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Protection From Steam at High Pressures: Development of a Test Device and Protocol

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Extensive use of pressurized steam in the 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 and evaluated. Several factors were considered while designing the test device to simulate work site conditions. Fabrics were exposed to steam at 2 distances (50 and 100 mm) and 2 pressures (207 and 69 kPa). Theoretical considerations included heat and mass transfer, and fabric structure and performance properties. The test device and procedure differentiated well among both fabrics and exposure conditions. For all fabrics, maximum heat transfer was observed at highest steam pressure and shortest distance. Laminated and coated fabrics performed better than a fabric without such treatments.

steam protection high pressure steam protective materials

1. INTRODUCTION

The purpose of this research was to develop a test device and procedure to measure heat transfer through fabric systems exposed to steam under conditions that are typical in the oil and gas sectors. Potential for exposure to such hazards is high in these sectors in Alberta, Canada. Although workers in these industries wear flame resistant (FR) protective clothing to prevent skin

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burn injuries from flash fires, steam is another substantial hazard for which little protection is provided. Incidents have been documented by the Canadian Petroleum Safety Council where workers have been injured due to steam exposure, including one fatality [1].

No performance standard for evaluating steam protective properties of clothing currently exists. By examining the rate of heat and moisture transfer through fabrics during steam exposure, and through understanding the mechanisms of such, differences among FR clothing materials can be evaluated and improved clothing systems can be developed. Although extensive research has been conducted to understand mechanisms of heat and vapour transfer through different clothing systems, most has focused on transfer from human skin towards the environment with relatively low heat fluxes [2, 3, 4, 5, 6, 7]. Li [2] concluded that the transfer of energy in mostly porous textile assemblies was governed by conduction by air and fibers, convection and radiation, while moisture transfer mechanisms included vapour diffusion in void space, moisture absorption by fibers, evaporation, and capillary effects. Li [2] and Wang and Yashuda [3] noted that heat and moisture transfer were two highly coupled processes wherein the heat transfer process was accompanied by phase changes such as moisture sorption/desorption and evaporation/condensation.

Li and Zhu [4] developed a mathematical model to predict the simultaneous heat and mass transfer through porous textiles and stated that the transport of the liquid moisture across textiles increased their thermal conductivity and changed the heat transfer and moisture absorption of fibers. Fukazawa, Kawamura, Tochihara, et al. [5] investigated the combined heat and water vapour transfer rate through clothes with condensation at simulated high altitudes; they found that the water vapour transfer rate was determined by the concentration gradient, while the saturation concentration was temperature dependent. Thus they concluded that the water vapour concentration and temperature gradient were the determinant factors in water vapour transfer and condensation in clothing.

Gibson [6] studied the degree to which water vapour transport properties of several different polymer membranes and membrane/textile laminates were affected by temperature. Tests were carried out in a dynamic moisture permeation cell, 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 to 50 °C. Gibson explained that in nonporous samples the transport of water vapour proceeded by pure diffusion, driven by vapour concentration differences.

The effect on heat transfer of moisture in fabrics, garments and garment assemblies exposed to high heat fluxes has been reviewed and reported elsewhere [8, 9, 10, 11]. In general, moisture has been found to decrease thermal insulation, and as the fabric is saturated, the thermal conductivity of water influences heat transfer more than that of the material. Heating and evaporation of moisture trapped in clothing assemblies may result in steam burns; on the other hand, moisture in the outer layers may offer protection from heat transfer.

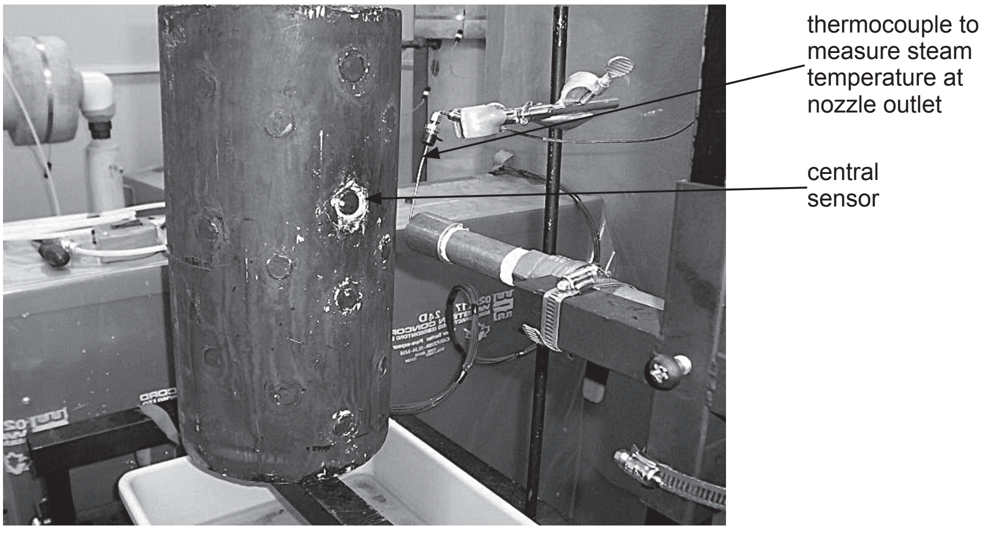
No study reviewed dealt with heat transfer through fabrics exposed to steam under the very high pressure conditions experienced in the oil and gas sectors. However, Le and Ly [12] studied heat and mass transfer through an absorbing fibrous medium consisting of layers of textile fabric in a condensing flow of steam at relatively high temperature and pressure as found in pressure-decatizing of wool fabric. Under such conditions they considered convection to be the primary mechanism of heat and mass transfer. Analyzing the transfer of steam through different textile layers to a sweating body, Rossi, Indelicato and Bolli [13] reported that energy transfer was dependent on the water vapour permeability, thickness and thermal insulation of the specimens. They concluded that materials which were impermeable to vapour provided better protection to hot steam than semipermeable ones. Desruelle and Schmid [14] developed a set of tools to study the effects of exposure to hot water steam on human physiology and to evaluate the protective capacity of fabrics under steam stress. Their test device included a steam generator that had a maximal internal temperature of 142 °C at a pressure of 300 kPa. They also used a thermal mannequin to evaluate the thermal protective capacity of garments. However, their work involved lengthy time scales (wherein the skin would likely be destroyed) and unrealistically held the skin surface at constant temperature, likely implying greater rates of heat transfer than would actually occur. In reality, the skin surface temperature would rise during the exposure, resulting in reduced heat transfer rates in response to reduced temperature difference. The authors concluded that fabric thickness and water vapour diffusion had significant effects on protection against steam exposure.

The objectives of this research were to (a) develop a test device and procedure to measure heat transfer through a fabric while exposing it to steam under moderately high pressures, and (b) validate the test device and procedure by evaluating the relative protective performance of some existing FR fabrics against steam while varying exposure pressure and distance.

2. DESIGN AND DEVELOPMENT OF TEST DEVICE

A cylinder, 230 mm in diameter and 460 mm in height, was built with fiberglass and polyester resin and fixed to a steel frame. Skin simulant

(a)



(b)

Figure 1. (a) Cylinder with sensors on the test device, (b) test device in operation.

sensors were mounted flush to the surface of the cylinder to measure energy transfer. These sensors were connected to a data acquisition system that was used to record the surface temperature of the sensor as a function of time. Sensors were evenly distributed over the front face of the cylinder as indicated in Figure 1a. Several factors were taken into consideration in the design of the test device (sections 2.1.–2.7.).

2.1. Shape of Fabric Mounting Surface

A cylindrical shape was selected to simulate a human torso. The rates of heat transfer to a flat surface differ significantly from those for a curved one when exposed to forced convection, such as occurs during steam exposure. On a planar surface the jet of steam impinging on the surface stagnates at the jet centre resulting in reduced rates of heat transfer. The fluid then spreads axisymmetrically from the jet centre and produces a changing convective heat transfer coefficient with distance from the stagnation point. If the steam temperature were constant this would result in rates of heat transfer that vary significantly with position. With a cylindrical form the convective heat transfer coefficient remains relatively constant for a fairly wide range of angles on either side of the stagnation point.

2.2. Mounting the Fabric on the Cylinder

The fabric could be mounted with or without a frame to provide an air gap between the cylinder and fabric. Preliminary experiments indicated that any space created by the frame was negated almost instantaneously by the pressure from steam impingement. Therefore, for the experiments reported here, the fabric was positioned over the cylinder, pulled taut and held in place with spring clips. Thus, the back side of the fabric specimen was, in most cases, in contact with the sensor surface.

2.3. Type of Temperature Sensor

Nine skin simulant sensors based on that developed by Dale, Crown, Ackerman, et al. [15] were placed on the front surface of the cylinder to measure the heat transfer through fabrics. The sensors were a 19-mm-diameter, 32-mm-thick plug of colerceran with a 30-gauge copper constantan thermocouple bonded to the surface to measure surface temperature. The thermal physical properties of colerceran are such that the surface temperature rises in a manner similar to human skin. The thermocouple wires were reduced in thickness to 0.1 mm before bonding to increase bond area and improve response time.

2.4. High Pressure Steam Source and Regulator

The highest pressure available in the main line in a laboratory setting was 345 kPa. A pressure regulator was installed to achieve uniform steam flow during the tests, further reducing the maximum pressure available for testing. Two pressures were selected for testing: 69 and 207 kPa.

2.5. Exposure Time

The exposure time was determined based on a probable worst case scenario. Although a person coming in direct contact with steam may try to escape almost instantly, in some situations this may not be possible. The exposure time was set at 10 s during all experiments.

2.6. Proximity Between the Hazard and Subject

After preliminary experiments, two distances (50 and 100 mm) between cylinder and steam nozzle were selected.

2.7. Nozzle Design

Three nozzle geometries giving different patterns of steam distribution on the fabric surface were considered. After preliminary experiments, a vertical slit design was selected because it most closely resembled a major industrial hazard, i.e., a piece of gasket blown out from between the two flanges typically used in a pipe connection.

3. EXPERIMENTAL METHODS

A laboratory experiment was conducted 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) to determine heat transfer through different FR fabrics exposed to steam. Two replications of the experiment were conducted with good consistency between replications.

3.1. Materials

In order to determine the ability of the test device and procedure to differentiate among fabrics with different performance, three FR fabrics were selected with the expectation that they should differ on steam permeability, based primarily on their differences in water vapour diffusion resistance (Dm). Diffusion resistance was determined following Standard CAN/CGSB-4.2 No. 49-99, Option 3 [16]. In this method, a test specimen is sandwiched between two layers of polytetrafluoroethylene (PTFE) film, one layer separating the specimen from a stream of dried air and the other forming the bottom of a dish of water. The rate of diffusion of water through the sandwich is calculated from the loss in mass of the water from the dish as a function of time. The water vapour resistance of the sandwich is then calculated and the resistance of the specimen is determined from the difference in the value for the sandwich to that obtained for the two films without the specimen in place. Diffusion resistance data and that on other fabric properties expected to influence steam permeability and heat transfer are given in Table 1. Fabric A had relatively low resistance to both air and water vapour diffusion and was also permeable to liquid water. Fabric B was impermeable to liquid water but permeable to vapour, and Fabric C was impermeable to both liquid and vapour. The mass and thickness of Fabrics A and B were relatively close while Fabric C was heavier yet thinner. Total heat loss following Standard No. ASTM F 1868-98 [17] was highest for Fabric A followed by Fabrics B and C.

3.2. Procedure

Fabric specimens (45 × 45 cm) were conditioned in a standard atmosphere of 20 °C and 65% relative humidity and were taken in a sealed polyethylene bag from the conditioning room to the lab where the tests were performed. Each specimen was clamped onto the cylinder within 60 s of its removal from the sealed bag. Steam was discharged on the test specimen for 10 s. A computer data acquisition system was used to collect sensor surface temperature information during the exposure and for a period of 80 s following the exposure (total time of 90 s). The relative humidity of the environment during the test was recorded, as was the steam temperature at the nozzle outlet. Air was applied to cool the sensors after every test. Figure 1b shows the test device in operation.

TABLE 1. Fabric Properties

Code	Description	Water Vapour Diffusion Resistance (Dm)[1]	Air Permeability[2]	Mass/Thickness[3]	Total Heat Loss[4]
A	meta aramid, plain weave, comfort finish	1.1	56.9	194/0.56	692
B	meta aramid, plain weave, polyurethane laminated	19.8	0.1	237/0.64	363
C	meta aramid, plain weave, tri-chloroprene coated	>150	0.0	520/0.34	227

Notes. 1—measured in millimetres of still air, according to Standard CAN/CGSB-4.2 No. 49-99, Option 3 [16], 2—measured in cubic centimetres per square centimetre per second ($cm^3/cm^2/s$) according to Standard CAN/CGSB-4.2 No. 36-2002 [18], 3—measured in grams per square metre (g/m^2) and millimetres according to Standard CAN/CGSB-4.2 No. 5.1-M90 and No. 37-2002 [19, 20], 4—measured in watts per square metre (W/m^2) according to Standard No. ASTM F 1868-98, part C [17].

3.3. Calculation of Dependent Variables

The highest (peak) temperature reached was obtained from each temperature/time plot. The temperature data obtained from skin simulant sensors were inversely transformed to obtain the heat flux. Heat flux was calculated over 90 s, 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 incident energy was defined as the integrated value of the area under the heat flux/time curve over 90 s.

3.4. Statistical Analyses

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. Three-way analyses of variance (ANOVA) were conducted to determine significant differences in each dependent variable for each of the independent variables as well as their interaction effects. Each replication was analysed separately and aggregate data from the two replications were also analysed. Main effects for each independent variable and two- and three-way interaction effects were determined. To identify differences among fabrics, Duncan's post hoc test was conducted.

4. RESULTS AND DISCUSSION

Data plots for a typical specimen of each fabric are provided in Figures 2–4, wherein different colored curves represent different sensors, with red representing the main or central sensor.

4.1. Temperature versus Time

For the severest condition at 207 kPa and 50 mm between nozzle and fabric surface (Figure 2), temperature rise is very sharp in Fabric A. Several other sensors close to the main sensor are also affected for Fabric A but much less so for Fabrics B and C. For Fabric B, the peak temperature reaches almost 75 °C by 10 s but falls sharply when the heat source is removed at 10 s. For Fabric C, the temperature rises very rapidly and reaches a peak above 80 °C after the heat source is removed.

The rapid rise in sensor temperatures for Fabric A is indicative of steam rapidly penetrating the fabric and raising the sensor temperature to that of the steam (~100 °C). The less rapid rise in sensor temperatures in Fabrics B and C is more indicative of the fabric providing a barrier to steam penetration and the energy transfer mechanism being dominated by conduction through the fabric. Note that even though the temperature of the steam is indicated as near 100 °C, the temperature falls with distance as room temperature air is entrained in the steam jet.

4.2. Heat Flux and Total Energy versus Time

Figures 3 and 4 show that at 207 kPa and 50 mm, heat flux and total energy transferred were highest for Fabric A, as they were for all pressure/distance conditions. The peak heat flux for this worst case scenario was above 110 kW/m^2, while the lowest peak heat flux was found in conditions where the distance was 100 mm at either pressure. Peak heat flux reached close to 90 kW/m^2 at 69 kPa and 50 mm.

For Fabric A under all conditions the heat flux rapidly rises to a peak as long as there is a gradient between steam temperature and sensor temperature, but drops sharply, even during the exposure period, once the steam and sensor temperatures reach an equilibrium condition. For all conditions several sensors in the vicinity of the main sensors were affected during the steam exposure. Fabric B had the lowest heat flux and energy transfer under all the conditions, but there is a distinct rise in the heat flux for higher pressure and shorter distance. Fabric C showed higher heat flux and energy transfer in the conditions where the distance was shorter than for the greater distance. It should be noted here that although impermeable, Fabric C was the thinnest of the fabrics tested while Fabric B was the thickest.

Considering energy plots for the worst case scenario (Figure 4), the curve declines slightly because once the steam is shut off the sensor

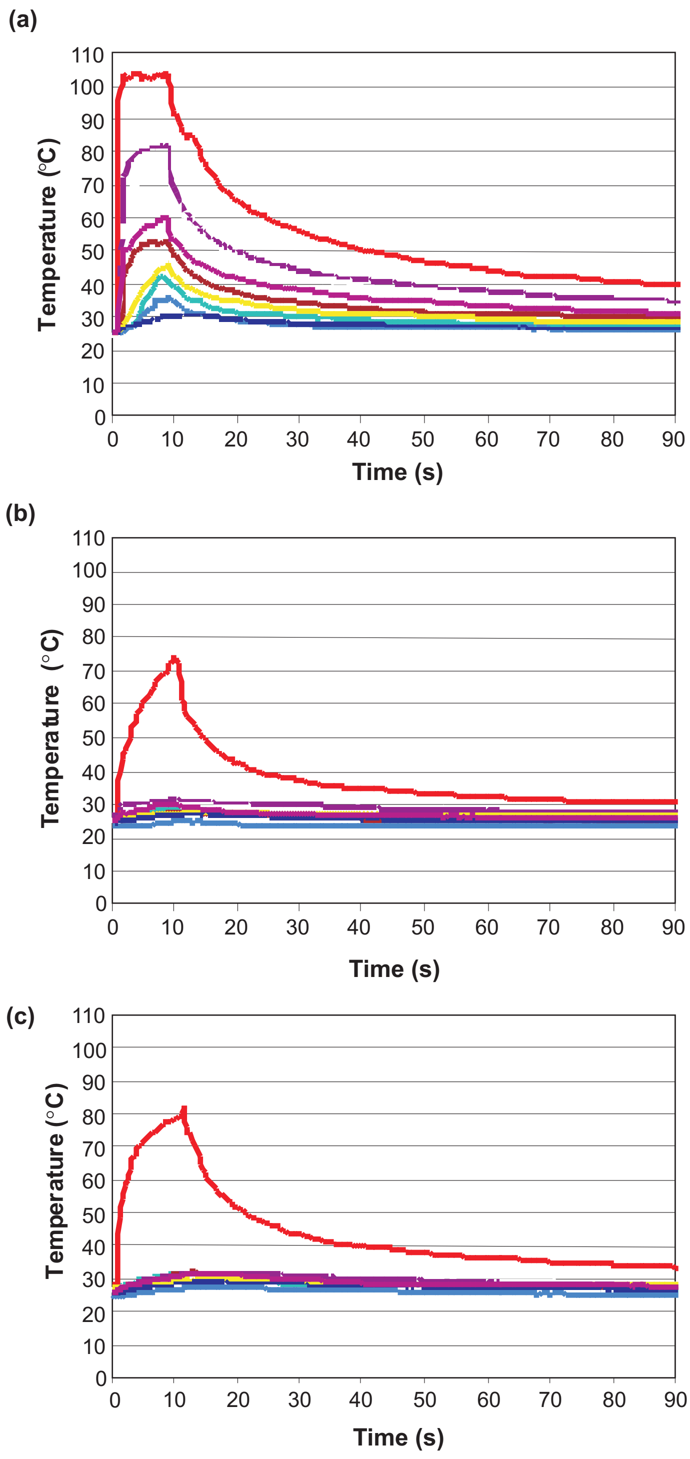


Figure 2. Typical temperature versus time plots at 207 kPa and 50 mm. *Notes.* a—fabric A, b—fabric B, c—fabric C. Different colors represent different sensors. Red represents the main sensor.

tends to give up the heat to the surrounding atmosphere. The temperature of the fabric declines as soon as the 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.

4.3. Analyses of Variance: Effects of Fabric, Pressure and Distance

Because the results for the two replications were similar, only analyses for the aggregated data are discussed here. The main effect for

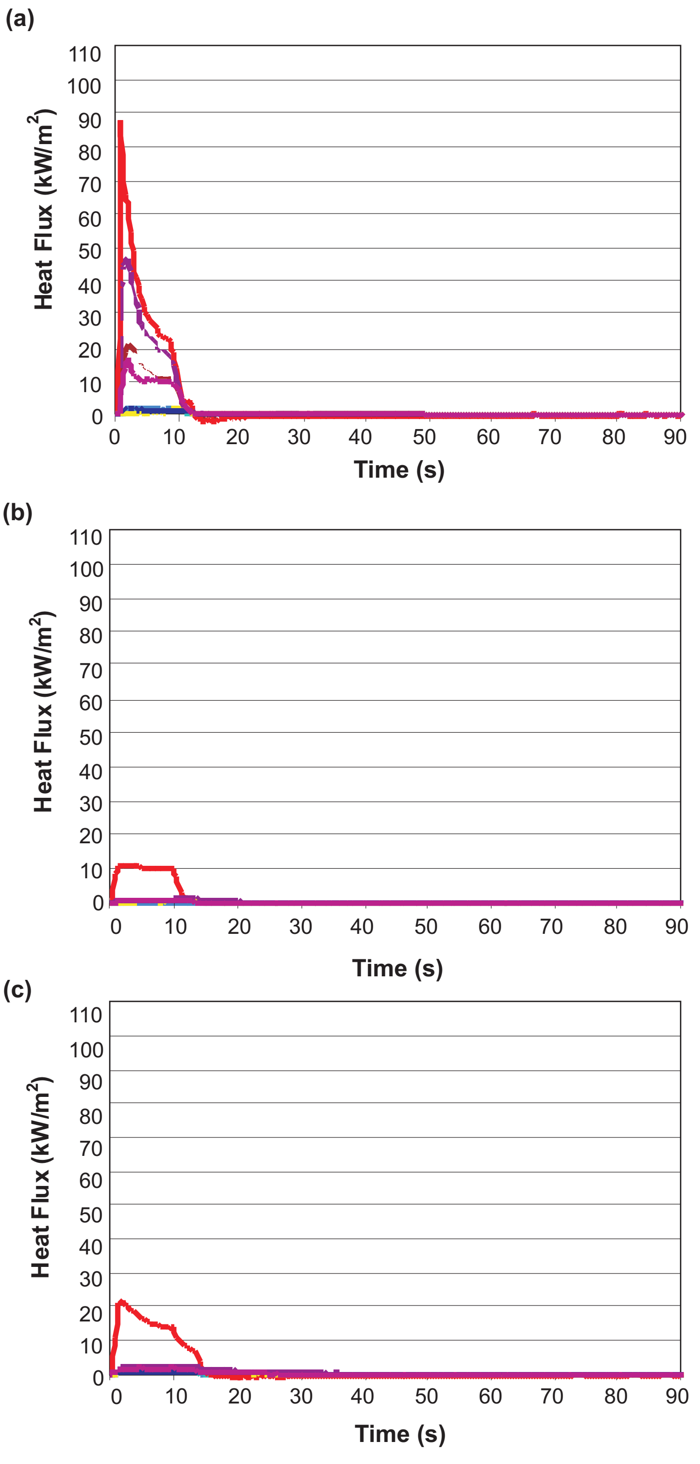


Figure 3. Typical heat flux versus time plots at 207 kPa and 50 mm. *Notes.* a—fabric A, b—fabric B, c—fabric C. Different colors represent different sensors. Red represents the main sensor.

fabric was highly significant ($p < .001$) for all four dependent variables suggesting that the test device and procedure were able to differentiate well among the three fabrics. Results of Duncan's post hoc tests of differences among fabrics (Table 2) confirm significant differences for all four dependent variables. All three fabrics differ significantly from each other for peak temperature, peak heat flux and total energy, but there is no significant difference between Fabrics B and C for time to reach peak heat flux. The peak temperature reached at the back side of the

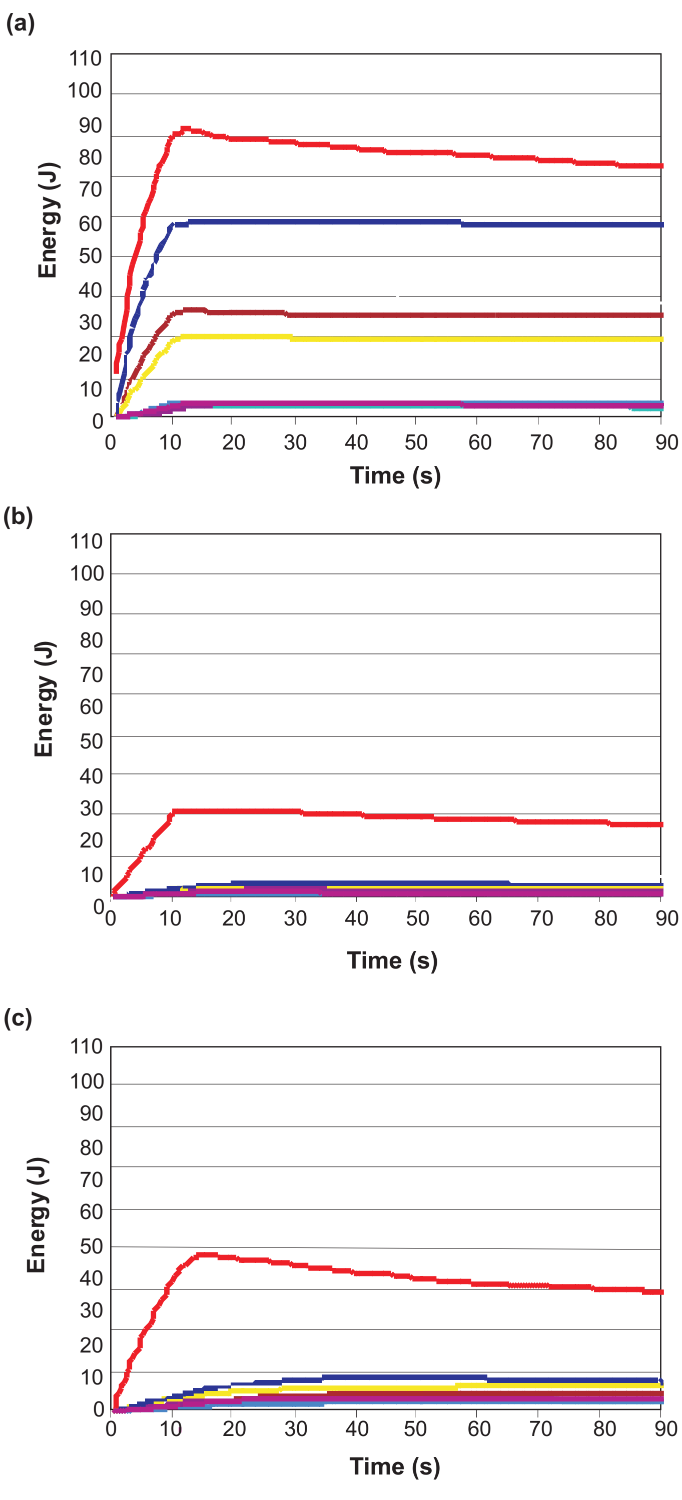


Figure 4. Typical energy versus time plots at 207 kPa and 50 mm. *Notes*. a—fabric A, b—fabric B, c—fabric C. Different colors represent different sensors. Red represents the main sensor.

fabric (in contact with the sensor) depends on the thickness, permeability and thermal resistance of the fabric. One would expect that the thicker fabrics would result in lower rates of heat transfer, but unless there is significant storage within the fabrics, the peak temperatures should occur at roughly the same time after exposure begins.

The main effects for both pressure and distance were significant for all dependent variables except for time to reach peak heat flux. Higher values were reported at 50 than at 100 mm for peak temperature, peak heat flux and total energy, with no significant difference for time to reach peak heat flux. This is an expected result as the air entrained in the steam jet would lower the steam/air mixture temperature in an amount that increased with distance. Similarly, higher values for peak temperature, peak heat flux, and total energy were observed at high pressure than at a low pressure. This too is expected, as the mass flow rate of steam will be higher at higher pressure. As a result, the entrained air will have a smaller effect at the higher pressure.

Most three-way interaction effects (fabric × distance × pressure) were not significant. However, many two-way interaction effects for fabric × distance were significant ($p < .001$), indicating that the differences in heat transfer among fabrics depended on distance between nozzle and fabric. On the other hand, most of the fabric × pressure interactions were not significant, suggesting that pressure has less influence on differences among fabrics. This differentiation among different test conditions (pressure, distance) can also be seen in Table 2. As well, significant distance × pressure interaction effects for peak temperature and total energy suggest that, for these dependent variables, the effect of one parameter may be dependent on the other. The effect of pressure tends to be greater at the shorter distance while the effect of distance tends to be greater at the higher pressure. Such differences are important to consider when designing a test protocol.

4.4. Effect of Fabric Performance Properties on Steam-Related Heat Transfer

Although determining the effects of fabric parameters was not the primary purpose of this research, it is interesting to note some such effects. Of the three fabrics tested, Fabric A has the highest air permeability and very low resistance to water vapour diffusion (Dm), making it vulnerable to penetration and permeation of steam at high temperature and pressure. Most of the heat and moisture transport is by convection and bulk moisture transport through the fabric interstices of Fabric A. As stated by Gibson [7], when airflow through fabric occurs, the measured heat and water vapour transfer both increase greatly. Steam easily penetrated through the fabric and instantaneously increased the temperature 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

TABLE 2. Heat Transfer Though Fabrics

Fabric		Peak Temperature (°C)				Peak Heat Flux (kW/m^2)				Time to Reach Peak Heat Flux (s)				Total Transferred Energy (J)			
	pressure (kPa)	69		207		69		207		69		207		69		207	
	distance (mm)	50	100	50	100	50	100	50	100	50	100	50	100	50	100	50	100
A	*M*	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
	SD	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	*M*	48^b	39^b	60^b	46^b	10	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
	SD	2.6	0.6	7.7	1.9	1.4	0.3	3.7	1.8	0.5	0.7	1.6	0.6	11	5	11	17
C	*M*	67^c	57^c	78^c	59^c	22	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
	SD	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

Notes. a, b, c—for each pressure/distance condition (column), fabric means with different superscripts differ significantly from each other.

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 heat transfer than did Fabric A. 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 which had the highest resistance to water vapour, but was thinner and more dense. For the latter, heat transfer was through conduction only so that thickness and dry thermal insulation were the key factors affecting steam-related heat transfer. Thus, the effects of fabric parameters need to be considered conjointly rather than individually. Developing such a model, however, was outside the scope of this study.

5. CONCLUSIONS AND IMPLICATIONS

The test device and procedure were 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 rates being at 50 mm and 207 kPa. Although no concrete conclusion could be made about the relationships between fabric parameters and heat transfer, it is known from previous research that factors such as thickness, fabric structure, finish, water vapour permeability, air permeability, thermal insulation and total heat loss influence the heat and vapour transmission. In this research fabric properties such as resistance to water vapour diffusion, air permeability, thermal insulation and total heat loss interact with fabric characteristics such as thickness and presence of a coating/laminate in determining steam penetration and heat transfer. Although our approach differed considerably from that of Desruelle and Schmid [14], the results of the two studies complement and support each other.

The results presented here are significant for the industries where steam is utilized in several different applications and where steam pressures in the pipelines are moderately high. It is evident that both distance and pressure influence heat transfer. The experiments were conducted at relatively low pressures compared to industrial settings where the typical steam pressure existing in lines for the day-to-day operations can be up to 620 kPa. In the current research it was observed that for all three fabrics the sensor temperature rose above 50 °C under most conditions, implying second-degree burn to the skin tissue [15], and could be much worse if the exposure time is higher.

This research has suggested a need to develop specifications for clothing systems to prevent partial or full-thickness burns from heat transfer onto the skin during or after exposure to high-pressure steam. One limitation of this research was that achieving reliable steam pressures above 207 kPa during the tests was not possible. Therefore, further work at higher pressure is needed to assess the hazard in more detail and to verify the validity of testing at somewhat lower pressures. However, above the critical pressure ratio (upstream and downstream of the orifice) the sonic flow at the nozzle exit may choke and we would expect little influence of increasing upstream pressures.

When gases flow through an obstruction, such as an orifice or nozzle or out of the end of a pipe into the surrounding atmosphere, the flow is generally modeled as proportional to the square root of the difference in pressure across the obstruction. If the downstream pressure is held constant and the upstream pressure is increased, the flow increases in proportion to the square root of the new pressure differential until a critical pressure ratio is reached. The pressure ratio is the ratio of the absolute pressures upstream to downstream. At that point, the flow in the restriction reaches sonic velocity and further increases in the upstream pressure have no effect on the exit velocity through the restriction. In essence, the flow is choked and the velocity in the restriction is the speed of sound in the flowing fluid at the temperature and pressure that exist at the restriction. Most gases that behave as ideal have critical pressure ratios (as defined here) of around 2.0. For steam the value is just below that, so that in this experiment with 207 kPa upstream pressure and ~100 kPa downstream (atmospheric) pressure, the ratio would be above the critical ratio and the flow should be choked.

Generally in textile or other material testing facilities it is rare to find steam pressures as high as 620 kPa as found in industry. 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 heat transfer. Besides pressure and distance, fabric characteristics and performance properties should influence heat transfer. Hence more work is needed to develop a numerical model incorporating the test 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 fully developed.

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