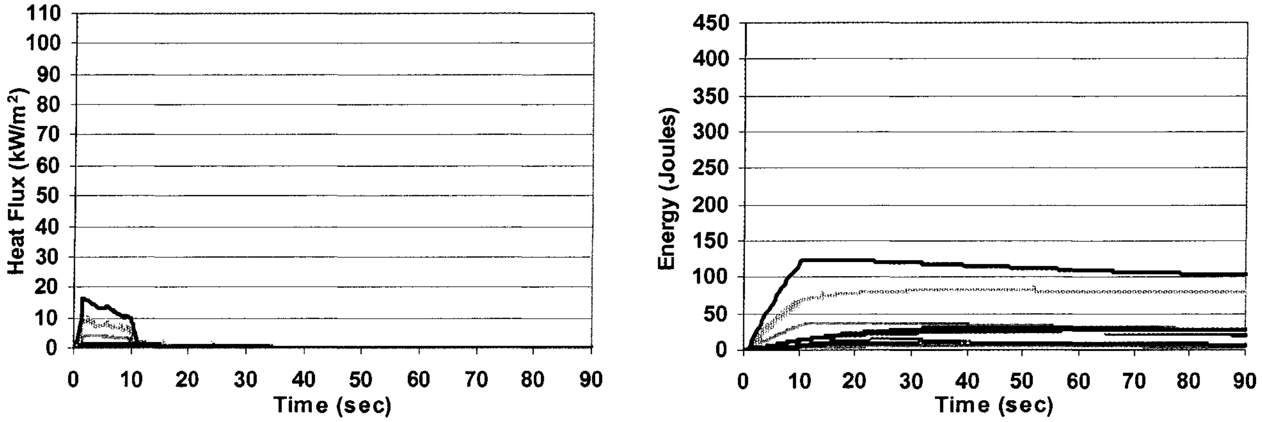
(a) *(b)*

Fabric A



(a) *(b)*

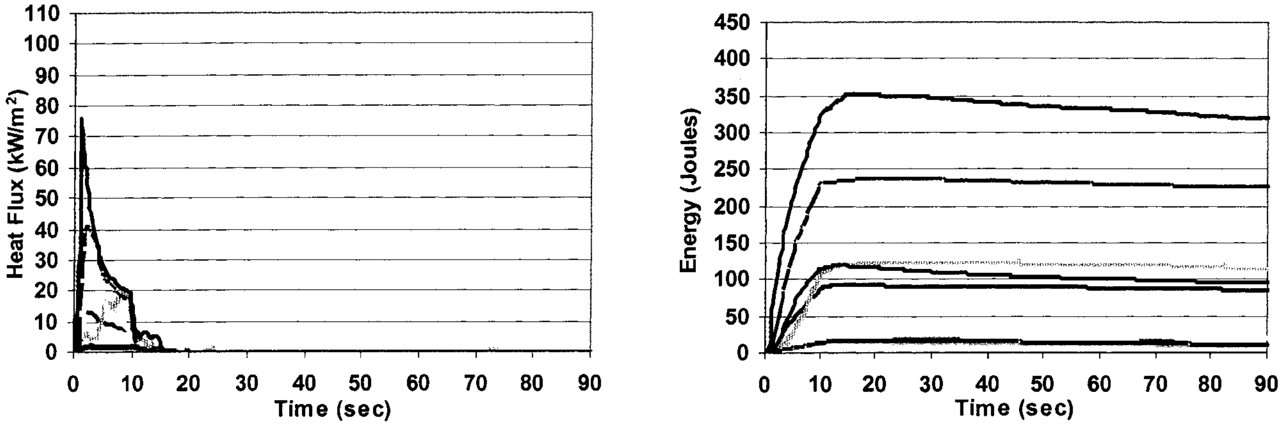
Fabric B



(a) *(b)*

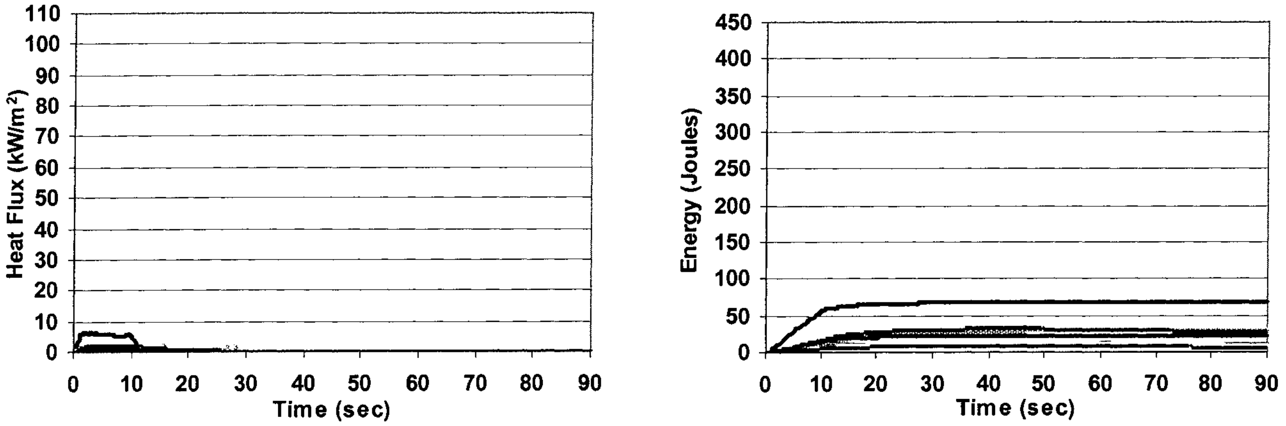
Fabric C

Figure 14. (a) Heat Flux (b) Energy Transferred - 207 kPa/100mm



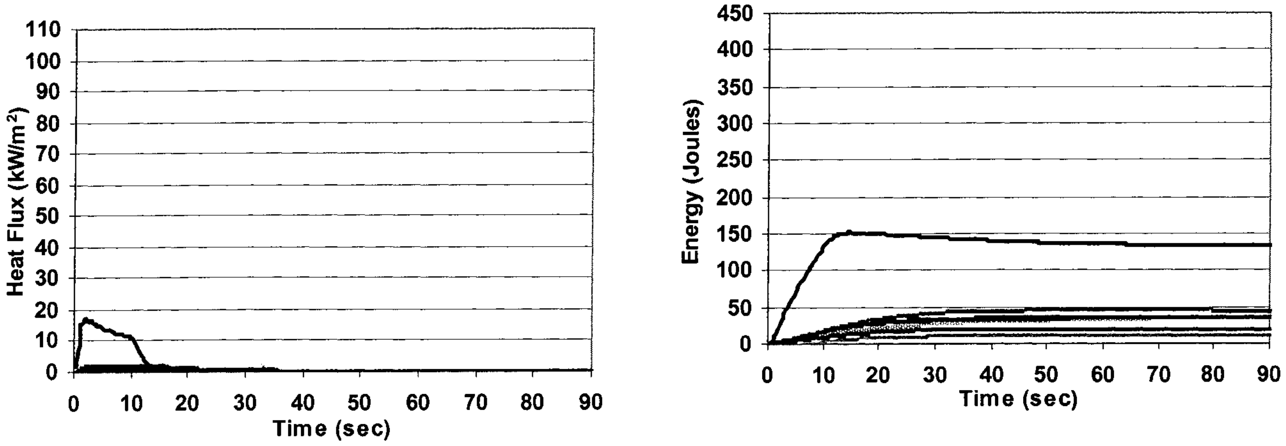
(a) (b)

Fabric A



(a) (b)

Fabric B



(a) (b)

Fabric C

Figure 15. (a) Heat Flux (b) Energy Transferred - 69 kPa/100mm

Discussions of Objectives and Hypotheses

Objective 1

The first objective of this research was to develop a test device to measure heat transfer through a fabric while exposing it to steam under the conditions that are typical in the oil and gas industry. This objective was partly accomplished. In industry the steam pressure is often found to be between 480 kPa (70 psi) and 700 kPa (100 psi), which was not possible to simulate in the lab. The maximum pressure under which the tests were performed was 207 kPa. However, the test device was designed keeping in mind the nature of the hazard. Hazard assessment led to a better nozzle design, a human-torso-shaped cylinder and an understanding of the effects of distance and pressure. These considerations proved to be important elements of the test device.

Objective 2

The second objective of this research was to validate the test device and procedure by measuring protective performance of some FR fabrics expected to differ on steam transfer. This objective was successfully met for three fabrics tested. The first null hypothesis that there are no significant differences in heat transfer among different fabrics, stands rejected as the heat transferred through different fabrics varied significantly. Fabric A has the least protection under all the conditions followed by fabric C and fabric B. The second and third null hypothesis are rejected too, as there were significant differences between the two distances and between the two pressures for peak temperature, peak heat flux and total energy. Conditions where distance was shorter and pressure was higher showed higher values for heat flux, energy and temperature. For both null hypotheses 2 and 3, there was no significant difference in time to reach peak heat flux because for all fabrics the sensor temperature rose immediately as soon as the fabric was exposed to steam. Since all hypotheses stated for objective 2 were rejected, it can be said that the test device and procedure differentiated well among fabrics for all conditions, and also differentiated among conditions. The effect of distance was found be more dominant compared to pressure, as most of the two way interactions were significant for fabric by distance.

Objective 3

Objective 3 was to relate steam protective performance to fabric characteristics like mass, thickness and fabric structure and to other physical properties like air permeability, water vapour diffusion, dry thermal insulation, evaporative resistance and total heat loss. This objective was not accomplished statistically. To determine the individual effect of these parameters on each dependent variable, means obtained for each dependent variable for each condition of distance and pressure were plotted against the means for thickness, thermal insulation (Rct), water vapour diffusion resistance (Dm) and total heat loss of the specimen. Because there are only three data points on each plot, it is difficult to see any obvious relationship between dependent variables and fabric parameters. No attempt has been made in this report to combine various parameter effects into one mathematical model. Nevertheless, when fabric properties are considered together rather than individually they can help explain the results of the experiments.

Fabric B, which is a thicker fabric, showed good resistance to heat transfer in most conditions. On the other hand Fabric C, which is considerably thinner with a higher mass (i.e., more dense) provided low resistance to dry heat transfer by conduction. Fabric A, being an open weave structure, was vulnerable to both heat and vapour transfer. On the other hand, Fabric B, a multilayer laminated fabric with tighter weave and a water resistant surface and a polyurethane film, restricting the steam penetration. For the conditions of the current research it is believed that condensation occurs immediately when the steam hits the surface of the fabrics with water repellent surfaces. For Fabrics B and C, as soon as the steam hits the fabric surface, it condenses and disperses around the area exposed to steam. Except for the area closest to the main sensor the condensed liquid remains as droplets rather than spreading over fabric surface, due to their water repellent surfaces. The interfacial tension between droplets and surface of the fabric, does not allow the condensed liquid to be easily absorbed into the fabric. However, the outer fabric surface does wet out in a small area around the main sensor where steam pressure is concentrated. For fabric B, with microporous film, the effect of condensation then plays an important role in vapour transfer. The microporous film normally allows water vapour molecules to pass through, but this did not happen in this case. The condensed (liquid) water on the surface cannot pass through the micro passages of the film and acts as a barrier to vapour transfer. For non isothermal conditions as found in this study, as the amount of condensation increases the vapour transfer decreases (Ren and Ruckman, 1999).

The results of this study can be compared with Rossi *et al's* (2004) study. Rossi *et al* concluded that steam transfer through fabric is a function of their water vapour permeability as well as thickness and thermal insulation. This holds true for the fabrics in this study. Rossi et al also concluded that impermeable materials such as Fabric C offer better protection compared to semi permeable ones such as Fabric B. In this study this was not observed due to the effect of condensation happening on the surface of Fabric B as discussed above and also because Fabric C is thinner and denser than Fabric B leading to greater dry heat transfer.

Chapter 5

SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

Summary

All clothing is protective to some extent, but it is the degree of protection from a specific hazard that is of major concern. Workers in oil and gas industries often come in direct contact with steam while conducting routine checks or during repairs. Workers in these industries wear flame resistant clothing to protect against flash fires. Although fewer, steam injuries are worse due to high pressure and temperature as pressurised steam can easily penetrate existing FR fabrics prevalent in the oil and gas industry. Moreover, these garments are not tested for protection against steam because there is no existing test method or even test equipment to measure heat transfer through fabric when exposed to pressurized steam.

In this research, a test device and procedure were developed and validated by measuring heat transfer through some flame retardant fabrics when exposed to steam under different exposure conditions. Empirical testing of fabric characteristics and other performance properties were carried out and an attempt was made to relate these fabric parameters to heat transfer.

For the test device to simulate the hazard, several considerations were taken into account during the design process. Some of the important considerations were: steam pressure, distance between nozzle and fabric surface, nozzle design and placement of sensors on the cylinder surface. The final design of the test device was accomplished after several preliminary experiments. The test device comprises a cylinder, simulating a human torso with built-in skin simulant sensors on its face. The sensors are connected to data loggers that measure temperature rise as a function of time. The test device also has steam inlet and outlet valves and a nozzle at the exit of steam outlet. Finally the test device is fitted with a pressure monitoring gauge, to measure pressure of the steam at the nozzle inlet.

To validate the test device and procedure it was necessary to determine whether they were able to differentiate among fabrics. Fabrics were selected based on the rankings of their resistance to water vapour diffusion and were therefore expected to differ on their heat and moisture transfer upon steam exposure. Three fabrics were exposed to four different conditions of pressure (69 kPa and 207 kPa) and distance between nozzle and fabric surface (50mm and 100mm). Four dependent variables were calculated for each exposure condition: peak temperature, peak heat flux, time to reach peak heat flux and total energy. The worst heat transfer was observed at the shorter distance and higher pressure. At this condition, temperatures for all the three fabrics reached their peak almost instantaneously, with the highest peak observed for Fabric A, followed by Fabrics C and B. For coated or laminated fabrics only the sensor directly in line with nozzle indicated significant heat transfer, while for the fabric specimens without coating/lamination several sensors indicated such a pattern.

Conclusions

The test device was able to differentiate among fabrics in terms of heat transfer when exposed to steam pressures up to 207 kPa. Under all four conditions fabrics differed significantly for peak temperature, peak heat flux and total energy. For each fabric, both distance and pressure had significant effects on peak temperature, peak heat flux and total energy, with the greatest heat transfer being at 50 mm and 207 kPa.

Although no concrete conclusion could be made about the relationships between fabric parameters and heat transfer, we understand from previous research that factors such as thickness, fabric structure, finish, water vapour permeability, air permeability, thermal insulation and total heat loss definitely influence the heat and vapour transmission. In this research fabric properties such as resistance to water vapour diffusion (Dm), air permeability, thermal insulation (Rct) and total heat loss seemed to interact with fabric characteristics such as thickness and presence of a coating/laminate in determining steam penetration and heat transfer.

Implications/Recommendations to the Industry

This research has shown that the test device developed in this study was able to distinguish among the fabrics at pressures up to 207 kPa. The results presented in this thesis are an eye opener for the industries where steam is utilized in several different applications and where steam pressures in the pipelines are significantly higher. It is evident from the results that both distance and pressure influence heat transfer. The tests were conducted at much lower pressures as compared to industrial set ups where the typical steam pressure existing in lines for the day to day operations was found to be 620 kPa (Fennel, 2003). In the current research it was observed that the temperature in all three fabrics rose above 50° C under most of the conditions, implying second degree burn to the skin tissue, and could be much worse if the exposure time is higher (Stoll and Chianta, 1969).

Further Research

In the current research achieving steam pressures above 207 kPa during the tests was a limitation. Therefore, further work at higher pressure is needed to assess the hazard in more detail so as to meet the requirements of industry. This research has stimulated a need to develop specifications for clothing systems to prevent partial or full-thickness burns from heat transfer onto the skin during or after an exposure incident.

Generally in a textile testing laboratory or in other material testing facilities it is rare to find steam pressures as high as 90 psi. It is therefore recommended that theoretical models that could predict heat transfer through different fabrics in the event of steam exposure be developed. This research has outlined three important variables (fabric, pressure and distance) that significantly influence the heat transfer. Besides pressure and distance, we know that fabric characteristics and performance properties should influence heat transfer. Hence more work is needed to develop a numerical model incorporating the testing parameters (pressure, distance and temperature of steam) and fabric characteristics and performance properties. Several different types of fabrics should be tested on the test device developed in this study to more accurately determine the combined influence of such fabric parameters on steam related heat transfer before such a model can be developed.

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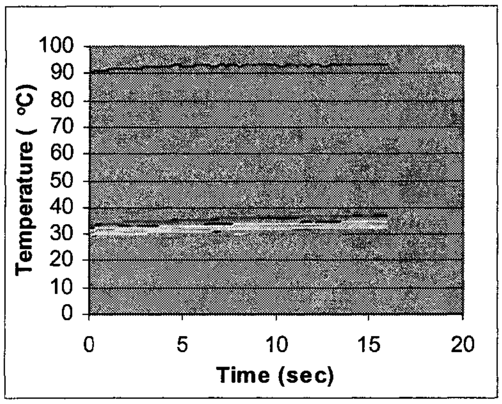
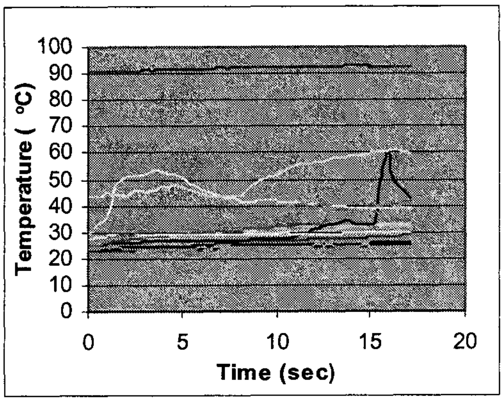
Appendix 1

First set of preliminary experiment results-Temperature vs time plots



FR cotton/Spacer/50mm



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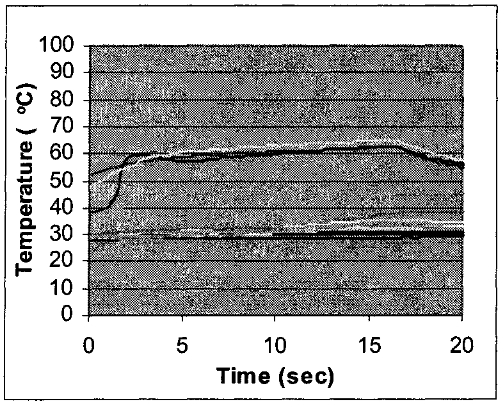

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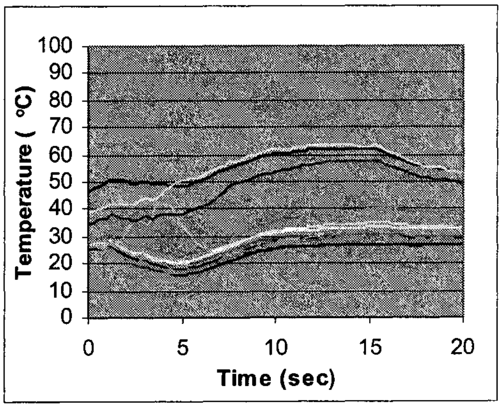

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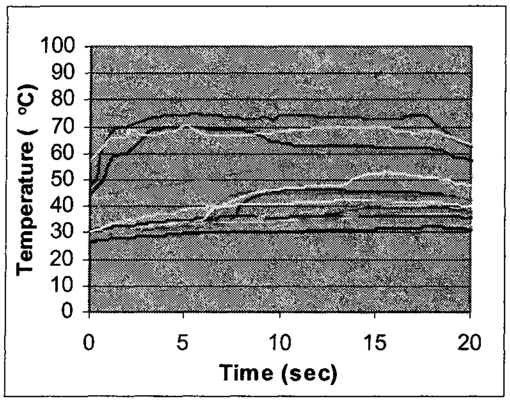
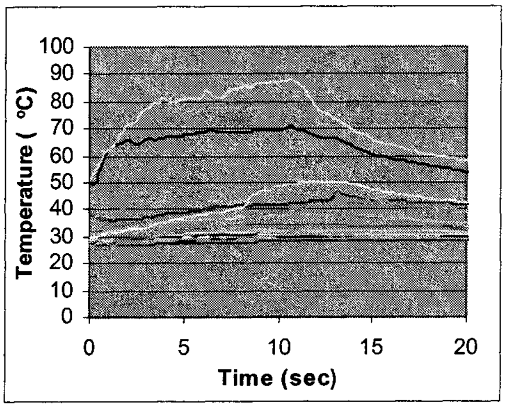


Aramid/Spacer/50mm



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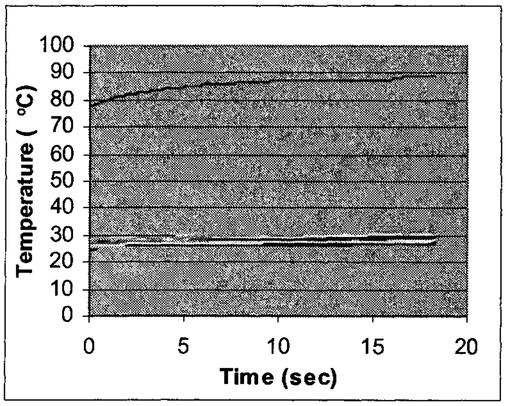
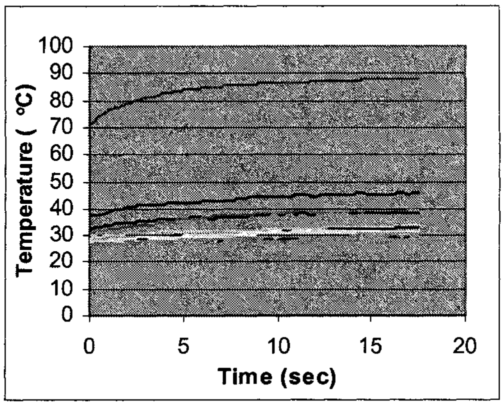


170 grm/m^2, 2 layer, Aramid-PU Spacer/50mm



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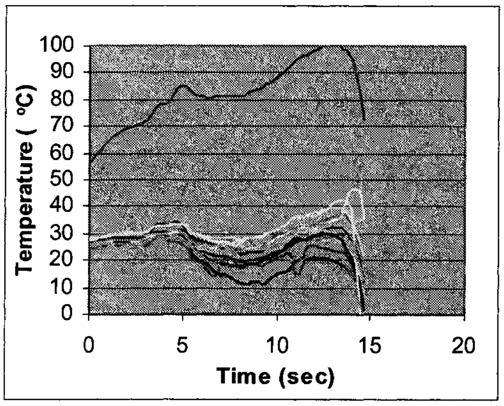

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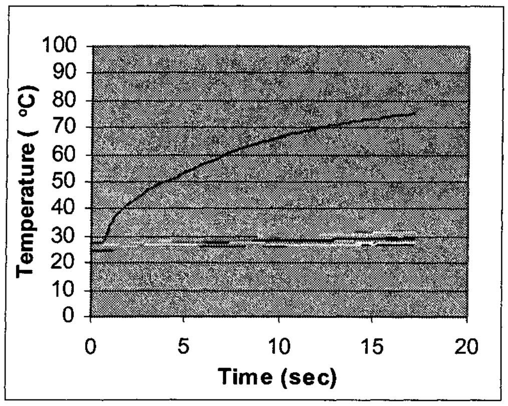
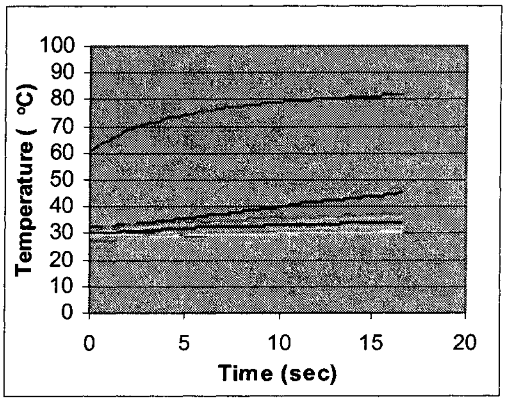


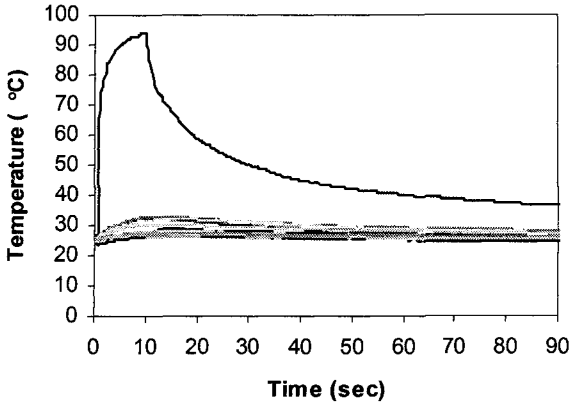
3 layer, Aramid-PU/Spacer/50mm



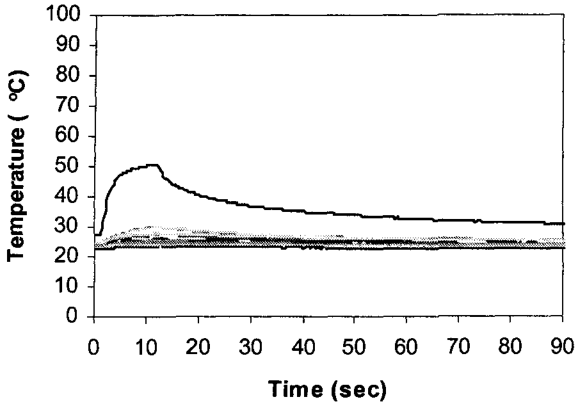
3 layer, Aramid-PU/ No Spacer/50mm

Appendix 2

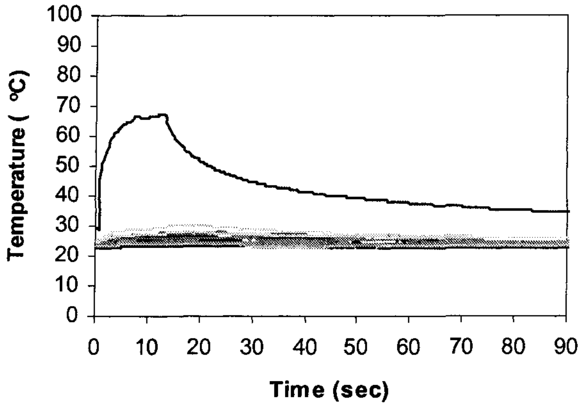
Second set of Preliminary Experiments - Temperature vs time plots



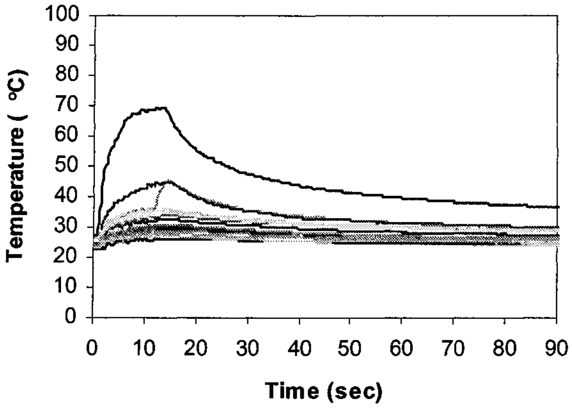
Aramid-PU/50mm/69 kPa



Aramid-PU/100mm/280 kPa



Aramid-PU/180mm/280 kPa



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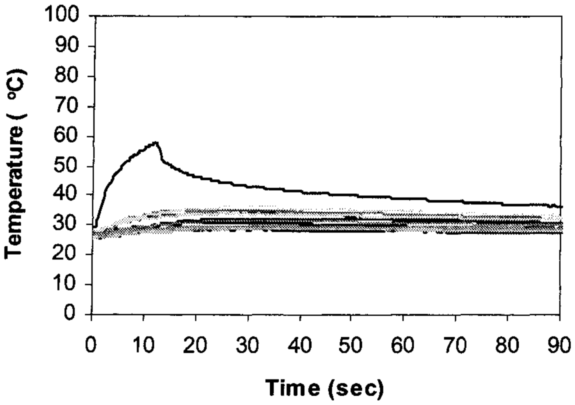
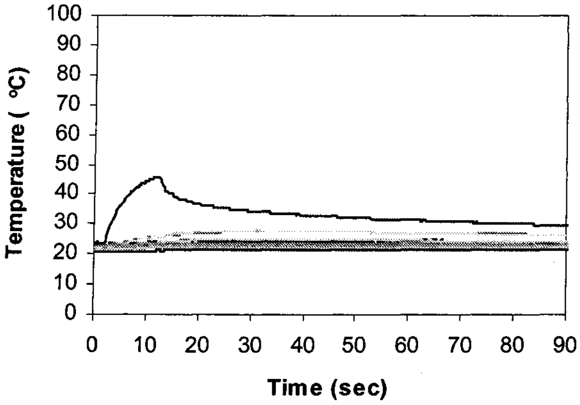
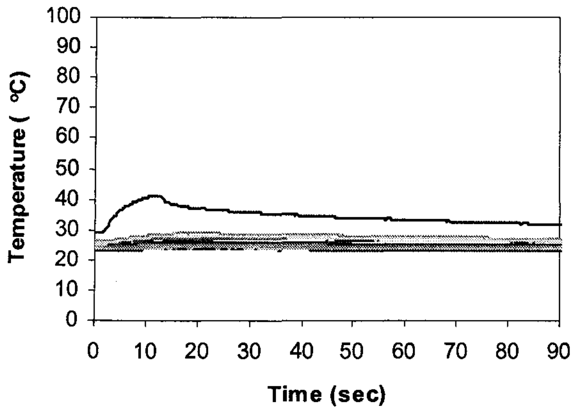


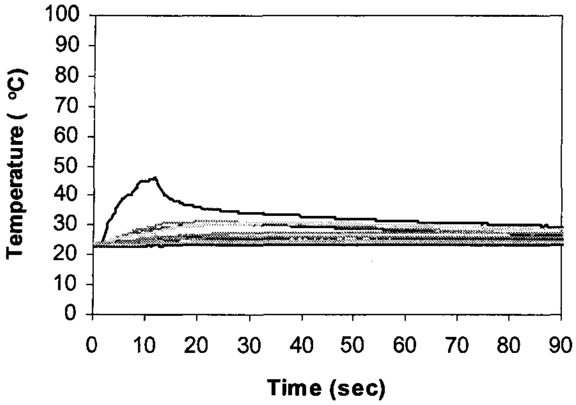
Carbon-Silicon/50mm/69 kPa



Carbon-Silicon/100mm/280 kPa



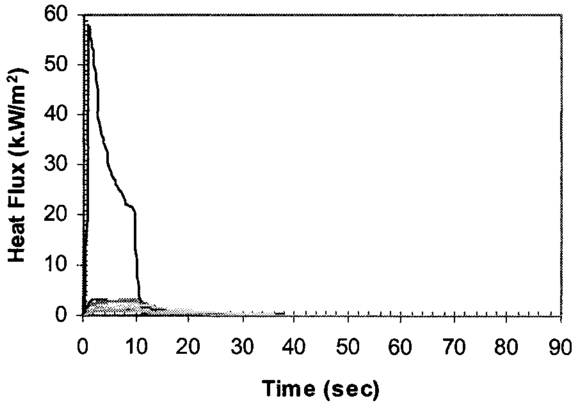
Carbon-Silicon/180mm/280 kPa



Carbon-Silicon/180mm/69 kPa

Appendix 3

Second set of Preliminary Experiments - Heat Flux and total energy plots



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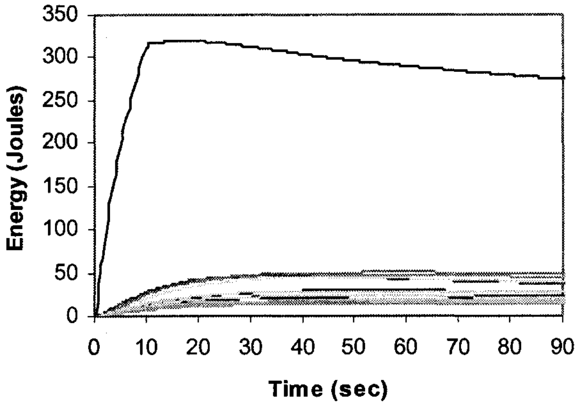

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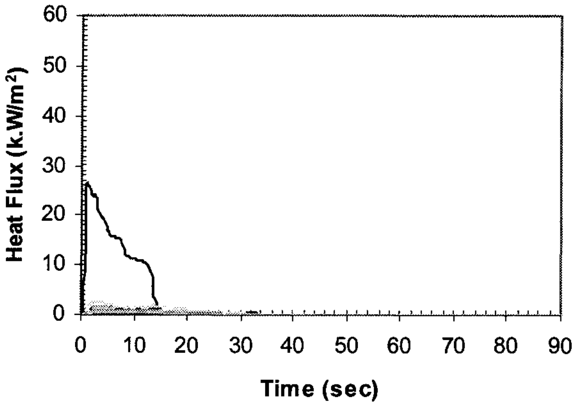
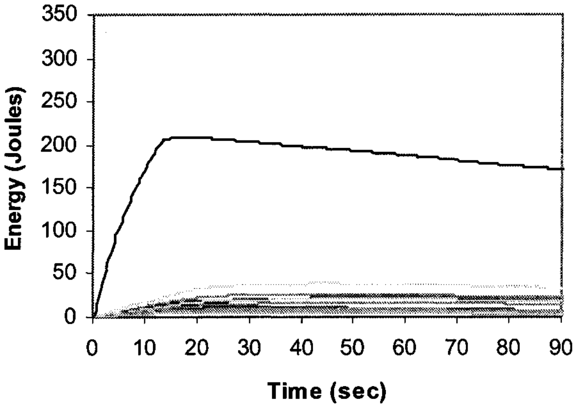


Aramid-PU/100mm/280 kPa



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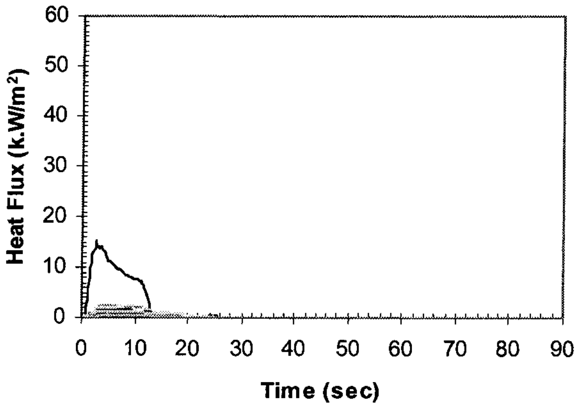

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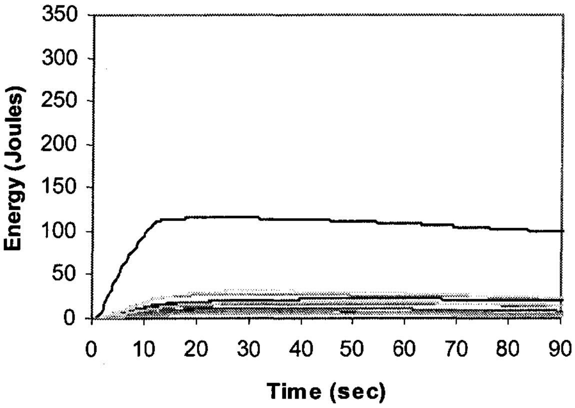

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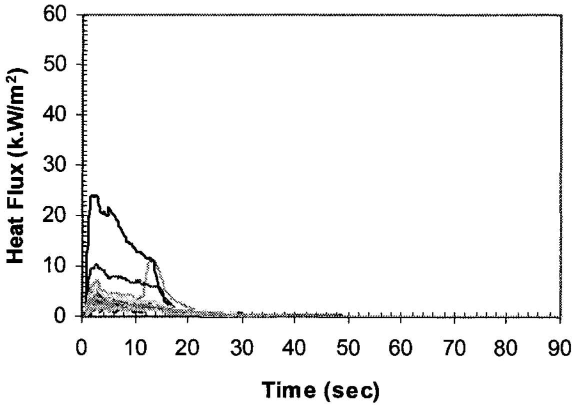

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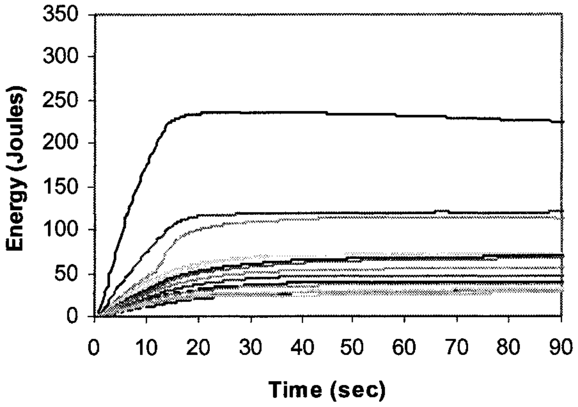
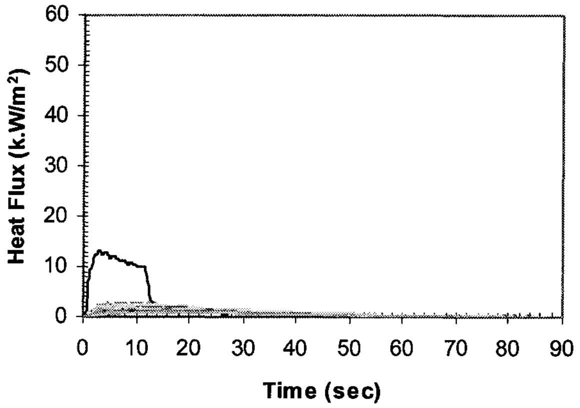
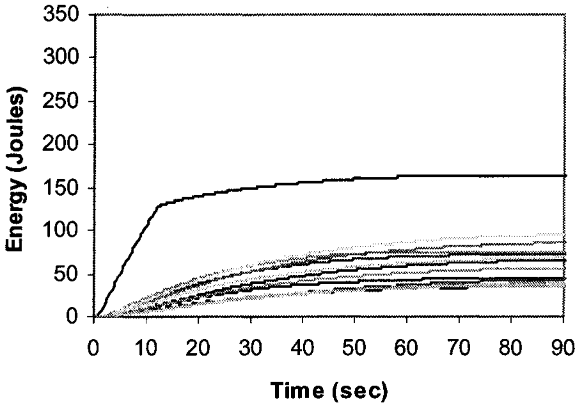


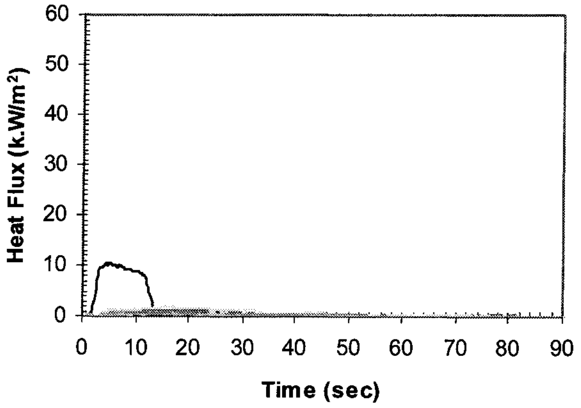
Aramid-PU/180mm/69 kPa



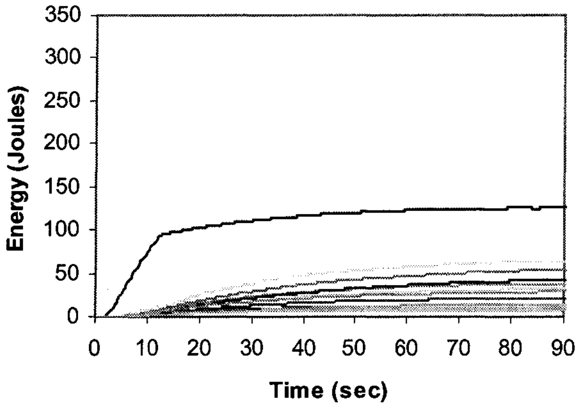
Carbon-Silicon/50mm/69 kPa



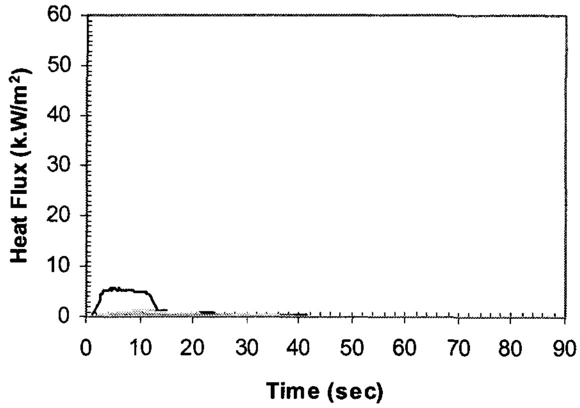
Carbon-Silicon/50mm/69 kPa



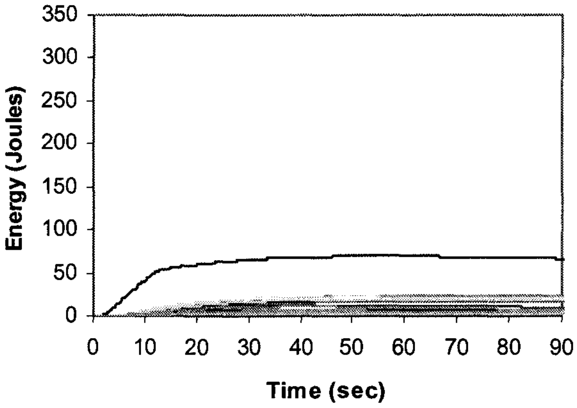
Carbon-Silicon/100mm/280 kPa



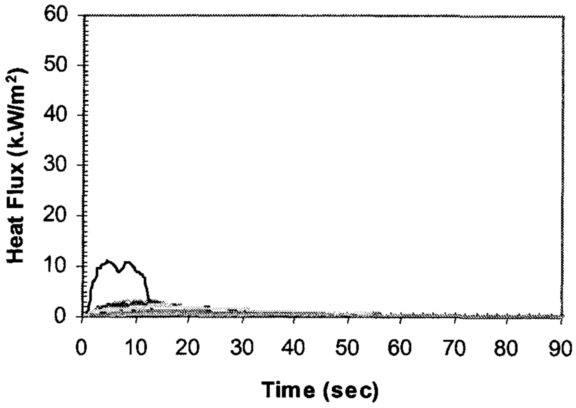
Carbon-Silicon/100mm/280 kPa



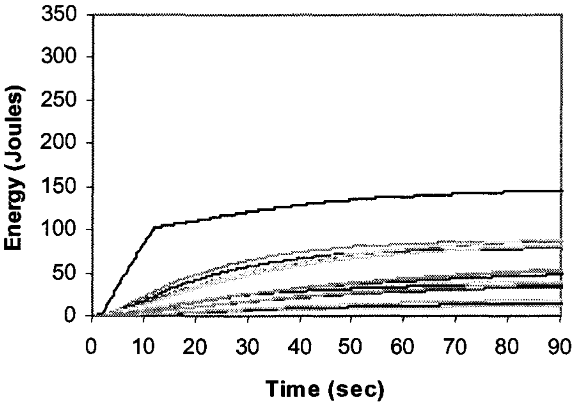
Carbon-Silicon/180mm/280 kPa



Carbon-Silicon/180mm/280 kPa



Carbon-Silicon/180mm/69 kPa



Carbon-Silicon/180mm/69 kPa

Appendix 4

Preliminary experiments: Means for peak heat flux and total energy

	Peak Transferred Heat Flux Mean				Total Energy Mean			
Fabric	Low Pressure/ Large Nozzle		High Pressure/ Small Nozzle		Low Pressure/ Large Nozzle		High Pressure/ Small Nozzle	
	d=180 mm	d=50 mm	d=180 mm	d=100 mm	d=180 mm	d=50 mm	d=180 mm	d=100 mm
C/S R1	9.94	13.33	5.55	10.13	129.83	173.9	68.67	121.76
C/S R2	8.55	13.48	6.15	11.32	88.51	129.4	77.2	146.2
C/ S T	9.1	13.4	5.84	10.84	105.04	151.6	72.93	136.42
A/PU R1	28.08	53.54	13.69	31.52	200.93	274.5	90.67	195.76
A/PU R2	29.35	49.46	14.47	27	158.22	251.4	106.8	170.64
A/PU T	28.5	51.71	13.92	29.58	186.69	264.6	95.28	184.99

d = distance between nozzle and cylinder
C/S - Carbon/Silicon
A/U – Aramid/Polyurethene
R – Replication
T – Total (R1&R2)

Appendix 5 Means and Standard Deviation for dependent variables-Replication-1 and 2

Fabric		**Peak Heat Flux**				**Time to reach Peak Heat Flux**				**Total Transferred Energy**				**Peak Temperature**			
	Pressure(psi)	10		30		10		30		10		30		10		30	
	Distance(mm)	50	100	50	100	50	100	50	100	50	100	50	100	50	100	50	100
A																	
Rep I	*Mean*	98	57	104	66	1.0	1.3	1.2	1.3	321	251	378	260	99	82	109	85
	Std Dev	16	5	7	10	0.4	0.1	0.3	0.2	9	26	12	48	1.4	3	4	9
Rep II	*Mean*	84	64	89	67	1.3	0.9	1.2	1.0	322	231	358	290	95	77	99	86
	Std Dev	7	12	4	2	0.1	0.3	0.1	0.2	9	20	11	6	1.3	0.5	3	4.5
B																	
Rep I	*Mean*	10	6	20	12	2.4	2.5	1.2	2.3	78	59	106	80	47.5	39	65.8	47.4
	Std Dev	1	0.3	1.7	2.3	0.6	1.0	0.1	0.7	7	5	13	15	2.4	0.5	5	2
Rep II	*Mean*	10	6	13	10	2.6	2.5	3.9	1.7	87	57	114	87	48	39.3	55	46
	Std Dev	2	0.3	2	0.5	0.5	0.4	3.0	0.4	13	6	10	20	3.1	0.7	6	1.7
C																	
Rep I	*Mean*	23	17	33	20	2.3	2.6	2.4	2.0	153	128	175	115	67	56	80	59
	Std Dev	1.7	0.3	1.2	2.8	0.4	0.5	0.4	0.2	6	6	6	8.5	2.4	1.4	1.4	3.2
Rep II	*Mean*	20	16	29	19	2.1	2.5	2.1	1.9	135	110	167	125	64	57	75	59
	Std Dev	1.6	0.9	1.3	7.4	0.3	0.6	0.3	0.5	13	9	24	34	1.8	0.9	0.5	11