TEXTILE FABRICS AS THERMAL INSULATORS

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Abstract

In recent times, a wide range of textile materials has been used as thermal insulators in many industrial applications. The thermal insulating properties of textile fabrics depend on their thermal conductivity, density, thickness and thermal emission characteristics. Experiments have been made with the aim of studying heat transfer by conduction through the different types of fabrics used as thermal insulators. 100% polyester and 100% polypropylene nonwoven fabrics are used in this work as case studies. The temperature variation through the selected fabrics is measured under different operating parameters such as densities and inlet temperature. The thermal response and behaviour for the selected fabrics used in this work as thermal insulators are illustrated. The relationship between the thermal conductivity and material density of the selected fabrics is studied. Polyester fabric has higher thermal resistance and specific heat resistance than polypropylene. Fabric thickness has a significant effect on the fabric temperature variations. The results of ?[Anova-two way measurements] are presented for 100% polyester and 100% polypropylene nonwoven fabrics. The temperature variation of the fabric increased with the testing time, and also decreased with the increase of fabric weight up to a certain limit beyond its optimum level. The results show that the selected nonwoven fabrics are suitable for usage as thermal insulators.

Key words:

fabrics, heat transfer, industry, textile and thermal insulator

1. Introduction

Many development applications for the new materials such as textile fabrics used as thermal insulators require a full study of their thermal insulating properties at different operating conditions. One of the most important of these studies is the effect of temperature with thermal conductivity and material density on the response of the textile fabrics as insulators. The thermo-insulating properties of perpendicular-laid versus cross-laid lofty non-woven fabrics are presented by Jirsak et al. [1]. In their study, the relationship between the thermal conductivity and material density of samples was studied. They concluded that the thermal conductivity decreases with increasing material density. Morris [2] presented a study of thermal properties of textiles, and concluded that their thermal conductivity increases with density, based on his observation that when two fabrics are of equal thickness, the one with a lower density shows the greater thermal insulation. However, he reported that there is a critical density of about 60.0 kg/m^3 below which the convection effects become dominant and the thermal insulation falls. Recently, a heat flux sensor was used to measure the thermo-insulating properties of textiles in an apparatus called the Alambeta [3]. The thermal properties of fabric insulators are investigated by Ukponmwan [4]. Heat and mass transfer analyses of textile fabrics are presented in many researches [5-8]. In these works, the effect of operating parameters such as temperature, humidity and heat & mass transfer coefficients are examined by mathematical and experimental studies. A model of heat and water transfer through layered fabrics was developed by Fohr et al. [9]. They aimed at studying the effect of weather conditions and human activities on the wearers' selection of clothing. Their model considers the occurrence of condensation or evaporation in accordance with the environmental conditions and their variations. The thermal expansion behaviour of hot-compacted woven polypropylene and polyethylene composites was studied by Bozec et al. [10]. The compression and thermal properties of recycled fibre assemblies made from the industrial waste of seawater products are presented by Sukigara et al. [11]. In their study, the effective thermal conductivity of fibre assemblies with steady-state and parallel plates was measured. Their results showed the lower

effective thermal conductivity of recycled fibre assemblies compared to pure wool fibre assemblies, which indicates that the effect of heat radiation on thermal conductivity cannot be disregarded.
In this work, the heat transfer through two different fabrics, polyester and polypropylene is studied. The experiments are carried out using a special test-rig to study the thermal behaviour of the selected textile fabrics used as thermal insulators in many applications. Temperature, density, thickness and weight are measured for the selected textile fabrics used as case studies. The thermal insulation properties of the selected textile fabrics are calculated and studied with respect to the importance of operating conditions such as inlet temperature, thickness, weight and density. The comparison between the selected textile fabrics as thermal insulators according to certain operating conditions is given. On the basis of this study, some applications for these materials are considered.

2. Governing Equations

The heat energy can be transferred through the textile fabrics by conduction, convection and radiation, as well as easily explainable phenomena such as heat exchange in porous media. The basic concepts of heat transfer through fabrics are explained as follows:

2.1. Thermal conductivity

Heat transfer by conduction depends on the materials' heat conductivity, i.e. their capacity for transferring heat from a warmer medium to a cooler one. The main characteristics of heat conductivity are as follows:
Conductivity factor λ [W/(mºC)] expresses the heat flow (Q), W, passing in 1 h through area (A) of 1 m^2 of the fabric thickness (L) at a temperature difference ($T_1 - T_2$) of $1^{\circ C}$, as given in the following equation:

$$\lambda = Q\,L \,/\, A\,t\,(T_1 - T_2) \tag{1}$$

Heat transfer coefficient K [W/m^{2o}C] expresses the heat flow passing during 1 h through 1 m^2 of fabric with actual thickness, (L) and difference temperatures of two media (air and fabric) 1ºC, as in the following equation:

$$K = Q \,/\, A\,t\,(T_1 - T_2) \tag{2}$$

2.2. Specific heat resistance, (r)

The specific heat resistance, r (($m^{\circ C}$) /W) is a characteristic inverse to the heat transfer factor λ, as in the following equation:

$$r = 1/\lambda = A\,t\,(T_1 - T_2) / (Q\,L) \tag{3}$$

2.3. Heat resistance, (R)

The heat resistance, R (m^{2o}C / W) is a characteristic inverse to heat transfer coefficient K, as in the following equation:

$$R = 1/K = A\,t\,(T_1 - T_2) / (Q) \tag{4}$$

The specific heat resistance r_r and the heat resistance R, characterise the fabrics' heat capacity to impede the transfer of heat through them.

2.4. Thermal resistance, (R_{th})

The thermal resistance, R_{th}, of textile fabrics is a function of the actual thickness of the material and the thermal conductivity k. This function is given by the following relationship:

$$R_{th} = L / k\,,\ ((m^{2o}C)/W) \tag{5}$$

where L is the actual thickness of the sample, m.

2.5. Heat flow, (Q)

The heat flow, Q, through the textile fabric is given as the following:

$$Q = - k A (T_1 - T_2) / L \tag{6}$$

where A is the surface area exposed to the hot air, T_1 is the initial air temperature and T_2 is the transient air temperature.
The textile fabrics have two thermal functions; they prevent air movement and provide a shield against radiant-heat losses. Within the period before the heat conducted by the fibres becomes predominant, the more densely the fibres are arranged within the fabrics, the better they will fulfil these two functions.

2.6. Energy equation

The energy equation for textile fabric is simply the transient heat conduction equation with a heat radiation source term; this equation is given as follows:

$$k \frac{\partial^2 T}{\partial X^2} = \rho\ C_P \frac{\partial T}{\partial t} + \frac{\partial q_r}{\partial X} \tag{7}$$

where k, ρ, C_P, T and t are the thermal conductivity, the density as calculated as $\rho = \omega/L$ (ω is the basic weight of the sample), specific heat, temperature and time for the selected fabrics respectively. X is the X-axis, and is given as:

$$0 \le X \le L,\ \ 0 \le t \le \infty \tag{8}$$

where L is the fabric thickness. q_r is the heat flux by radiation at any point within the fabric, and can be written as in [12]:

$$q_r(x) = 4\sigma\ T_o^3\ (T_1 - T_2) \text{ at } 0 \le X \le L \tag{9}$$

where σ is the Stephan-Boltzman constant and equals 5.67×10^{-8} W/m^2K^4, and T_o is the mean temperature in our experiment (T_o=298K). Figure 1 shows the schematic drawing of the fabric insulator model.

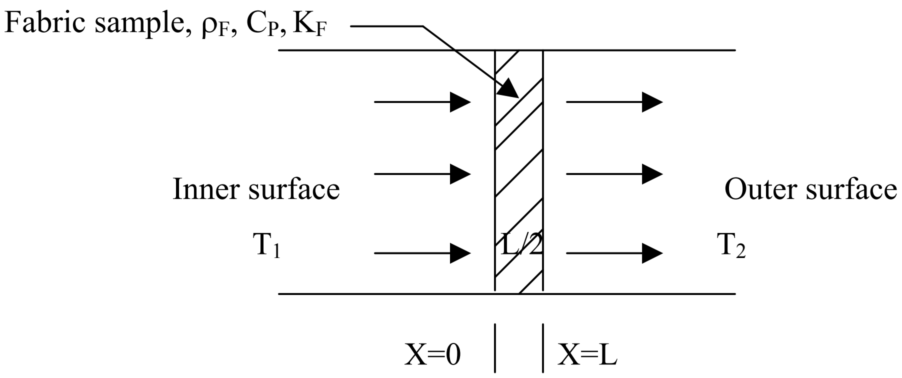

Figure 1. Schematic drawing of the fabric insulator model

2.7. Thermal Insulating Value (TIV)

TIV represents the efficiency of the textile fabric as an insulator. It is defined as the percentage reduction in heat loss from a hot surface maintained at a given temperature. The TIV increases to 100% when a ‘perfect’ insulator is obtained. The TIV of textile fabric depends upon the thermal conductivity of the fabric, the thickness of the assembly and the thermal emission characteristics of the surface fabric. It is expressed as a percentage which represents the reduction in the rate of heat loss due to the insulation, relative to the heat loss from the surface.
Thus, the following relation represents this value:

$$(TIV)\% = 100\ [\ 1 - (K_t / \varepsilon_o) / (L + (K_t / \varepsilon_1)\ ] \tag{10}$$

where ε_o and ε_1 are the emissivity of one and the other surface of the insulator (textile fabric) respectively.
A typical value of emissivity of textile fabric is 2.06 cal. / m^2 s°C. The conversion of TIV to the tog unit can be written as follows:

$$(TIV)\% = 100\ [1- (I_o / I_1)] \quad (11)$$

where I_o and I_1 are the tog values of unclothed and clothed bodies respectively, where 1 tog=0.418 m^2 s°C / cal.
Table 1 gives the calculated values of the TIV in percent for the samples of the selected fabrics.

Table 1. Thermal insulating values (TIV) of the selected fabrics

Selected fabrics		Thickness, m	(TIV),%
Polyester	Sample 1	3.54×10^{-3}	41.21
	Sample 2	4.32×10^{-3}	49.3
	Sample 3	4.88×10^{-3}	50.5
	Sample 4	5.62×10^{-3}	51.3
	Sample 5	7.97×10^{-3}	52.15
Polypropylene	Sample 1	3.76×10^{-3}	41.95
	Sample 2	4.44×10^{-3}	49.89
	Sample 3	4.6×10^{-3}	50.05
	Sample 4	5.7×10^{-3}	51.98

3. Experimental Work

In order to investigate the heat transfer and thermal behaviour of textile fabrics as thermal insulators, an experimental test-rig was especially designed and constructed to measure the temperature variation with test time through the selected textile fabrics during the heat exchange process between the hot air inlet and the fabric sample.
Our experiments were carried out on two non-woven fabrics. The fabric samples are prepared by the ?[drying rout web formation][technique and produced on a needle-punching machine. One group of samples were made from polyester fibres with different weights per unit area, and another group made from polypropylene with the same weight. The fabric samples were subjected and exposed to different levels of heat in the emission side (the heat source side), and then the temperatures are measured on the other side of the fabric sample, in order to evaluate its thermal resistance and behaviour as a thermal insulator.
Tables 2 and 3 give the numerical values of parameters for the samples of the selected textile fabrics (polyester and polypropylene, respectively) and the inlet heat exposure levels as the temperatures that are used in the presented study

Table 2. Numerical values of parameters for polyester samples

Sample	Weight, kg/m^2	Thickness, m	K, W/m^2 °C	λ, W/m °C	Density, ρ, kg/m^3	Exposure temperature, $T_{F,°C}$
1	400×10^{-3}	3.54×10^{-3}	0.06	0.02	112.99	40, 80, 120, 160 and 200
2	600×10^{-3}	4.32×10^{-3}	0.08	0.025	138.9	40, 80, 120, 160 and 200
3	700×10^{-3}	4.88×10^{-3}	0.097	0.29	143.5	40, 80, 120, 160 and 200
4	800×10^{-3}	5.62×10^{-3}	0.11	0.033	142.4	40, 80, 120, 160 and 200
5	1000×10^{-3}	7.97×10^{-3}	0.17	0.05	125.5	40, 80, 120, 160 and 200

Table 3. Numerical values of parameters for polypropylene samples

Sample	Weight, kg/ m^2	Thickness, m	K, W/m^{2o}C	λ, W/m°C	Density, ρ, kg/m^3	Exposure temperature, $T_{F,°C}$
1	400×10^{-3}	3.76×10^{-3}	0.073	0.022	111.99	40, 80, 120, 160 and 200
2	600×10^{-3}	4.44×10^{-3}	0.09	0.026	135.1	40, 80, 120, 160 and 200
3	650×10^{-3}	4.62×10^{-3}	0.10	0.30	140.7	40, 80, 120, 160 and 200
4	800×10^{-3}	5.7×10^{-3}	0.11	0.034	140.4	40, 80, 120, 160 and 200

4. Results and Discussions

The results of the laboratory experiments and calculations show that the thermal insulating properties of textile fabrics (ρ, K, C_P) affect the insulation response. Figures 2 to 24 illustrate the thermal response and behaviour of the selected fabrics (polyester and polypropylene) that were used in this work as thermal insulators. Temperature variations with time for polyester samples (1-5) at different exposure temperatures (40, 80, 120, 160 and 200ºC) through 25 experiments are plotted in Figures 2 to 6. From the figures, it is found that the fabric temperature (T_F) variations increase rapidly in the initial stage of the exposure temperature. This may be because the temperature difference between the fabric sample and the exposed hot air is high in the early stage of the exposure process. Through 20 experiments, temperature variations with time of the polypropylene samples 1-4 at different exposure temperatures are shown in Fig. 7-10. Figures 11 and 12 show the effect of polyester and polypropylene thickness on fabric temperature (T_F) respectively. It is found that higher fabric thickness means good insulation. The specific heat resistance values for the selected fabrics is shown in Fig. 13. It is found that polyester samples have higher specific heat resistance than polypropylene samples. In addition, the thermal resistance of the selected fabrics is shown in Figure 14. From these figures, we see that the polyester has higher specific heat resistance and thermal resistance than polypropylene. This may be because the thermal conductivity of the polyester is lower than polypropylene. Figures 15 to 22 show the effect of exposure temperatures on the heat flow through the polyester and polypropylene for each of samples 1 to 4. It is found that the heat flow rises rapidly during the early stage of the hot air's exposure to the fabric. This is due to the high temperature difference between the fabric surface (cold) and the hot air. Also, high exposure temperature means a high heat flow through the fabric. Figures 23 and 24 show the surface plot and contours of measured fabric temperatures for 100% polyester and 100% polypropylene nonwoven fabrics respectively. The figures show the influence of nonwoven fabric weight and time on the temperature variations when exposed to different temperatures (40, 80, 120, 160 and 200ºC). It is found that the temperature variations of the fabric increased with the increase of time, and decreased with fabric weight up to a certain limit beyond its optimum level. This may be due to the fibre quantity increasing with the increase in of fabric weight; in other words, the compactness of nonwoven fabrics increased with the increase in the basic weight, and consequently the fabric thickness. This is the reason for the thermal behaviour of these fabrics. As the results of the ?[Anova-two way], the relations between the temperature variations of the polyester and polypropylene fabrics, respectively weight and time, are given as the following expression (Figures 23 and 24):

$$Z = 14.68 + 0.035 * X + 0.66 * Y - 0.0\ \mathbf{X}*X - 0.0\ X*Y - 0.003*Y*Y$$

$$Z = 21.55 + 0.036 * X + 0.511 * Y - 0.0\ \mathbf{X}*X - 0.0\ X*Y - 0.003*Y*Y$$

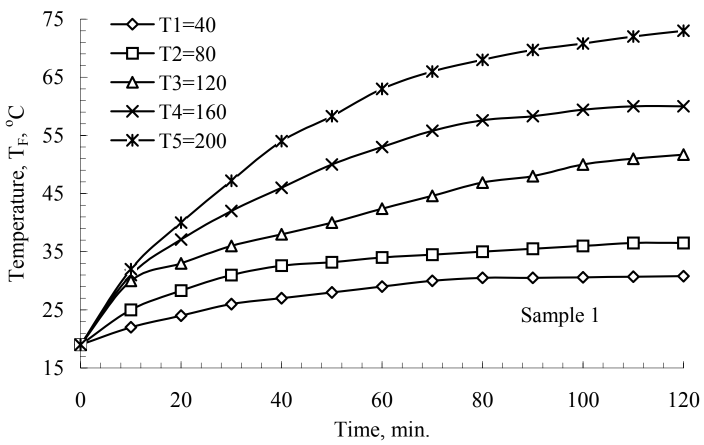

Figure 2. Temperature variations of polyester (sample1) at different exposure temperatures

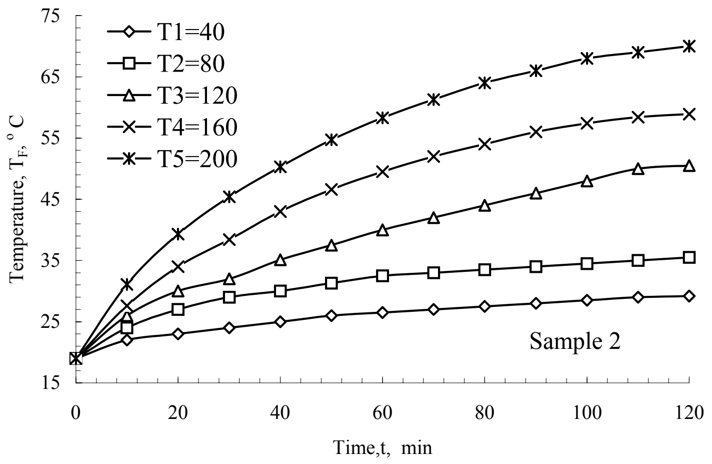

Figure 3. Temperature variations of polyester (sample 2) at different exposure temperatures

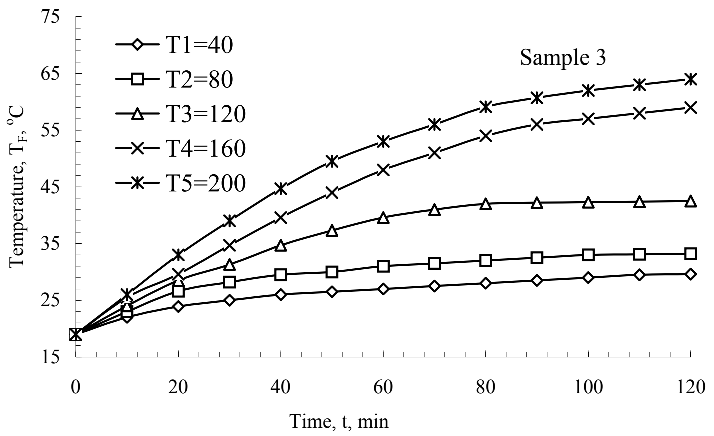

Figure 4. Temperature variations of polyester (sample 3) at different exposure temperatures

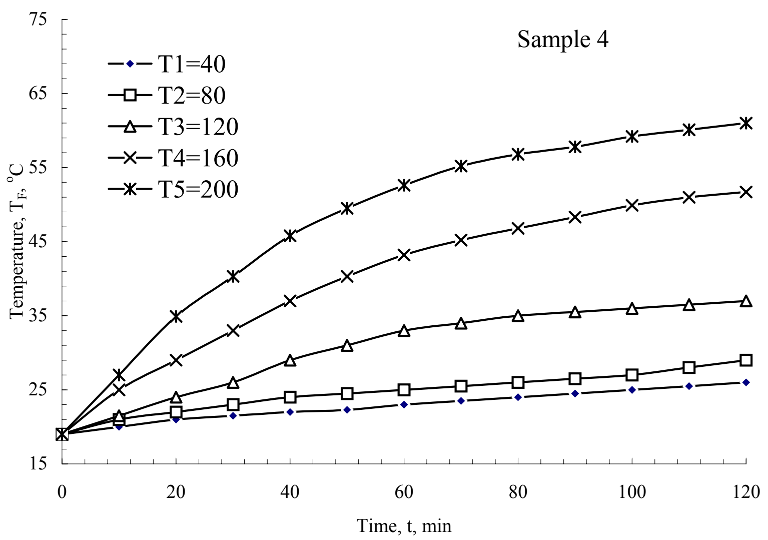

Figure 5. Temperature variations of polyester (sample 4) at different exposure temperatures

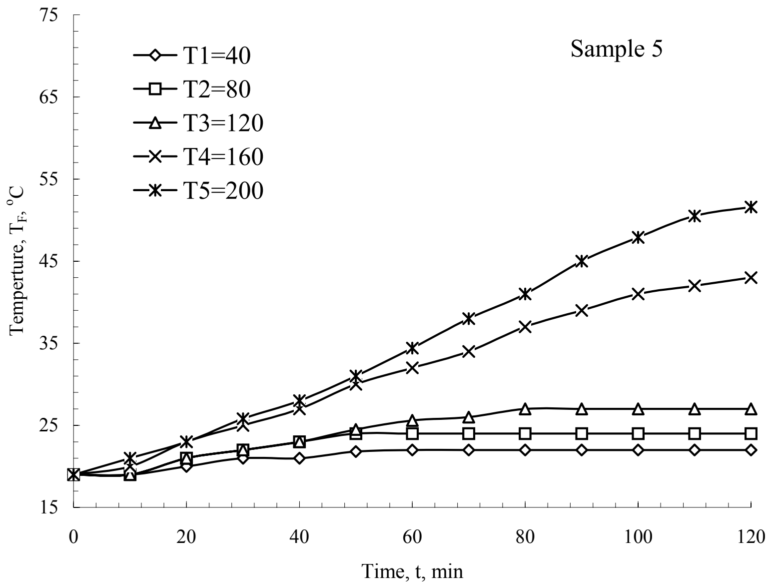

Figure 6. Temperature variations of polyester (sample5) at different exposure temperatures

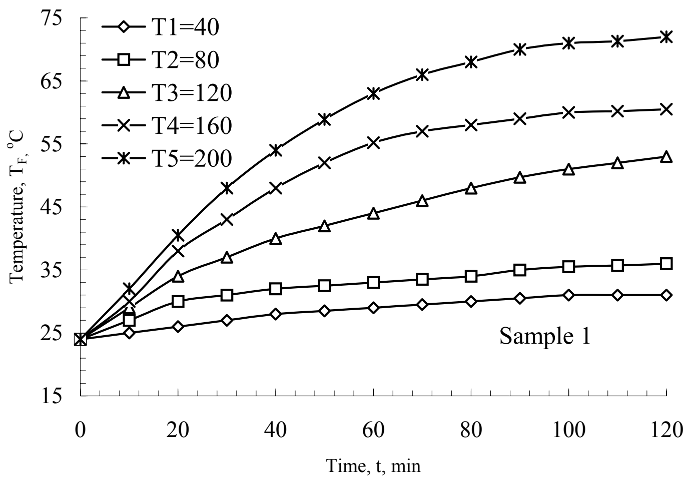

Figure 7. Temperature variations of the polypropylene (sample 1) at different exposure temperature

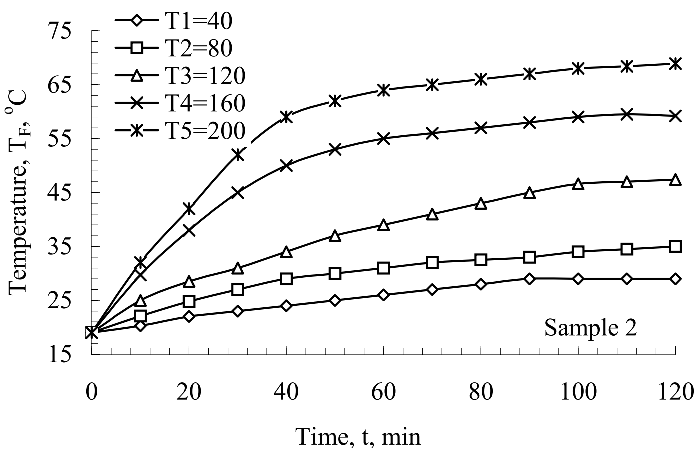

Figure 8. Temperature variations of the polypropylene (sample 2) at different exposure temperature

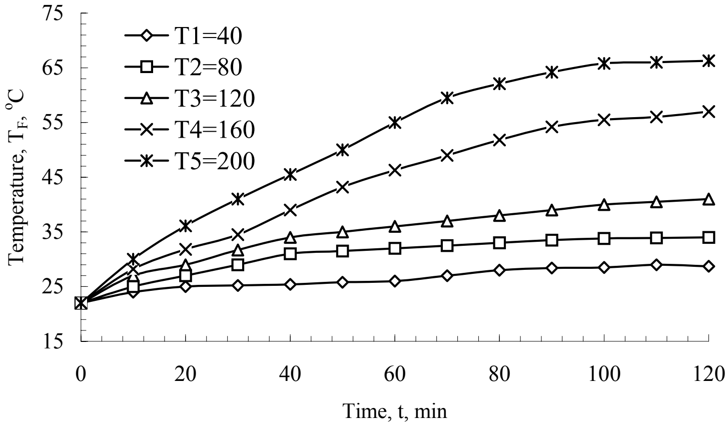

Figure 9. Temperature variations of polypropylene (sample 3) at different exposure temperatures

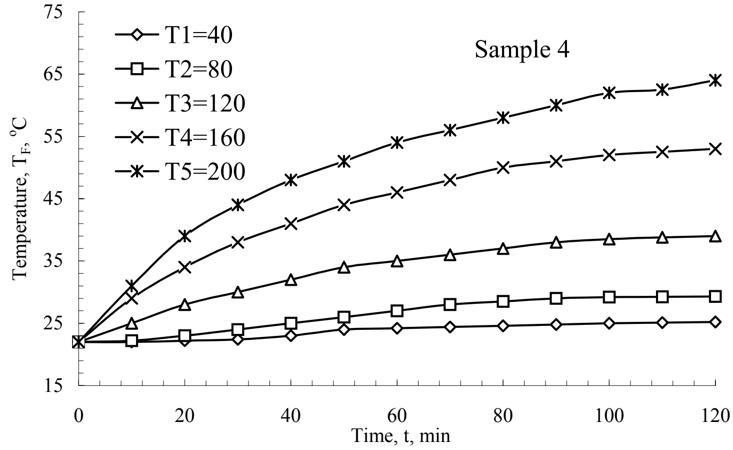

Figure 10. Temperature variations of polypropylene (sample 4) at exposure temperatures.

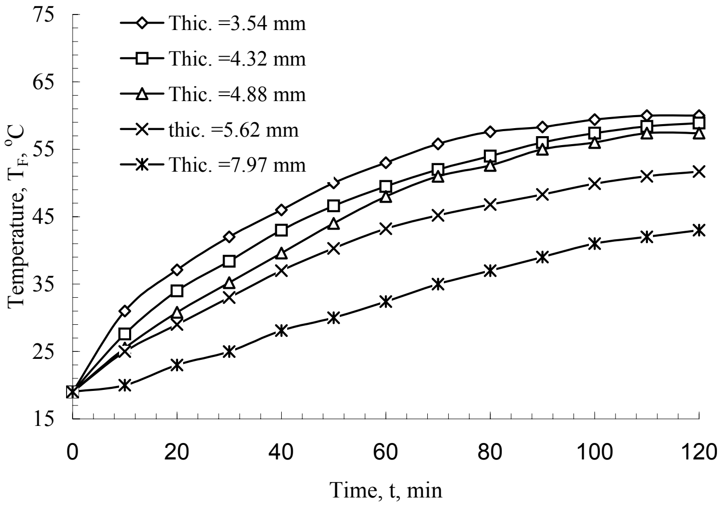

Figure 11. Effect of polyester thickness on temperature variation

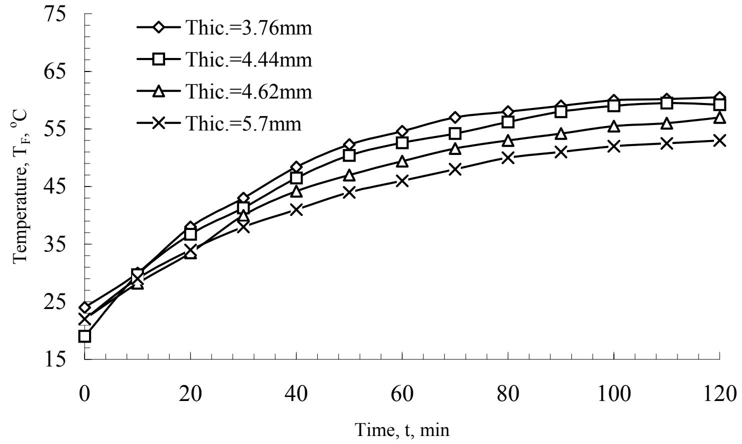

Figure 12. Effect of polypropylene thickness on temperature variation

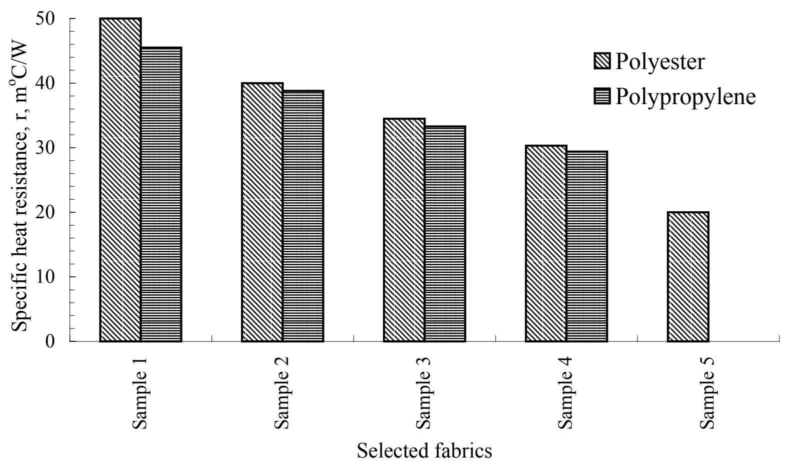

Figure 13. Specific heat resistance for the selected fabrics

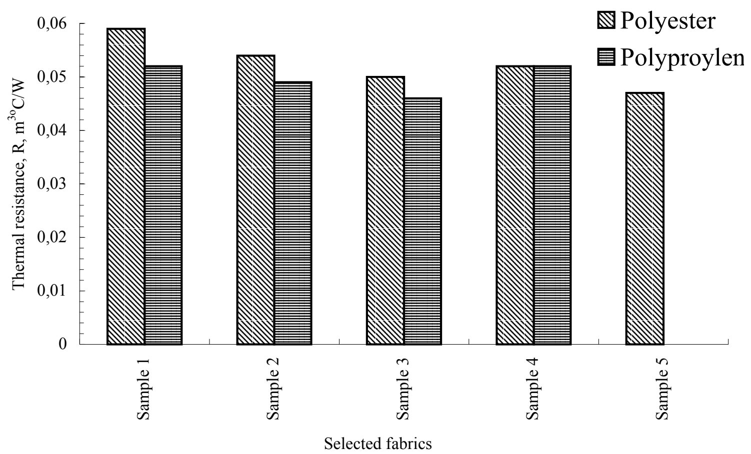

Figure 14. Thermal resistance for the selected fabrics

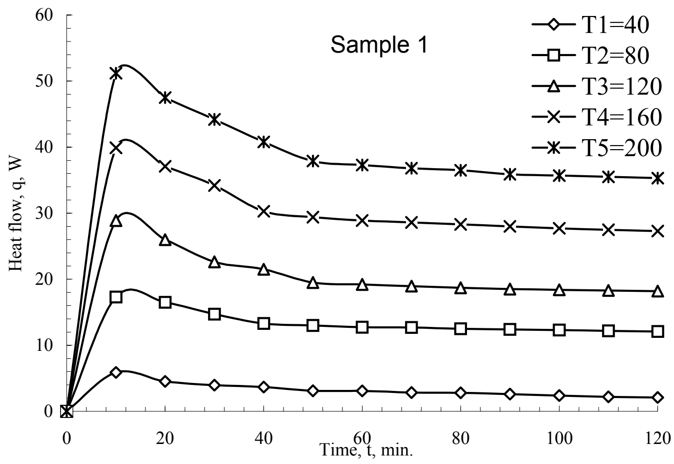

Figure 15. Effect of temperature exposure on the heat flow through the polyester, sample 1

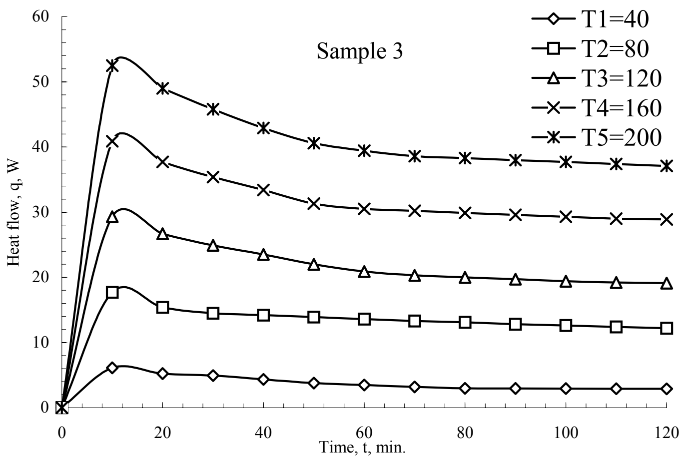

Figure 16. Effect of temperature exposure on the heat flow through polyester, sample 2

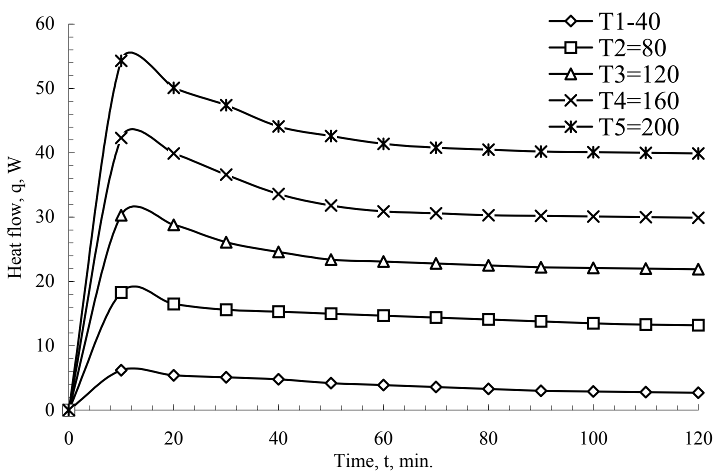

Figure 17. Effect of temperature exposure on heat flow through the polyester, sample 3

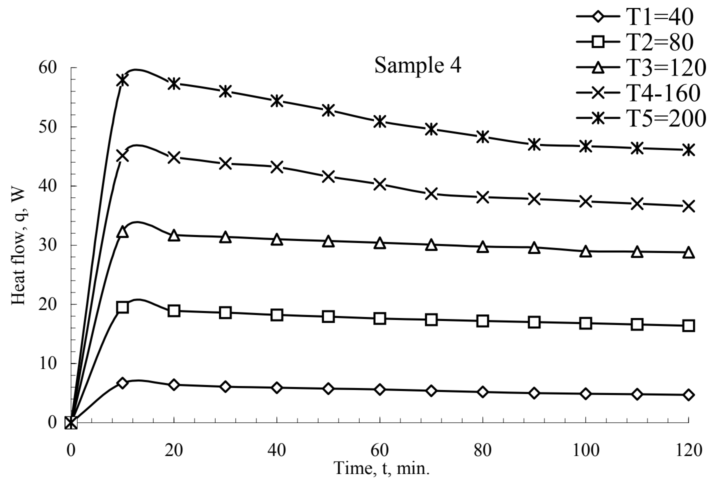

Figure 18. Effect of temperature exposure on heat flow through polyester, sample 4

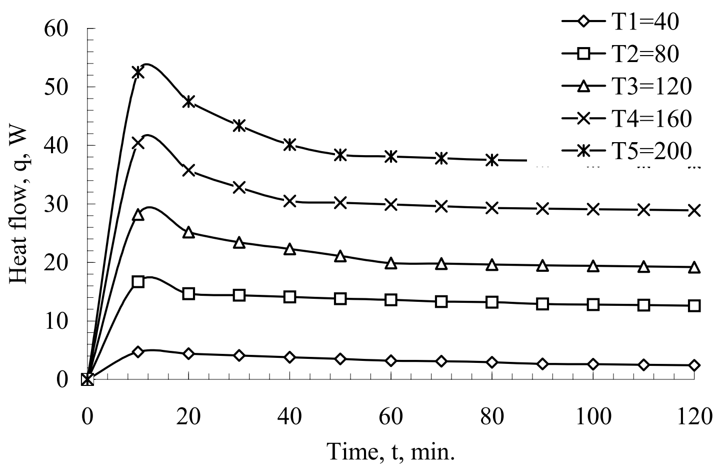

Figure 19. Effect of temperature exposure on heat flow through polypropylene, sample 1.

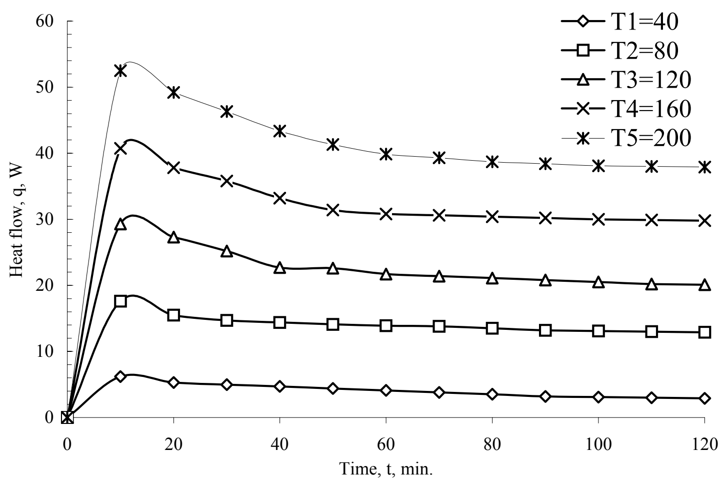

Figure 20. Effect of temperature exposure on heat flow through polypropylene, sample 2

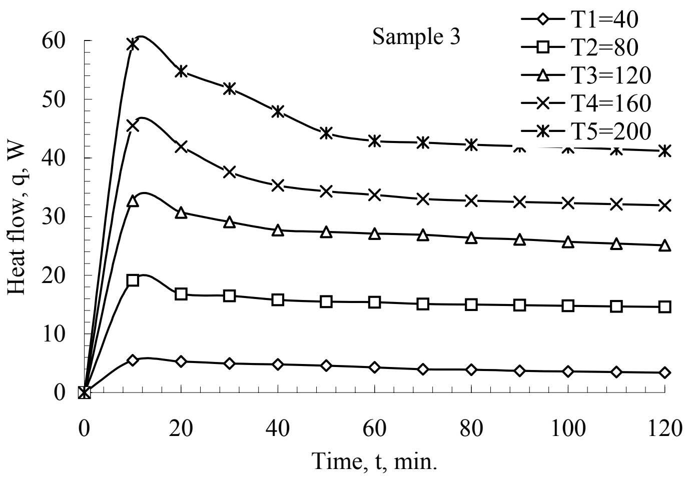

Figure 21. Effect of temperature exposure on heat flow through polypropylene, sample 3

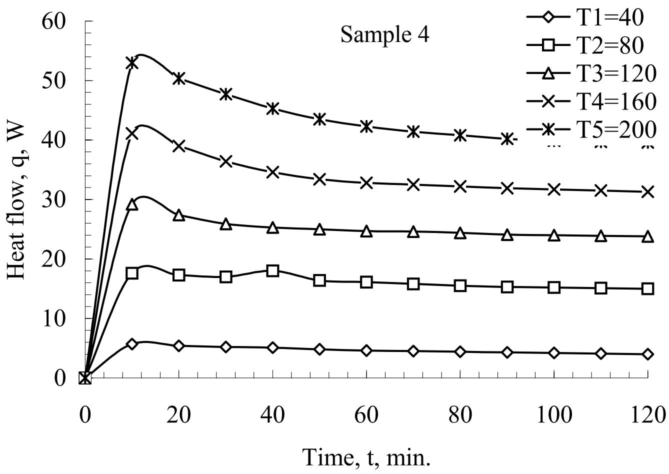

Figure 22. Effect of temperature exposure on heat flow through polypropylene, sample 4

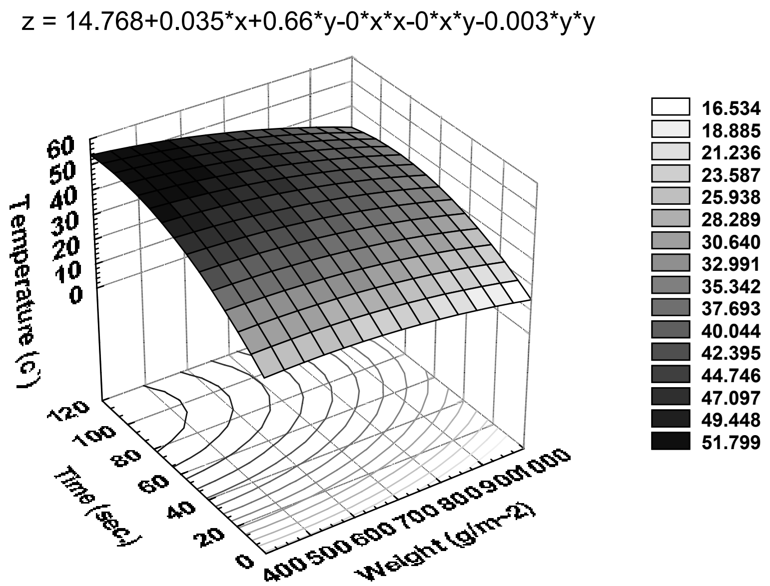

Figure 23. Surface plot of temperature variation of 100% polyester nonwoven fabrics at different weights and times

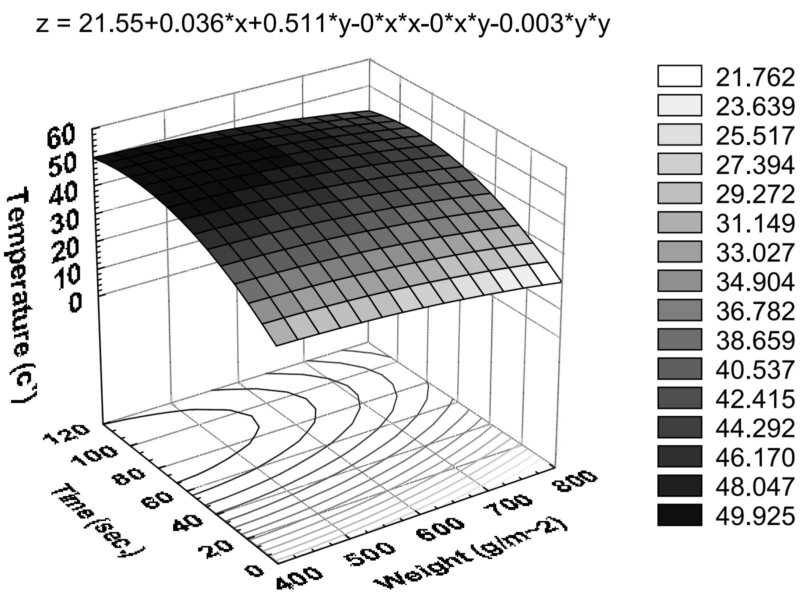

Figure 24. Surface plot of temperature variation of 100% polypropylene nonwoven fabrics at different weights and times

5. Conclusions

Based on the previously calculated and experimental results of the selected fabrics that are used as thermally insulators, the following conclusions can eb drawn:

1. The laboratory experiments and calculation have shown that selected textile fabrics can be used as good thermal insulators in a range of exposure temperatures from 40 to 200ºC.
2. The study concludes that the selected fabrics have high thermal performance and thermal response as insulators.
3. The effect of fabric thickness on the fabric temperature variations has the obvious significance that higher thickness means good thermal insulation.
4. Both the thermal conductivity and thermal resistance of all the selected fabric samples increases with the increase in fabric density.
5. Fabric thickness affect the transient fabric temperatures; fabric temperature variation decreases with increasing fabric thickness.
6. The exposure temperature affects the heat flow through the selected fabrics, while heat flow increases with increasing exposure temperatures.
7. The temperature variations of the fabric increase with the increase in time, and also decrease with fabric weight up to a certain limit beyond its optimum level.

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