

Thermal resistance of fibre-fabric combinations in convective environments

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Combined fibre-fabric assemblies of fibres of different deniers and fabrics of different covers have been evaluated for their thermal resistance in convective environments. It has been found that fibre-fabric assemblies are more effective than fibre webs alone in these environments and the fabrics with higher cover perform better than the fabrics with lower cover.

Keywords: Convective environment, Fibre-fabric assemblies, Fibre web, Thermal resistance, Wind tunnel

1 Introduction

The human body must constantly be in a thermal balance with the environment so that its internal temperature is maintained at about 37°C without any appreciable variation. Clothing must be designed in such a manner that thermal exchanges between man and his environment are maintained at a rate so as not to cause discomfort under vastly different environmental conditions and for this, thermal insulation characteristics of a fabric are of significant importance.

According to Cassie¹, it is the air entrapped in a fabric that gives it good insulation. The term 'entrapped' is used to refer to the drag or resistance to air movement. Various workers have reported the effect of air velocity on the heat loss of fabrics. Rees² gave curves for different fabrics, open fabrics showing a rapid increase in heat loss at high wind speeds. Peirce and Rees³ did some experiments on fabrics shielded from air by a thick cloth of high wind resistance to give the thermal resistance of the fabric only, excluding that of air. The value of thermal resistance was found to be additive when layers were increased. This additive nature of thermal resistance is not strictly true when very open fabrics are used. Under such conditions, the combination has a resistance much greater than the sum of the separate resistances. It was suggested that the most efficient structure for heat insulation is not a woven fabric but a sandwich of fibres held between two fabrics.

The type of apparatus used also has an important role in the values of thermal resistance of

fabric. Marsh⁴ listed three basic methods of measuring thermal transmission—Disc method, cooling method and the constant temperature method. Kawabata⁵⁻⁷ used the transient method to study heat flow from a source of finite heat content to fabric. Modifications of the above methods have been adopted by many research workers to measure the thermal resistance of fabrics and one of this⁸⁻¹⁰ has been adopted in the present investigations. Provision has also been made to take the convective heat losses into account by using a wind tunnel on the fabric/web/fibre-fabric assembly surface and a variable speed fan to provide different wind velocities in the wind tunnel.

Combined fibre-fabric assemblies are known to provide effective thermal insulation in extreme cold environment without excessive clothing weight. However, it is necessary to understand the factors which contribute to this effectiveness, especially in the windy environments. In this paper, the effect of the type of fabric and the fibre denier on the thermal resistance of a fibre-fabric combination has been studied under conditions of varying wind velocities over different fibre-fabric assemblies.

2 Materials and Methods

Two commercially available plain woven cotton fabrics with widely varying air permeabilities and cover factors were combined with the two fibre webs produced from 1 denier 51 mm and 3 denier 51 mm polyester fibres to obtain four different fibre-fabric combinations (Fig. 1). The specific-

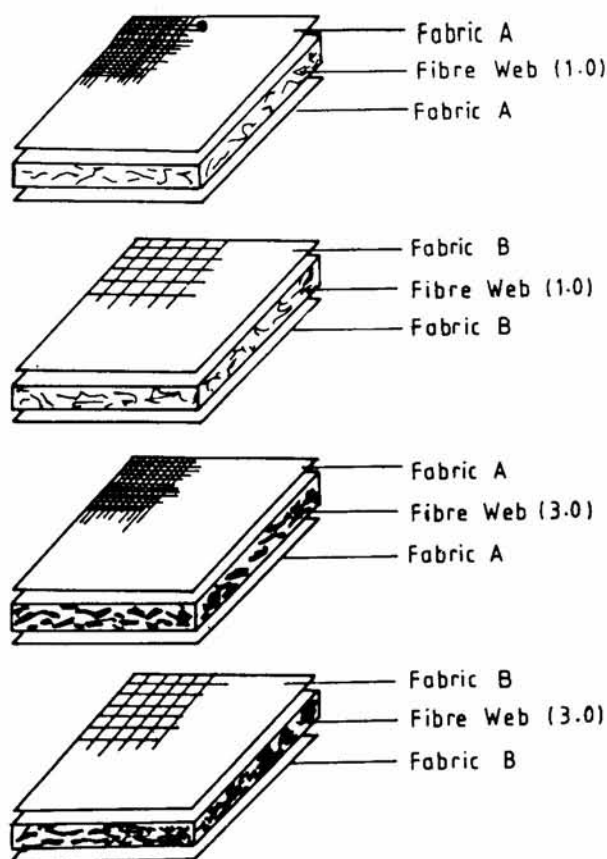


Fig. 1—Schematic representation of four fibre web-fabric combinations evaluated for their thermal resistance in convective environment

ations and properties of the fabrics used are given in Table 1. The % total area covered by yarns was calculated assuming the yarns to be circular having a packing coefficient of 0.65. Fabric cover is given by

$$\text{Fabric cover(\%)} = \left(\frac{d_1}{p_1} + \frac{d_2}{p_2} - \frac{d_1 \cdot d_2}{p_1 \cdot p_2} \right) \times 100 \quad \dots (1)$$

where d_1 is the diameter of warp yarn; d_2 , the diameter of weft yarn; p_1 , the warp yarn spacing; and p_2 , the weft yarn spacing.

Yarn diameter (d) is given by

$$d = 4.44 \times 10^{-3} \sqrt{\frac{\text{Tex}}{\rho}} \text{ cm} \quad \dots (2)$$

where Tex is the yarn linear density in tex; and ρ , the fibre density in g/cm^3 (assumed to be 1.52 g/cm^3 for cotton).

Air permeability was obtained using a Shirley air permeability tester. Since it was not possible to create the required pressure drop across the fabric using a single fabric layer, multiple layers of both

Table 1—Properties and specifications of plain woven fabrics

Parameter	Fabric A	Fabric B
Fabric cover, %	83	59
Relative air permeability ^a ($\text{cc/cm}^2/\text{sec/cm}$ of water)	4.2	16.7
Area weight, g/m^2	132	42
Thickness, mm	0.20	0.14
Ends/cm	45	39
Picks/cm	41	46
Warp linear density, tex	14.0	5.2
Weft linear density, tex	14.8	5.6

^aAir permeability of 10 layers of fabrics.

the fabrics were used to obtain the comparative values of air permeability. Fabric thickness was measured under a pressure of 20 g/cm^2 using a Essdiel (SDL) thickness tester.

Fibre webs of equal mass per unit area were prepared from the two polyester fibres on a Shirley miniature card. Carded web from 36 g of hand-opened fibre mass was collected on a drum. This fibre web was then carded again and the collected fibre web, after second carding, was used to cut the web samples of $21 \text{ cm} \times 21 \text{ cm}$ for testing.

2.1 Measurement of Thermal Resistance

The instrument used for the measurement of thermal resistance is shown in Fig. 2. The measuring principle used in this instrument is that for two conductors in series normal to the direction of the heat flow, the ratio of the temperature drop across the conductors is proportional to their thermal resistances. Thus, if the temperature drops across a material of known thermal resistance and that across a fibre-fabric assembly in series with it are measured, the thermal resistance of the fibre-fabric assembly can be evaluated. The temperatures are measured using the copper-constantan thermocouples with their cold junctions dipped in mercury contained in test tubes immersed in crushed ice-water mixture. A rectangular wind tunnel is fitted over the instrument which has an open side and a fan fitted on the other side to blow air at the required velocity over the surface of the specimen by varying voltage supplied to the fan. The wind velocity in the tunnel is monitored with the help of an anemometer.

When a steady state has reached and temperatures are no longer changing with time when a fixed amount of heat energy is being supplied by the heaters and flowing across the two resistances

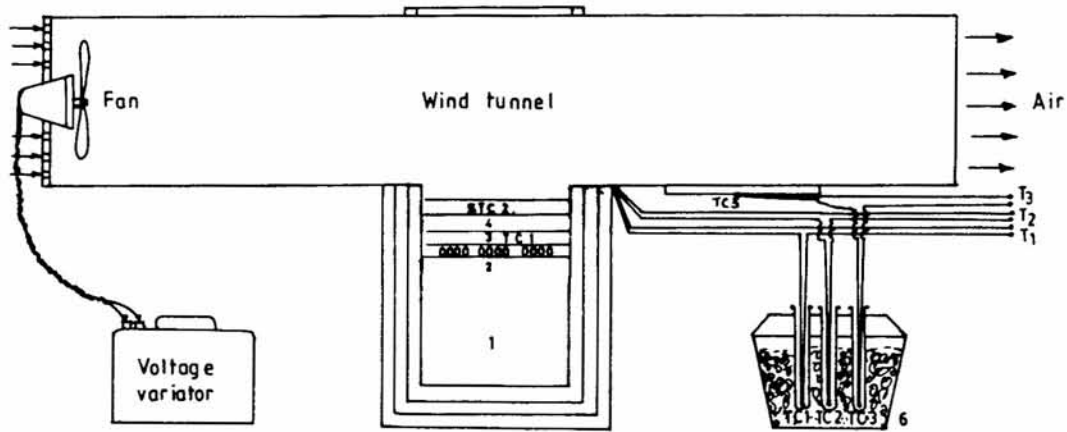


Fig. 2—Schematic diagram of the thermal resistance tester with a wind tunnel arrangement [1—Glass wool; 2—Heaters; 3—Steel plate; 4—Standard thermal resistance sheet; 5—Test specimen; 6—Water-ice mixture. TC1, TC2 and TC3 are thermocouple junctions]

in series, let T_1 , T_2 and T_3 be the temperatures registered by the three thermocouples TC1, TC2 and TC3, indicating the temperatures at the base of the standard resistance, on the standard resistance sheet and on the top of fabric surface respectively. Then, the thermal resistance of the fabric (R_F) is calculated from the following relationship⁹:

$$\frac{R_F + R_{SR}}{R_S} = \frac{T_2 - T_3}{T_1 - T_2} \quad \dots (3)$$

where R_S is the thermal resistance of the standard resistance sheet and R_{SR} , the surface resistance offered by the layer of the air in contact with the fabric. This surface resistance changes with the wind velocity.

The unit of thermal resistance used is 'tog' which is defined as resistance that will maintain a temperature difference of 0.1°C with a heat flux of 1 W/m^2 .

Surface resistance was obtained at various wind velocities by conducting the test without any fibre-fabric assembly on the surface of the standard resistance sheet. The temperatures T'_1 , T'_2 and T'_3 indicated by the three thermocouples TC1, TC2 and TC3 respectively were used to obtain the surface resistance:

$$\frac{R_{SR}}{R_S} = \frac{T'_2 - T'_3}{T'_1 - T'_2} \quad \dots (4)$$

The surface resistance values at different wind velocities between 0 and 0.8 m/s were used to obtain a relationship between the surface resistance R_{SR} and the wind velocity W .

Thermal resistances of both the fabrics, designated as fabric A and fabric B, and of fibre webs, designated as web (1.0) and web (3.0), were obtained without any air flow across the fabric, i.e. zero wind velocity and at fan speeds regulated to give wind velocities of 0.1, 0.4, 0.6 and 0.8 m/s. Four fibre-fabric combinations (Fig. 1) were also tested at the same levels of wind velocities.

3 Results and Discussion

The relationship between the surface resistance R_{SR} (in togs) as obtained from Eq. (2) and the wind velocity (W) in m/s was found to be linear with a very high correlation coefficient of 0.99, the standard error of R_{SR} estimate being 0.0288 and that of W coefficient, 0.0430. The relationship obtained is

$$R_{SR} = 1.292 - 0.783 W \quad \dots (5)$$

Combining the Eqs (3) and (5), the resistance of fibre-fabric combination (R_F) can be found from the following relationship:

$$R_F = \frac{T_2 - T_3}{T_1 - T_2} R_S - (1.292 - 0.783 W) \quad \dots (6)$$

The value of the thermal resistance (R_S) of the standard sheet used in the instrument was 0.783 togs.

Thermal insulation characteristics of individual components (fabrics and fibre webs) at different wind velocities are given in Table 2. Thermal insulation of a relatively closely woven fabric 'A' with higher thickness is found to be much higher than the thermal insulation of fabric 'B' at all the wind velocities. Heat losses due to radiation in the case

Table 2—Thermal resistance of individual components in togs at different wind velocities

Component	Wind velocity, m/s				
	0	0.1	0.4	0.6	0.8
Fabric A	0.152	0.152	0.148	0.143	0.143
Fabric B	0.046	0.045	0.044	0.041	0.039
Web (1.0)	7.525	7.429	6.297	5.231	4.383
Web (3.0)	6.903	6.825	5.264	4.726	4.247

of open fabrics are much higher, resulting in much lower values of thermal resistance. The thermal resistance values of the fibre webs are very high in comparison to the thermal resistance values of the fabrics because of their higher thicknesses (52 mm and 51 mm for 1 den and 3 den fibre webs respectively). The higher thickness allows the webs to entrap very high amount of air in the web structure, resulting in very high thermal resistance offered by them. However, because of the high porosity of the webs, the loss of thermal insulation with the increasing wind velocity is also very high due to increasing convective heat losses.

Webs made from the finer denier fibres show greater thermal resistance than the webs made from coarser fibres because the total number of fibres and their surface area in the finer fibre web are much higher which lead to the entrapment of the air in smaller interices and much greater air drag, resulting in higher thermal insulation.

3.1 Effect of Combining Fabrics with Fibre Webs

Figs 3 and 4 show the thermal resistance of the fibre-fabric combinations at different wind velocities. It is observed that though the thermal resistance of the fabrics is very less compared to that of the fibre webs, the resultant thermal resistance of fibre-fabric combination is far higher than the sum of the individual resistances reported in the Table 2 when these fabrics are used as a cover for webs. This is because of the inclusion of a layer of air between the fibre web surface and the bottom of the fabric and the greater immobilization of air by the surfaces of the fibres and fabrics.

Covering by fabric B improves the insulation but there is a little change in the increasing heat losses with increasing wind velocities. This is because of the open structure of fabric B which is not very effective in preventing the convective heat losses. However, there is a greater improvement in insulation when fabric A is used, particularly at high air velocities. Fabric A being less permeable is able to prevent the convective heat

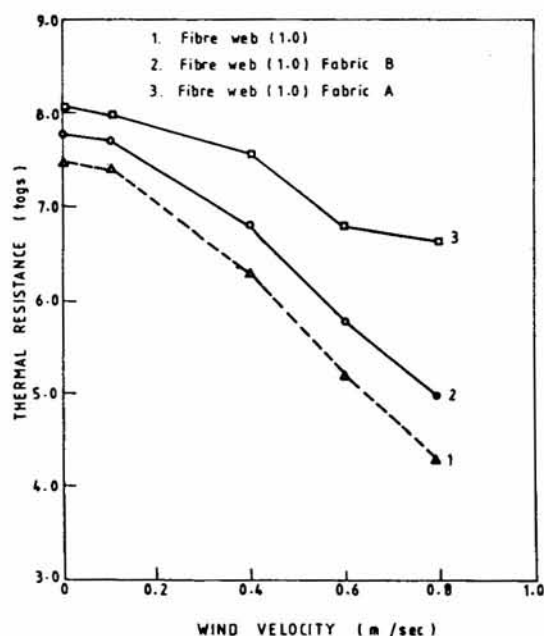


Fig. 3—Effect of sandwiching 1 denier polyester fibre web with fabrics of different covers

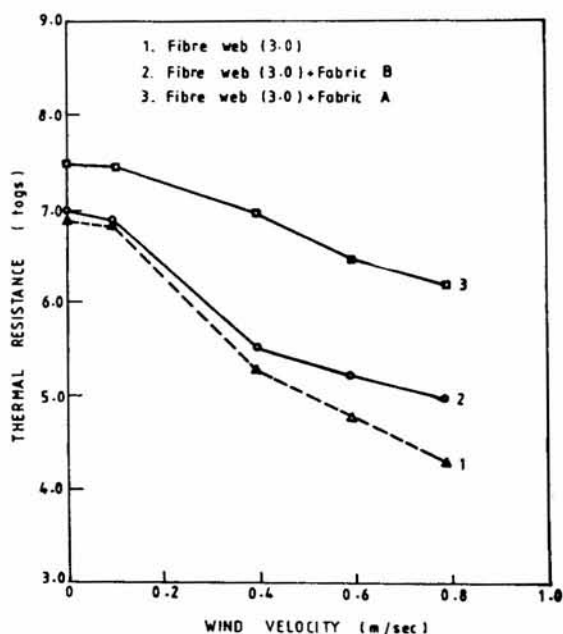


Fig. 4—Effect of sandwiching 3 denier polyester fibre web with fabrics of different covers

losses and thus offers higher thermal resistance, particularly at higher wind velocities.

All combinations used in the analysis show similar trends of variation of thermal resistance with wind velocity, with an initial gradual reduction followed by a steep decrease. In the initial portion of all the curves, i.e. from 0 to 0.1 m/s, the wind is not sufficient to move the air which is clinging on to the fibres and the fabric surface. As the velocity

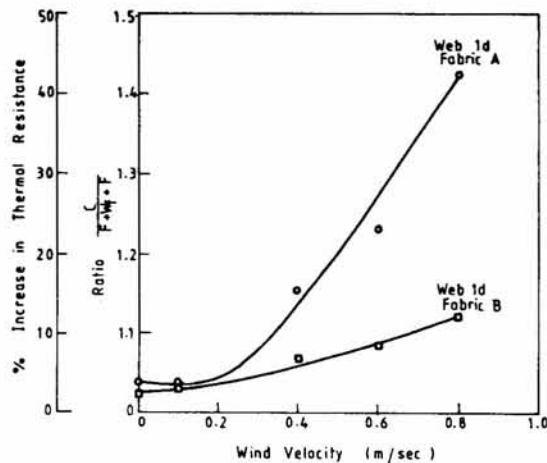


Fig. 5—Increase in the thermal resistance of the composite in relation to the sum of thermal resistances of the fibre web and the fabric layers in the composite as a function of the wind velocity using a web of 1 den fibre

increases the mobility of air increases, resulting in greater heat loss and, therefore, greater reduction in thermal resistance.

To demonstrate the effectiveness of fibre-fabric composites in preventing the heat losses, specially at higher wind velocities, the ratio of the thermal resistance of composite (C) and the sum of the thermal resistances of fabrics and web in the composite ($F+W_f+F$) and the percentage increase in thermal resistance of composite over the sum of their individual thermal resistances have been plotted against the wind velocity in Figs 5 and 6. It is seen from these figures that composites have higher thermal resistance and are more effective in preventing the thermal losses, specially at higher wind velocities. A fabric of higher cover (Fabric A) is more effective than a fabric of lower cover (Fabric B) in reducing the heat losses through the web due to convection, resulting in higher percentage increase in thermal resistance of fibre-fabric composite in relation to the sum of the individual thermal resistances.

4 Conclusions

Fibre webs of finer fibres provide more effective thermal insulation than the webs of coarser fibres. However, the thermal resistance of webs re-

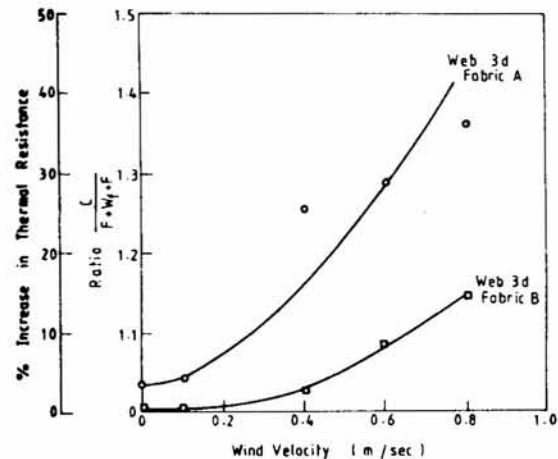


Fig. 6—Increase in the thermal resistance of the composite in relation to the sum of thermal resistances of the fibre web and the fabric layers in the composite as a function of the wind velocity using a web of 3 den fibre

duces rapidly with the increasing wind velocity. The effectiveness of fibre webs improves considerably if they are sandwiched between woven fabrics, and the fabrics of higher cover are more effective in preventing the convective heat losses in windy environment. Considerations of fibre fineness, fabric cover and wind velocity conditions are necessary while designing the fibre-fabric combinations for cold windy environments.

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