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Thermal resistance of two and three-layer fabric assemblies for extreme cold weather protective clothing

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Two (FA2) and three (FA3) layer fabric assemblies have been fabricated in different configurations using cloth shirting angola, pile acrylic fabric, non-woven polyester fabric (batting), coated nylon fabric and nappa leather for designing and development of multilayer clothing to provide protection in extreme cold weather. The configurations of FA2 are cloth shirting angola, PU coated nylon fabric; pile acrylic fabric, PU coated nylon fabric; cloth shirting angola, nappa leather; and acrylic pile fabric, nappa leather. On the other hand, the configurations of FA3 are cloth shirting angola, non-woven polyester fabric, PU coated nylon fabric; pile acrylic fabric, non-woven polyester fabric, PU coated nylon fabric; cloth shirting angola, non-woven polyester fabric, nappa leather; and pile acrylic fabric, non-woven polyester fabric, nappa leather. Thermal resistance of these multilayer clothing assemblies has been evaluated using high-resolution FLIR thermal imaging camera operating in 8-12μm waveband and PID controlled Acmas hot plate in natural convection mode. The maximum thermal resistance, offered by FA2 and FA3, are 5.59 and 6.24 tog respectively. Rational spatial configurations of FA2 and FA3 are as per the temperature of human body parts, and these may be used in designing and development of protective clothing for extreme cold weather.

Keywords: Acrylic, Heat transfer, Multilayer clothing, Nappa leather, Nylon, Polyester fabric, Polyurethane, Protective clothing, Thermal imaging, Thermal insulating materials, Thermal resistance

The primary function of extreme cold weather (ECW) protective clothing is to protect individuals from adverse effects of natural environment. ECW is weather with near freezing temperature, like Siachin and Leh are as in India. Extreme cold is a dangerous situation and brings health emergencies in susceptible people, such as those without shelter or living in poorly insulatedhomes[1]. Heat loss rate increases rapidly with temperature drop and becomes prominent due to wind chill effect[2-4]. These factors impose challenge in maintaining core temperature (37°C) of personnel. In extreme cold regions, the requirement of protective clothing is very critical[5]. Thermal resistance is most influential among functional properties, viz. thermal insulation, moisture permeability, water and wind resistance, of clothing for cold climate[6,7]. Convection, conduction, radiation, respiration and sweat evaporation are accountable for minimising thermal comfort of personnel[8,9].

Several efforts have been made to develop materials and evaluation of properties for cold weather applications. The heat transmission study through multilayer clothing assemblies is very important for the prediction of comfort in clothing. A number of studies have been done to observe the effect of different fabric parameters on thermal properties of fabrics, and models have been developed to predict heat transfer through fabrics[10-14]. Quite a few reveals that thermal resistance is directly proportional to fabric thickness[15,16], while other shows non-linear behaviour of thermal resistance with thickness[17,18]. Bulky and non-woven fabrics show higher non-linear behaviour because of dependency on several factors[19]. The effect of types of fibre, mass per unit area, punch density and depth of penetration of punched non-woven fabrics on thermal resistance was also studied[20,21]. Artificial neural network models have been suggested by researchers to predict thermal resistance of different fabric such as plain, rib, knitted, woven and non woven, of different materials[22-25]. Das *et al.*[14] developed a mathematical model to predict heat transmission through a multilayer clothing system considering the air gap among layers but convection was neglected. Most of the models proposed by various research groups are based on some assumptions that added deviations from realistic conditions and there is variation in proposed thermal resistance of fabrics and fabric ensembles. Hence, thermal resistance measurement becomes essential to design and develop a product.

Studies on thermal resistance measurement are generally focused on three-layer clothing[5,26]. Conduction and radiation are the most common study modes of heat transfer. Laing *et al.*[27] has conducted an experiment to study the effect of air layer and addition of layer by selecting two levels. Das *et al.*[28] also studied thermal resistance of multilayer clothing

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assemblies under different convective modes considering air gaps between fabric layers. The ECW clothing counteracts various environment conditions, and weight penalty is one of the important issues. Hence, there is a need to design lightweight clothing with adequate thermal insulation and its thermal insulation measurement with more practical and accurate thermal evaluation method. With the advancement in infrared (IR) detector technology and image processing techniques, thermography is gaining attention of the scientific community not merely in non-contact radiometric properties measurement of objects but also in thermo-physical phenomenon studies[29-31]. The usage of IR thermography in textile is at initial stage and offers merits over other techniques.

The present work is mainly concerned with the preparation of light weight multilayer clothing assemblies and their thermal resistance measurement accounting conduction, radiation and convection. The outermost layer is exposed to environment during measurement to simulate realistic situation. Multilayer clothing assemblies (two and three layer) in different configurations (04 samples of each) of size 1ft × 1 ft have been prepared by using popular insulating materials such as pile acrylic fabric, cloth shirting angola, polyester batting, PU coated nylon fabric and nappa leather. Thermal insulation measurement of the multilayer fabric assemblies has been carried out by FLIR thermal imaging camera and PID controlled Acmas hot plate.

Experimental

Cloth shirting angola, pile acrylic fabric, non woven polyester fabric (batting), coated nylon fabric, nappa leather are prominent thermal insulating materials used in clothing to provide protection from cold environment effects. These materials have been used in fabric assemblies (FA) for ECW. Cloth shirting angola drab polyester wool blended and pile acrylic sliver knitted fabric have been opted for conductive insulation with excellent wicking. The construction particulars of pile acrylic fabric and cloth shirting Angola are given in Tables 1 & 2 respectively. Non-woven polyester fabric offers good conductive thermal insulation and polyurethane coated nylon fabric provides convective insulation with wind and waterproof properties. Nappa leather offers excellent strength against rubbing is used for additional mechanical strength.

Table 1 — Construction particulars of pile acrylic fabric

Fabric particulars	(Mean± SE)
Yarn count, den	272.18±0.41
Ground Pile	3.0
WPI	15.2±0.3
CPI	21.8±0.52
Fibre composition (acrylic : polyester), %	33.25 : 66.75
Pile height, mm	13±0.28
Pile density per inch^2	330.8 ±2.3
Thickness, mm	7.4±0.06

Table 2 — Construction particulars of cloth shirting angola fabric

Fabric particulars	(Mean ± SE)
Yarn count, den	572.2±2.7
warp weft	634.5±1.9
EPI	22.8±0.34
PPI	19.6±0.46
Pile height, mm	13±1
Fibre blend ratio (polyester : wool), %	63.35:36.65
GSM	260
Weave	2/2 twill

Four FA2 and FA3 assemblies of size 1 ft × 1ft were fabricated separately in four different configurations, as shown in Table 3. A thin metallic square ring was inserted between two-layer fabric assemblies for support so that the fabric layers remain in horizontal position without sagging. ASTM D1777-96 (2002) method and ASTM D 3776 have been followed for measurement of thickness and areal density of materials respectively.

Thermal insulation or resistance (m^{2}K/W) is the ratio of temperature difference between opposite surfaces of a fabric along the direction of heat flow rate through a unit area in the steady state and is the ratio of thickness to thermal conductivity. Heat transmission in fabrics takes place by conduction, radiation and convection. Therefore, effective thermal conductivity of fabrics will be sum of thermal conductivities due to all the mechanism. Thermal insulation measurement of the FA has been done by FLIR thermal imaging camera (model no. SC7900VL with optics 50 mm and wave length range 7.7–11.5μm, FPA 320x256, NETD 24mK) and PID controlled Acmas hot plate (temperature range: room temperature 20°C to 350°C with accuracy ±1°C) as heating source. The thermal camera was focused vertically to the hot plate at a distance of 100 cm. The background/room temperature was in range of 29-31°C throughout the measurement. The average temperatures of background and hot plate during measurement were 30ºC and 60°C respectively. At 60°C temperature, radiant flux per unit area (P=Q/A) of hot plate was 38.0 watt/m^2, as obtained by Altair thermal image analysis software. The average

Table 3 — Configurations of two-layer and three-layer clothing assemblies

Description	Inner layer	Middle layer	Outer layer	Areal density gsm	Thickness mm
FA2-1	Cloth shirting angola	-	PU coated nylon	510	1.1
FA2-2	Fabric pile acrylic sliver knitted	-	PU coated nylon	680	15.6
FA2-3	Cloth shirting angola	-	Nappa leather	710	1.1
FA2-4	Fabric pile acrylic sliver knitted	-	Nappa leather	880	15.6
FA3-1	Cloth shirting angola	Non-woven polyester	PU coated nylon	650	8.1
FA3-2	Fabric pile acrylic sliver knitted	Non-woven polyester	PU coated nylon	820	24.6
FA3-3	Cloth shirting angola	Non-woven polyester	Nappa leather	850	8.1
FA3-4	Fabric Pile Acrylic Sliver Knitted	Non-woven polyester	Nappa leather	1020	24.6

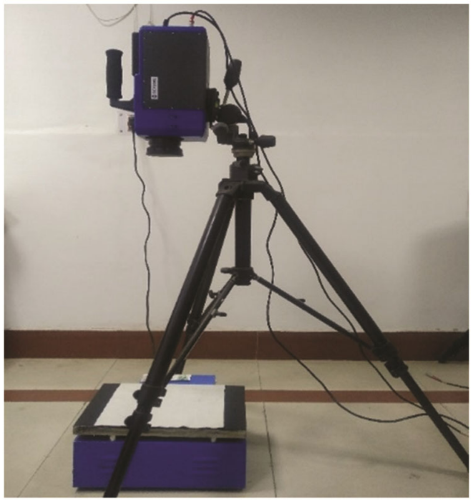


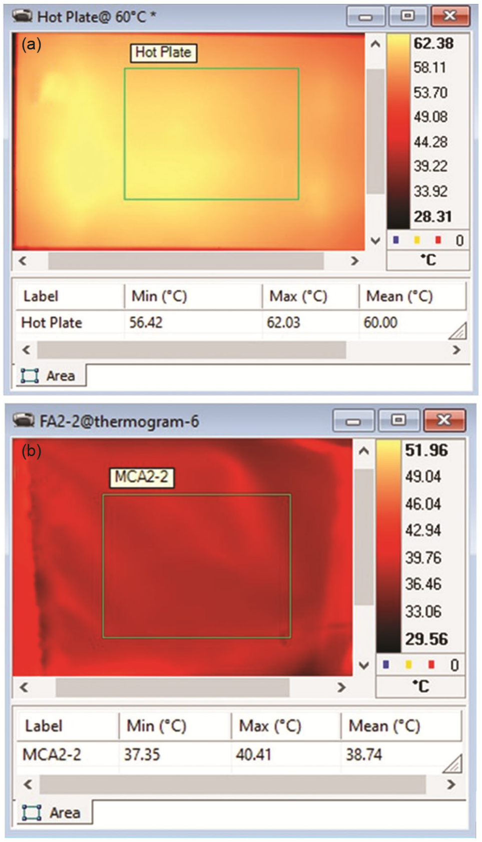
Fig. 1 — Experimental set up for thermal resistance measurement

temperature of background, hot plate and FAis derived by irradiance on camera using the following equation:

$$\left(\int_{\lambda_1}^{\lambda_2}\frac{C_1}{\lambda^5\left(e^{C_2/\lambda T}-1\right)}d\lambda\right)_{object}=\frac{1}{\varepsilon}\left[(W_{total})_{\lambda_1,\lambda_2}-(1-\varepsilon)(W_{reflected})_{\lambda_1,\lambda_2}\right] \quad ...(1)$$

where λ_1, λ_2 are the cut off wavelengths; c_1, c_2, the constants; T, the temperature of object; ε, the emissivity of object; W_{total}, the total received power; and $W_{reflected}$, the reflected power from the ambient sources.

The thermal insulation measurement set upis shown in the Fig. 1. The FA was placed on hot plate, once the hot plate attains the steady state temperature of 60°C, and thermal images of FA were captured at an interval of 5 min until it attains steady state. Recorded thermal images were analysed for average temperature, considering unit emissivity by Altair thermal image analysis software of FLIR thermal camera. Atypical thermal image in 8-12 µm of hot plate at 60°C is shown in Fig. 2(a). Heat flow rate per unit area in vertical upward direction (P)is derived from thermogram of hot plate at 60°C at background temperature of 30°C. Another typical thermal image of FA2-2 after attaining steady state is shown in Fig. 2(b). It shows spatial temperature distribution over the sample. The average temperature



Label	Min (°C)	Max (°C)	Mean (°C)
Hot Plate	56.42	62.03	60.00

Label	Min (°C)	Max (°C)	Mean (°C)
MCA2-2	37.35	40.41	38.74

Fig. 2 — (a) hot plate and (b) a typical thermal image of FA2-2\

(T_{FA}) of FA2-2 is 38.74°C in steady state. Similarly, other thermal images were analysed by Altair software for obtaining average temperature. Thermal resistance offered by FA has been calculated using following equation:

$$\text{Thermal resistance } (R), m^2K/W = \frac{(T_{HP}-T_{FA})}{(Q/A)} \quad \ldots(2)$$

where T_{HP} the temperature of hot plate; T_{FA}, is the temperature of FA in steady state; and *P*, the heat flow rate per unit area in vertical upward direction and equal to *Q*/*A*.

When FA is placed above hot plate, it is subjected to incident radiant flux and various insulating phenomenon occurs simultaneously, viz. multiple reflections, absorption by fabric layers and entrapped air. The outermost layer of all the assemblies is either polyurethane coated nylon fabric or nappa leather. This layer is moisture permeable and provides convective thermal insulation against wind. Other layers and entrapped air add conductive and radiative resistances to multi-layer clothing assemblies. These phenomena are accountable for overall radiative, conductive and convective losses. Thus, FA acts as barrier to incident heat and residual energy transmits through FA. This transmitted energy has been captured by thermal camera and is accountable for observation of temperature of outer layer of FA. The temperature of inner layer/ surface and heat flow rate from per unit area of fabric assemblies will be equal to the temperature of hot plate and thermal emittance of the hot plate in steady state respectively.

Results and Discussion

Thermal resistance of FA2 and FA3 as described in Table 3 has been studied both at source temperature of 60°C and room temperature of 30°C by thermal imaging camera.

Two-layer Assemblies

The temporal thermal profiles, wavelength range 7.7–11.5 µm, of all the four FA2 assemblies in thermal contact (just above hot plate) with hot plate at 60°C is shown in Fig. 3(a). The temperature of outer layer increases with time and becomes steady in 30 min. Temperature of all FA2 starts escalating with fast rate up to 20-25 min and subsequently rises slowly and becomes static. Hence, FA2 acquires steady state and its outer surface temperature is the final temperature that has been used in calculation of thermal resistance of fabric. The FA2-1, FA2-2, FA2-3 and FA2-4 bring down the source temperature (T_{HP}) 60°C to 45.16, 38.74, 44.41 and 39.06°C respectively. This temperature profile is resultant of cumulative effective resistance offered by fabric assemblies due to radiation, conduction and convection.

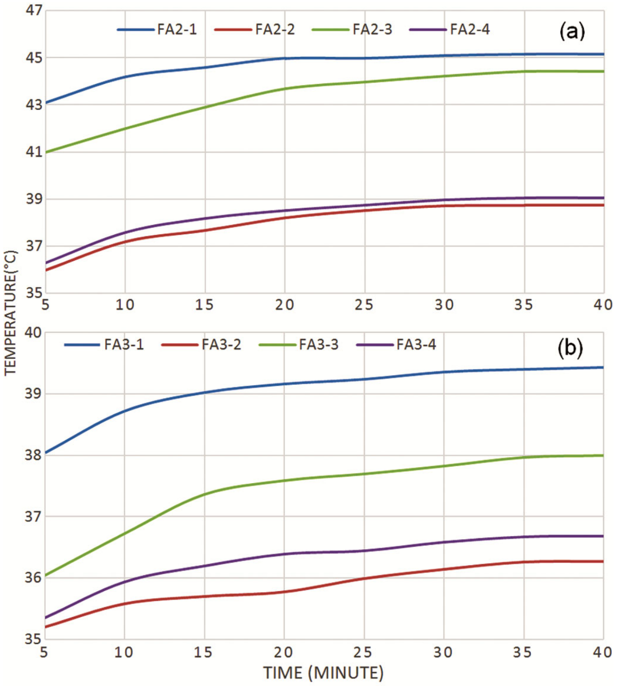


Fig. 3 — Temperature profile of (a) two-layer and (b) three-layer assemblies

Table 4 — Thermal resistance of FA2 and FA3

Specimen	Temp of FA (T_{FA}), °C	$\Delta T=T_{HP}-T_{FA}$ °C	Thermal resistance	
			m^2K/W	tog
FA2-1	45.16	14.84	0.3905	3.91
FA2-2	38.74	21.26	0.5595	5.59
FA2-3	44.41	15.59	0.4103	4.10
FA2-4	39.06	20.94	0.5511	5.51
FA3-1	39.43	20.57	0.5413	5.41
FA3-2	36.27	23.73	0.6244	6.24
FA3-3	38.00	22.00	0.5789	5.79
FA3-4	36.68	23.32	0.6136	6.14

Thermal resistances of the four FA2, derived by Eq. (2), are given in Table 4. Thermal resistances of FA2-1, FA2-2, FA2-3 and FA2-4 are 3.91, 5.59, 4.10 and 5.51 tog respectively. Thermal resistances offered by FA2-2 and FA2-4 are better than those offered by remaining two FA2s. It is due to fabric pile acrylic sliver knitted. This has not only poor thermal conductivity, but also entrapped air. Pile fabric layer reduces contact area due to its structure to hot plate that enhances radiative resistance. Conductive resistance (d/KA) and radiative resistance $\{1/\varepsilon\sigma A\ (T_e^2+T_a^2)\ (T_e+T_a)\}$ offered by a layer, depend on emissivity (ε), Stefan's constant (σ), temperature of emitting surface (T_e), temperature of absorbing surface (T_a), thickness of layer (d), effective thermal conductivity (K) and cross section area (A). When continuous fabrics such as plain weave fabrics, are placed in contact with source, all inner surface comes in thermal contact with source and resulting heat propagates through conduction only. In other case, when pile fabric is put on the source, piles partially touch the surface of source that contributes in conduction and rest area that is the non-contact area of source and pile fabric contributes in radiation. Therefore, pile fabric contributes in both conductive and radiative resistances. The effect of PU coated nylon fabric and nappa leather as outer layer is similar; both provide convective insulation from surrounding, but acts as barrier for air entrapped among layers. The effect of non woven fabric on thermal resistance is outstanding due to entrapped air that has been reported in several studies. The comparative study of single fabric carried out by Venkataraman *et al.*[32] supports same and claimed maximum thermal resistance of 3.7 tog polyester/ polyethylene non-woven fabrics coated with aerogel.

Three- layer Assemblies

The temporal thermal profiles of all the four FA3 in thermal contact with hot plate at 60°C are shown in Fig. 3(b) and their thermal resistances are given in Table 4. Temperature of all FA3 increases exponentially, initially increases with fast rate for 20-25 min and then slowly until becomes static. The heat is transferred from inner layer to subsequent layers and radiant flux emitted by hot plate is attenuated by cumulative effect of radiative, convective and conductive losses. Temperature incremental rate of outermost layer is small due to low transmission of heat and after certain time FA3 attains steady state. In steady state, its outer surface temperature is the final temperature. The FA3-1, FA3-2, FA3-3 and FA3-4 bring down the source temperature (T_{HP}) from 60°C to 39.43, 36.27, 38.0 and 36.68°C respectively. This is because of different thermal resistances offered by different FA-3.

Thermal resistances of FA3-1, FA3-2, FA3-3 and FA3-4 are 5.41, 6.24, 5.79 and 6.14 tog respectively. When FA is exposed to hot plate, then innermost layer imposes resistance to heat flow. A fraction of incident energy is absorbed by it and remaining energy is transmitted to subsequent layer. FA3-1 shows lowest thermal resistance 5.41 tog, while FA3-2 offers maximum thermal resistance 6.24 tog that is due to difference in innermost layer configurations that means fabric acrylic sliver knitted having higher thermal resistance than cloth shirting angola.

Thermal insulation offered by FA3 is higher than that of FA2 due to more number of fabric layers and air entrapped layer. Das *et al.*[14] predicted thermal resistance of three layer assemblies with air gap variation in non-convective mode and measured using guarded hot plate. In this study, maximum thermal resistance of three layer assemblies (polyester wadding sandwiched between plain-woven polyester fabrics) with two layers of air gap of thickness 7mm was 3.49 tog. The another study shows that the thermal resistance of three layer with air gaps (plain woven polyester fabric, polyester warp kitted spacer fabric and polyester weft knitted aluminium coated fabric) was 3.48 tog measured in natural convective mode using guarded hot plate[28]. From these studies and present study, it is obvious that the effect of fabric pile acrylic sliver knitted and non-woven polyester fabric on thermal insulation of clothing assemblies is significant but the contribution of pile fabric is more effective. It is due to low effective thermal conductivity that is resultant because of the fabric structure and air entrapped. The effect of pile fabric as innermost layer is also considerable because its contact area with hot plate is less as compared to other fabric used as inner layer due its weave structure. Thermal insulation values of fabric assemblies used for ECW clothing are in the range of 1.55 - 6.2 tog with assembly weight 1 - 4 kg while the two and three layer fabric assemblies of present study offer thermal resistance of 5.59 and 6.24 tog respectively.

It is observed that thermal resistance improves with reduction in contact surface area of fabric-to-fabric or heating source that is evident from the assemblies having fabric pile acrylic sliver knitted. The pile fabric is found most effective as thermal insulator fabric out of all the materials used in present study. Thermal resistances of FA2 is found in the range of 3.91 - 5.51 tog and for FA3 it varies from 5.41 tog to 6.24 tog with thickness. For optimum clothing system, rational spatial distribution of FA2 and FA3 in different sizes may be applicable to design and develop protective clothing for ECW.

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