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STUDY OF HEAT TRANSFER THROUGH MULTILAYER CLOTHING ASSEMBLIES: A THEORETICAL PREDICTION

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Abstract:

It has long been recognised that heat transfer through clothing is a main constraint to the comfort properties of clothing. The present work relates to the development of a mathematical model for the prediction of heat transmission through multilayer clothing with air in between two successive layers of fabric in a multilayered clothing assembly. A mathematical model was developed using general equations of heat transfer through porous media and was validated using experimental results. A series of multilayered fabric assemblies were created with different combinations of fabric layers and air gaps of different thicknesses. The predicted total thermal resistance of these fabric assemblies was obtained from the model and the values were compared with experimental results. The total thermal resistance of these fabric assemblies were measured using a guarded hot plate for validating the model. Fairly good correlations between the predicted and experimental values of thermal resistance were observed.

Key words:

Air gap, extinction coefficient, heat transfer, multilayered clothing assembly, refractive index, thermal resistance.

Introduction

It is very important to study the transmission of heat through multilayer clothing assemblies for the prediction of comfort in clothing. Numerous researchers have developed models for simulating heat transfer from clothing. This becomes more important when it is the main constraint for the comfort properties of the fabric. It is therefore important to optimise the construction of clothing assemblies. To do this, it is essential to understand the heat transfer through fibrous materials, which has received the attention of many researchers [1-5] who have studied the various modes of heat transfer through fibrous materials. A number of studies [6-9] have addressed the effect of different fabric parameters on the thermal properties of fabrics, and models have been developed [10- 17] to predict heat and moisture transfer through fibrous materials. Most researchers have considered convection as a special case which is dependent on environmental conditions. It has been observed in the literature that conduction and radiation are considered to be the two most important modes of dry heat transfer through textiles in still air conditions.

All the previous studies of heat transfer focused on single batting (the middle layer) covered by inner and outer layers of fabric. In these situations, there is no consideration of the air gap present in between the two successive fabric layers in a multilayered clothing assembly. The air gap is present between the inner fabric layer and batting as well as in between the batting and the outer fabric layer, and should be considered for correct prediction of heat transmission through a three-layer clothing assembly. The present work is primarily concerned with the study of heat transfer when an air gap present in between fabric layers, which may be nearly equivalent to a more realistic situation. The basic objective of the present work was to develop a mathematical model to predict heat transmission through a multilayer clothing system considering the air gap in between two layers and validation of the model through experimental studies. The paper also reports the study of heat transfer through combinations of fabric layers with different thicknesses of air gaps in between the fabric layers.

Mathematical model

Symbols

L - Thickness, m
k - Conductivity of the material, W/m ^{0}C
A - Area of the fabric surface, m^2
v - Volume, m^3
V - Total volume of sample, m^3
M - Mass of material, kg
gsm - Mass of material per m^2, g/m^2
n - Index of refraction
b - Blackbody
q - Heat flux, Wm^{-2}
E_b - Blackbody emissive power, Wm^{-2}
c_p - Specific heat of the sample, J kg^{-1} K^{-1}
c - Speed of light in the medium, ms^{-1}
f_v - Fibre volume fraction of the multilayered assembly
K - Boltzmann constant,JK-1
K_R - Rosseland mean extinction coefficient, m^{-1}
$E_{b\lambda}$ - Spectral blackbody emissive power, Wm^{-2}
h - Plank's constant, J s
t - Time, s
T - Temperature, K
x - Spatial coordinate through the insulation thickness, m
R - Thermal resistance, m^2 ^{o}C /W
ρ - Density, kgm^{-3}
σ - Stefan Boltzmann's constant (5.66 × 10^{-8} W/m^2 K^4)
λ - Wavelength of radiation, µm
β_{ex} - Spectral extinction coefficient, m^{-1}

Subscripts

r - Radiation
c - Conduction
f - Fibre
a - Air
T - Total

Heat transfer through fibrous insulation involves combined modes of heat transfer, i.e. (i) solid conduction through fibres and gas conduction; (ii) natural convection in the space between fibres; and (iii) radiation interchange through the participating media.

The mathematical model proposed in the present work is based on simplified basic equations of heat transfer through porous media. The salient features of the model are as follows:

(i) The fabric assembly is assumed to possess a cellular geometry in which the conductive heat transfer takes place through yarns/fibres.
(ii) The fabric assembly is assumed to be cuboid comprised of infinite cylindrical fibres.
(iii) All the fabric assemblies can be modified into a simple geometry of air pores and fibres.
(iv) The model was designed for still air conditions, so heat transfer by convection may be neglected.
(v) Heat transfer by conduction has been considered as an analogous circuit model of thermal resistances in series.
(vi) Heat transfer by radiation takes place through yarns as well as air pores.

Convective heat transfer in fabrics is negligible [18], so in the present study, convective heat transfer in fabrics has been neglected. Therefore, the conservation of energy for one-dimensional heat transfer in the insulation by conduction and radiation is given by Sparrow and Cess [19] in the form of a partial differential equation.

$$\rho c_p \frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(k_c \frac{\partial T}{\partial x}\right) - \frac{\partial q_r}{\partial x} \qquad (1)$$

And the effective thermal conductivity k_e is defined by

$$k_e = k_c + k_r \qquad (2)$$

Where k_c is the conductivity of the sample due to conduction and k_r is the conductivity of the sample due to radiation. In the present work, the conduction as well as radiation components of effective thermal conductivity in multilayer clothing were determined.

Conduction component of effective thermal conductivity

Assumptions made for heat transfer through multilayer clothing are:

(i) The heat transfer due to convection is negligible.
(ii) The heat flows only in one direction (from high temperature to low temperature).
(iii) Fibres in clothing are considered to lie perpendicular to the heat flow.

The conduction component of the overall effective conductivity can be determined using Fricke's method [20]. By applying Fricke's method for a fibrous medium, determined for specimens where fibres are perpendicular to the heat flow, the thermal conductivity of a fibrous material is:

$$K_{cf(s)} = \left[1 - \left\{\frac{1-\dfrac{K_a}{K_f}}{1+\dfrac{2\left(\dfrac{K_a}{K_f}\right)\left(\dfrac{v_f}{v_a}\right)}{1+\dfrac{K_a}{K_f}}}\right\}\right] K_f \qquad (3)$$

where:

K_a - Thermal conductivity of air (0.02596 w/m⁰C),
K_f - Thermal conductivity of the fibre,
v_a - Air volume in a porous material,
v_f - Solid fibre volume in a porous material,
K_{cf} - Thermal conductivity of multilayered fabric used in the present work as shown in Figure 1. This is determined by considering an analogous circuit model in series as shown in Figure 2.

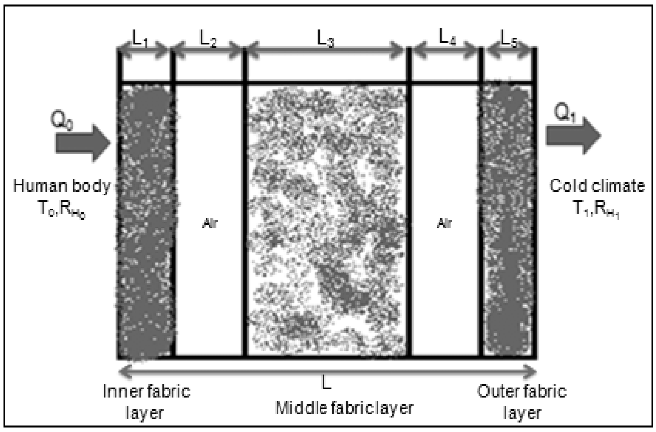

Figure 1. Schematic diagram of heat transfer model through a multilayer clothing assembly

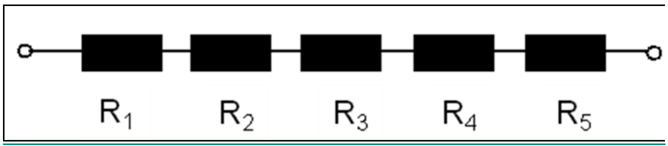

Figure 2. The circuit model for resistances in series

Where total thermal resistance for conduction is given by

$$R_T = \sum_{i=1}^{5} R_i \qquad (4)$$

where:

R_T - Total thermal resistance of the sample,
R_i - Thermal resistance of the individual layers,

$$\mathrm{R_T = R_1 + R_2 + R_3 + R_4 + R_5}$$

or

$$\frac{L}{K_{cf(T)}} = \frac{L_1}{K_{cf(1)}} + \frac{L_2}{K_{cf(2)}} + \frac{L_3}{K_{cf(3)}} + \frac{L_4}{K_{cf(4)}} + \frac{L_5}{K_{cf(5)}} \qquad (5)$$

$K_{cf(T)}$ can be determined by equation (5), which is the total thermal conductivity of the multilayer clothing due to conduction.

Radiation component of effective thermal conductivity

Assumptions made for radiative heat transfer through multilayer clothing are:

(i) Multilayer clothing is considered to be an optically thick medium.
(ii) The fabric assembly is considered to be cuboid containing air and fibres as randomly oriented cylindrical particles.
(iii) The cylindrical particles are uniformly distributed in the medium.
(iv) The fibres are considered as participating media as they can scatter, emit and absorb electromagnetic waves.
(v) The refractive index of the medium is calculated based on the weighted average volume fractions of air and fibres

Radiation through multilayer clothing can be considered as a diffusion process because the medium can be considered to be optically thick. The radiative heat flux through the medium is given by Siegel [21] as

$$q_r = -\frac{16n^2\sigma}{3K_R}T^3\frac{\partial T}{\partial x} \tag{6}$$

Hence, the thermal conductivity due to radiation is

$$k_r = \frac{16n^2\sigma}{3K_R}T^3 \tag{7}$$

Where n is the refractive index and K_R is the extinction coefficient.

Prediction of overall refractive index (n) of the material

In most of the previous studies, the refractive index of the fabric assembly was taken as 1 (the refractive index of a vacuum). But, the actual refractive index of the material may be different. The overall refractive index of a multilayered fabric assembly is considered to be the weighted mean of the refractive indices of the constituent materials (i.e. fibres and air in the present situation). Thus, the overall refractive index (n) of the multilayer clothing assembly can be given by

$$n = \frac{v_{fT}n_f + v_{aT}n_a}{v_f + v_a} \tag{8}$$

$$n = \frac{\sum v_{fi}n_{fi} + \left[V - \left(\sum v_{fi}n_a\right)\right]}{V} \tag{9}$$

$$n = n_a + \frac{1}{V}\left[\sum \frac{m_{fi}}{\rho_{fi}}\left(n_{fi} - n_a\right)\right] \tag{10}$$

$$n = n_a + \frac{1}{L}\left[\left\{\sum \frac{gsm_i}{\rho_{fi}}\left(n_{fi} - n_a\right)\right\}\times 10^{-3}\right] \tag{11}$$

where n_a and n_f are the refractive indices of air and fibres, respectively, L is thickness of an individual layer, gsm is the mass per unit area of fabric layer (g/m^2), σ_f is density of the fibre and the subscript i denotes the different layers in the multilayer assembly.

Prediction of the extinction coefficient (K_R)

In order to quantify thermal radiation within the insulation, the temperature-dependent extinction coefficient is needed. Physically, the extinction coefficient represents the decay rate of the radiation intensity passing through the material. The Rosseland mean extinction coefficient is a more commonly used material parameter than the spectral extinction coefficient, as it represents the overall effect of energy decay in the material. The Rosseland mean extinction coefficient is defined by Liu and Lees [22] as

$$\frac{1}{K_R} = \int_{\lambda_1}^{\lambda_2} \frac{1}{\beta_{ex}}\frac{\partial E_{b\lambda}}{\partial E_b}d\lambda \tag{12}$$

For black bodies, the monochromatic emissive power was derived by Planck as

$$E_{b\lambda} = \frac{2\pi hc^2}{\lambda^5\left(e^{\frac{hc}{KT\lambda}} - 1\right)} \tag{13}$$

By combining equations (12) and (13)

$$\frac{1}{K_R} = \int_{\lambda_1}^{\lambda_2} \frac{1}{\beta_{ex}}\frac{2\pi h^2c^3e^{\frac{hc}{KT\lambda}}}{4K\sigma\lambda^6T^5\left(e^{\frac{hc}{KT\lambda}} - 1\right)^2}d\lambda \tag{14}$$

In equation (14), the only parameter which is unknown to us is the spectral extinction coefficient β_{ex}.

Prediction of the spectral extinction coefficient (β_{ex})

An approximate expression of the spectral extinction coefficient for randomly-oriented cylinders has been suggested by Lee and Tien [23]. The spectral extinction coefficient is given by

$$\beta_{ex} = \frac{\beta\pi nkf_v}{\lambda}\left[1 + \frac{4}{\left(n^2 - k^2 + 1\right)^2 + \left(2nk\right)^2}\right] \tag{15}$$

Equation (15) provides an approximate expression for the spectral extinction coefficient of a fabric assembly of randomly-oriented cylindrical fibres. A value of β = 1.1 was suggested for infrared wavelengths.

By substituting the values of constants and solving the above equations, one can obtain the value of radiative thermal conductivity (k_r) of the multilayered clothing by equation (7).

After determining the values of effective thermal conductivity due to conduction and radiation, the total thermal conductivity of the clothing can be determined using equation (2).

Some standard parameters used in the theoretical calculations

– Density of polyester fibres	1380 kg/m3
– Average temperature of the body	300K
– Wavelength range for blackbody at 300K	2-60 µm
– Refractive index of polyester fibres	1.58
– Refractive index of air	1

Flow chart for the calculation of effective thermal conductivity

In Figure 3a a flow chart for the calculation of effective thermal conductivity is presented. Integral calculations were done with the help of a definite integral calculator.

Experimental

The experiments were carried out with different multilayered fabric assemblies for the verification of the developed model. The thermal resistance of a series of multilayered fabric assemblies were measured and the results were compared with the values obtained from the developed model. Figure 1b shows the three-layer fabric assembly, where L_1, L_3 and L_5 are the thicknesses of the inner, middle and outer fabric layers, respectively. The thicknesses of the entrapped air layers between the fabric layers are L_2 and L_4.

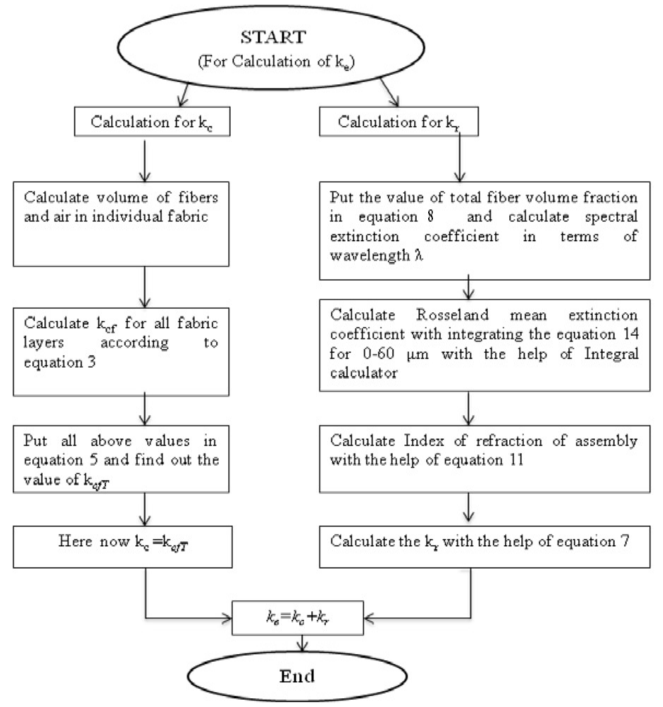

Figure 3a. Flow chart for the calculation of effective thermal conductivity

Materials

100% polyester plain woven fabrics for the inner and outer layers and 100% polyester non-woven wadding and warp knitted spacer fabrics were used in the middle layer for making the multilayered (three-layer) fabric assemblies. The details of these fabrics are given in Table 1. These fabrics were arranged in different combinations to have different multilayered assemblies, as given in Table 2. The multilayered fabric assemblies were prepared by placing the desired fabrics over each other. In the present study, proper arrangements were made to create a multilayered fabric assembly with three fabric layers (inner, middle and outer) and two air gaps in between the fabric layers. The air gap thicknesses between the fabric layers were varied to obtain different multilayered assemblies. Details on the combinations of the multilayered fabric assemblies with different thicknesses of air gaps are given in Table 3.

Table 1. Details of individual fabrics for layered assemblies

Fabric Type	Fabric code	Thickness, mm	Mass per unit area, g/m^2	Thermal resistance of individual layer, m^2 ^{0}C/W
Plain woven 100% polyester fabric	F_1	0.2	72	0.012
Non-woven 100% polyester wadding	F_2	3.2	110	0.182
Non-woven 100% polyester wadding	F_3	5.0	80	0.215
Non-woven 100% polyester wadding (high loft)	F_4	20.0	150	0.928
Warp knitted 100% polyester spacer fabric	F_5	5.0	160	0.110

Table 2. Combinations of different fabrics in layered assemblies

Fabric assembly	Inner layer	Middle layer	Outer layer
A	F_1	F_2	F_1
B	F_1	F_3	F_1
C	F_1	F_5	F_1
D	F_1	F_4	F_1

Table 3. Details of fabric assemblies with different thicknesses of air gaps

Assem-bly	Mass per unit area, g/m^2	Sample no.	Layer thickness, mm					Total thickness, mm
			L_1	L_2	L_3	L_4	L_5	
A	254	A_1	0.2	0	3.2	0	0.2	3.6
		A_2	0.2	0	3.2	2	0.2	5.6
		A_3	0.2	2	3.2	2	0.2	7.6
		A_4	0.2	2	3.2	4	0.2	9.6
		A_5	0.2	4	3.2	4	0.2	11.6
		A_6	0.2	5	3.2	5	0.2	13.6
		A_7	0.2	6	3.2	6	0.2	15.6
		A_8	0.2	7	3.2	7	0.2	17.6
B	224	B_1	0.2	0	5	0	0.2	5.4
		B_2	0.2	0	5	2	0.2	7.4
		B_3	0.2	2	5	2	0.2	9.4
		B_4	0.2	2	5	4	0.2	11.4
		B_5	0.2	4	5	4	0.2	13.4
		B_6	0.2	5	5	5	0.2	15.4
		B_7	0.2	6	5	6	0.2	17.4
		B_8	0.2	7	5	7	0.2	19.4
C	304	C_1	0.2	0	5	0	0.2	5.4
		C_2	0.2	0	5	2	0.2	7.4
		C_3	0.2	2	5	2	0.2	9.4
		C_4	0.2	2	5	4	0.2	11.4
		C_5	0.2	4	5	4	0.2	13.4
		C_6	0.2	5	5	5	0.2	15.4
		C_7	0.2	6	5	6	0.2	17.4
		C_8	0.2	7	5	7	0.2	19.4
D	294	E_1	0.2	0	20	0	0.2	20.4
		E_2	0.2	0	20	2	0.2	22.4
		E_3	0.2	2	20	2	0.2	24.4

Note: L_1, L_3 and L_5 are the thicknesses of the inner, middle and outer fabric layers, respectively. L_2 and L_4 are the thicknesses of entrapped air layers between the fabric layers.

Methods

The thickness of the woven fabric was measured at a pressure of 20 gf/cm^2 and the non-woven wadding, spacer fabric and multilayer assemblies were measured at a pressure of 0.3 gf/cm^2. An average of ten thickness readings from different places was taken for each sample. The mass per unit area of fabrics was measured by measuring the mass of fabric samples 10cm×10cm in size with an electronic balance.

The thermal dry thermal resistance of the individual fabric layers as well as the multi-layered fabric assemblies was measured using a guarded hot plate, as per the ASTM D1518 method. The temperatures of all the plates (test plate, guarded ring and the bottom plate) were maintained at approximately 33±0.2°C). The fabric sample being tested (50cm×50cm) was placed on the test plate. The fabric acted as a barrier to the loss of heat from the hot test plate. In such cases, Fourier's Law of heat conduction can be applied:

$$\varphi_z = -K\left(\frac{\Delta T}{d}\right) = \frac{Q}{A} \tag{16}$$

Where φ_z is the heat flux in the Z direction (vertical upward direction), ΔT is the temperature difference across the two surfaces of the fabric, Q is the heat exchange rate through an area A perpendicular to the direction of heat flow, d is the thickness of the sample (fabric) and K is the thermal conductivity of the material. The thermal resistance (R) of the material is given as

$$R = \frac{d}{K} \tag{17}$$

The measurement of thermal resistance was carried out in convective as well as in non-convective mode. In convective mode, only natural convection takes place, whereas in non-convective mode, a top plate is used to cover the top surface of the sample to cut off the convection air current. In the present work, for the validation of the theoretical model, the non-convective mode was adopted.

Non-convective measurements

A top plate was placed on top of the test plate and guard ring surface and the heaters were switched on and adjusted so as to keep the test plate temperature at the desired value. The guard ring heater was also adjusted so that its temperature was maintained at ± 0.2°C with respect to the test plate. The equilibrium point was defined as the steady state at which the test plate temperature and the heater input remained constant. The steady state was to be maintained for a period not less than 30 minutes with fluctuations in temperature levels not exceeding ± 0.1°C. The readings were noted every 5 minutes, over a period of 30 minutes after the steady state was reached. Then, the specimen was placed in between the top plate and the test plate (Figure 3b). After reaching steady state, the thermal resistance of the fabric was calculated.

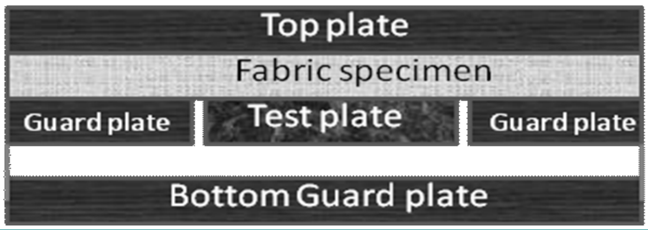

Figure 3b. Schematic diagram of the guarded hot plate in the non-convective mode of measurement

Results and discussion

In an attempt to determine the theoretical value of thermal resistance in non-convective media of a particular multilayered fibrous assembly, the conduction and radiation components of effective thermal conductivity were calculated using equations (5) and (7), respectively. Total thermal resistance was calculated using the inverse proportionality relationship between thermal resistance and thermal conductivity.

Validation of the mathematical model

The theoretically predicted and experimentally measured thermal resistance of all the fibrous assemblies are given in Table 4. It can be observed from Table 4 that by using the theoretically predicted refractive index of the fabric assemblies, the % error values in the predicted thermal resistance were less than those derived from conventional methods in which the refractive index of the fibrous assembly was considered to be unity (n=1). Figures 4a to 4d show the correlation between the experimental results and predicted values for all five assemblies used for validation of the mathematical model. The coefficients of determination for the first three fabric assemblies were from 0.991 to 0.997, so it was evident that the experimental and predicted values were highly correlated. In assembly D, the value of the coefficient of determination was very low, which may be due to the extra insulation (due to the extra high loft non-woven wadding, F_4) generated by the air pockets within the fabric assembly which was not in case with the other four assemblies. The measured thermal resistance of fabric assembly D was also much higher than the predicted values. This may be due to the fact that the measurement of the thermal characteristics of the extra high loft non-woven wadding, F_4, was very difficult, leading to experimental errors.

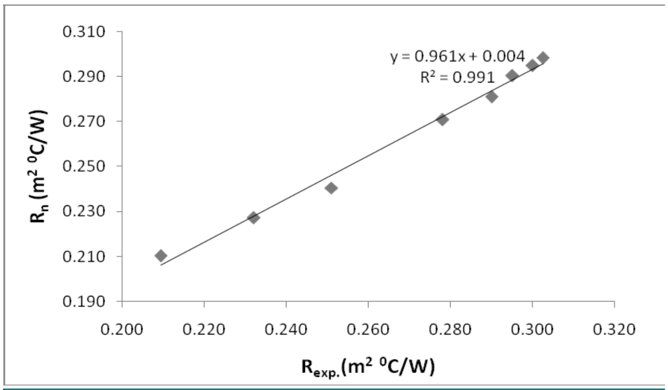

Figure 4a. Correlation between the experimental results and the predicted values for assembly "A"

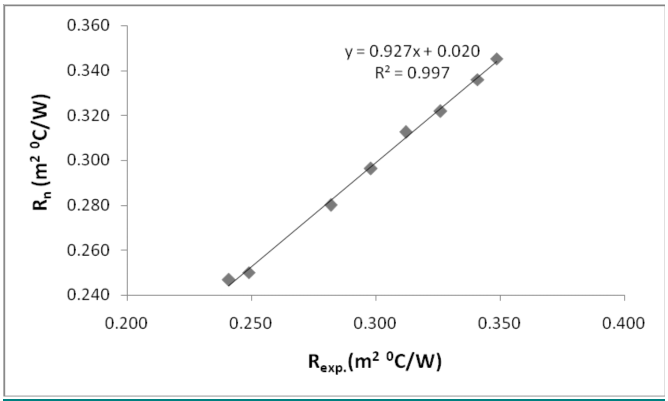

Figure 4b. Correlation between the experimental results and the predicted values for assembly "B"

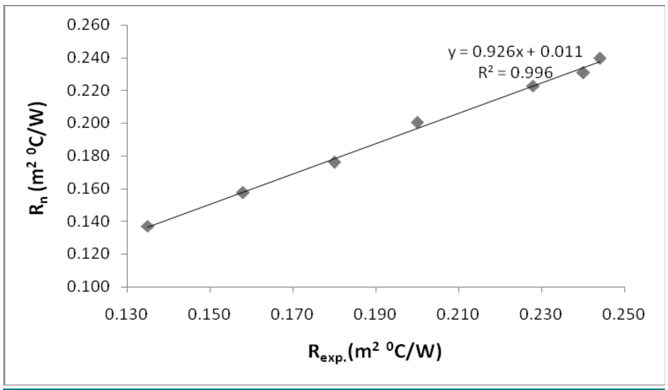

Figure 4c. Correlation between the experimental results and the predicted values for assembly "C"

Table 4. Calculated and measured properties of fabric assemblies

Assembly	Sample no.	Total thickness, mm	Predicted refractive index (n)	Predicted thermal resistance, $m^{2}\,^{0}C/W$		Measured thermal resistance, $m^{2}\,^{0}C/W$	% Error	
				$R_{n=1}$	R_n	R_{exp}	$R_{n=1}$	R_n
A	A_1	3.6	1.030	0.199	0.210	0.209	4.76	0.43
	A_2	5.6	1.019	0.220	0.227	0.232	5.26	2.04
	A_3	7.6	1.014	0.235	0.241	0.251	6.45	4.13
	A_4	9.6	1.011	0.266	0.271	0.278	4.4	2.57
	A_5	11.6	1.009	0.277	0.281	0.290	4.59	3.11
	A_6	13.6	1.008	0.286	0.290	0.295	2.89	1.55
	A_7	15.6	1.007	0.291	0.295	0.300	2.87	1.7
	A_8	17.6	1.006	0.295	0.298	0.303	2.38	1.38
B	B_1	5.4	1.017	0.239	0.247	0.241	0.75	2.39
	B_2	7.4	1.013	0.244	0.250	0.249	1.97	0.39
	B_3	9.4	1.010	0.275	0.280	0.282	2.49	0.71
	B_4	11.4	1.008	0.292	0.296	0.298	1.97	0.54
	B_5	13.4	1.007	0.309	0.313	0.312	1.06	0.19
	B_6	15.4	1.006	0.318	0.322	0.326	2.35	1.30
	B_7	17.4	1.005	0.333	0.336	0.341	2.33	1.46
	B_8	19.4	1.005	0.342	0.345	0.349	1.81	0.94
C	C_1	5.4	1.024	0.131	0.137	0.135	2.95	1.55
	C_2	7.4	1.017	0.153	0.158	0.158	3.44	0.30
	C_3	9.4	1.014	0.171	0.176	0.180	4.75	2.22
	C_4	11.4	1.011	0.196	0.200	0.200	1.81	0.22
	C_5	13.4	1.010	0.219	0.223	0.226	3.09	1.32
	C_6	15.4	1.008	0.227	0.231	0.228	0.27	1.21
	C_7	17.4	1.007	0.237	0.240	0.240	1.44	0.17
	C_8	19.4	1.007	0.241	0.244	0.244	1.31	0.03
D	E_1	20.4	1.006	0.946	0.954	1.428	33.77	33.16
	E_2	22.4	1.006	0.958	0.969	1.430	32.98	32.24
	E_3	24.4	1.005	0.965	0.975	1.410	31.58	30.83

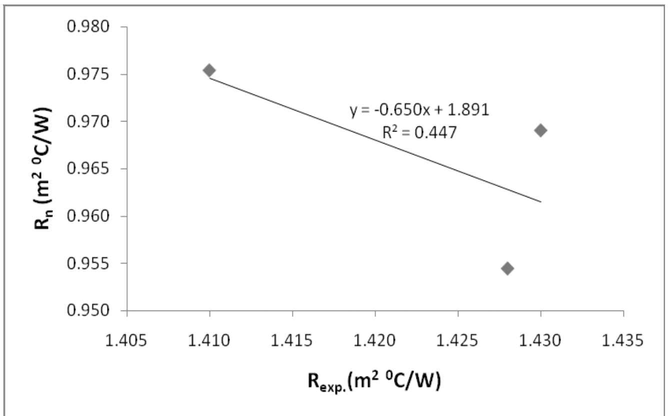

Figure 4d. Correlation between the experimental results and the predicted values for assembly "D"

Effect of the thickness of air layers between the fabric layers of the assembly

In this part of the study, the combinations of fabric layers in each assembly were same, but the thicknesses of the air gaps, i.e. L_2 and L_4, were varied. Therefore, the variation in thicknesses between different samples within an assembly was only due to the variation in air gap thickness. Figures 5a to 5c show the effect of the thickness of air gaps on thermal resistance in the multilayered fabric assembly It can be observed from Table 4 and Figures 5a to 5c that the total thermal resistance of the multilayered clothing assemblies initially

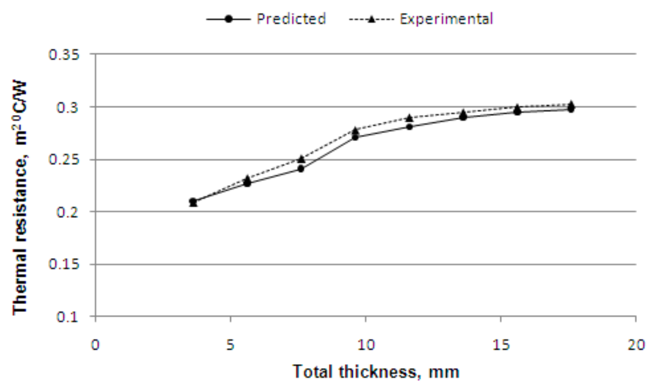

Figure 5a. Effect of the thickness of air gaps on the thermal resistance of assembly "A"

increased at a faster rate with the increase in the thickness of the air gap, but at a certain point, the increase in resistance reached a plateau. This may be due to the initial formation of insulating air pockets in between the fabric layers which reduced the heat flow due to conduction. At a certain thickness of air gap, radiative heat transmission may dominate over the insulating air pockets.

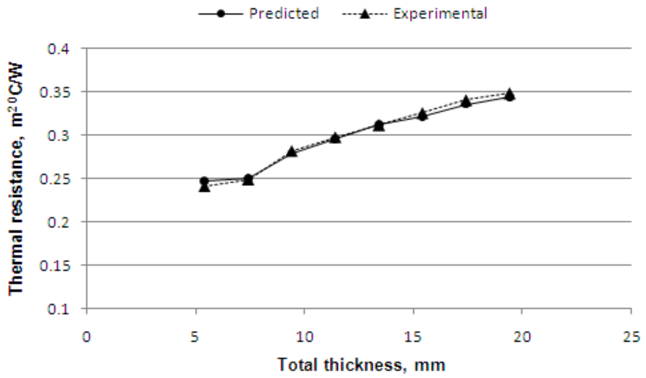

Figure 5b. Effect of the thickness of air gaps on the thermal resistance of assembly "B"

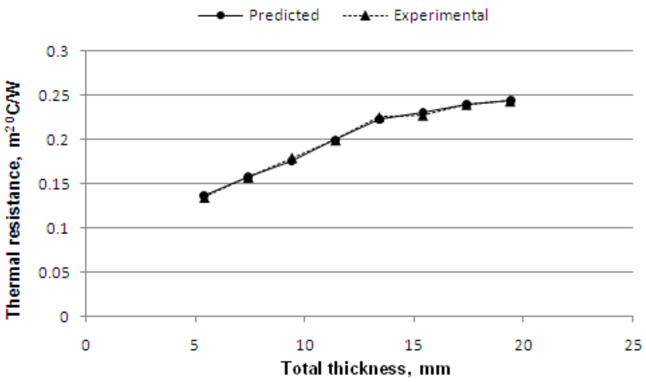

Figure 5c. Effect of the thickness of air gaps on the thermal resistance of assembly "C"

Conclusions

A theoretical model was developed based on some basic assumptions. Fairly good correlations were observed with the experimental results. The following conclusions may be drawn from the present work:

- All the multilayered fabric assemblies can be defined as cuboids filled with randomly oriented infinite cylinders (fibres).
- Conductive heat transfer can be calculated with by analogy to electrical resistance and Fricke's law.
- Radiative heat transfer can be modelled using the anisotropic model for randomly oriented infinite cylindrical particles of very high aspect ratio.
- The predicted refractive index on the basis of the weighted average of fibre and air volumes in the assembly gives better results in the prediction of thermal conductivity due to radiation.
- The air present between the fabric layers of multilayered clothing has a significant effect on the thermal resistance of multilayer clothing.

Acknowledgements

The authors are extremely thankful to the Directorate of Extramural Research and Intellectual Property Rights, Defence Research and Development Organisation, New Delhi for providing the funds to conduct this research. We are also indebted to the laboratory staff for their help during the study.

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