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Analytical model to study a new design concept for providing comfort in hot arid climate

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A special design of clothing based on 'sombrero-effect' by inclined wedge providing shadow on the base material has been proposed and investigated analytically in this study to improve the thermo-physiological comfort under dry and hot environment. The design involves small strips of opaque surface on the base fabric of the outerwear to provide tiny shadows at an inclination. The analysis of the heat and mass transfer in the proposed design enables numerical prediction of cooling heat flow at skin surface level. The predicted values are then compared with experimental data by simulating the conditions using a vertical skin model. The effects of certain material properties, particularly the colour of fabric and type of fibre have been studied and the role of the important design parameter, such as 'shade angle' or the angle of inclined strips has been investigated experimentally. It is observed that the analytical framework of heat and mass transfer in such a system is able to give useful results.

Keywords: Clothing comfort, Cotton poplin fabric, Heat convection, Heat transfer, Mass transfer, Hot arid climate, Microclimate

1 Introduction

Deserts constitute nearly 7% of the land area of the globe and hot dry deserts and semi-deserts are living place of nearly 6% of global population. The typical air temperature ranges there between 35°C and 55°C and relative humidity of air remains less than 40%; often becomes 4 - 10%. The heat flux of solar radiation during noon can become 750 W/m^2 or even more. The clothing used in these extreme climates must give sufficient protection from direct exposure to sun and provide thermo-physical comfort to the wearer who is generally exposed to dangerous intense solar radiation and high air temperature during the day. It is well known that the nomadic population in sub-tropical desert regions use special style of clothing but a scientific investigation of the various design factors of clothing for such application is not reported often.

Human body has a typical core temperature of 37°C, and the skin has a typical temperature of 33°C - 34°C under normal condition[1]. The tolerance of the thermo-physiological system in case of human is narrow and therefore care must be taken to respect such narrow tolerance and maintain thermo-physiological comfort by ensuring an optimum heat flow across the skin. An ordinary human being can be considered to be in a thermo-physiologically comfortable state when the average outward (or cooling) heat flux across his skin from body core to environment is around 90 – 120 W/m^2. This net heat flux is generally a function of the metabolic condition, environment condition along with the design and properties of the clothing. The body generally loses heat due to pure heat convection transfer and sweat evaporation associated with free convection (when air temperature is lower than the skin temperature), or due to forced convection, when a human walks with common velocity (3 – 4 km/h), which is around 1 m/s. The radiation loss from the body is largely compensated by the incident scattered radiation from surrounding and the net balance depends on the temperature of the surrounding. The heat gained by the body is primarily due to the metabolic heat generated inside, the convective heat transfer from air to skin when air temperature is higher than skin and radiation incident on skin, particularly direct radiation from hot sources such as Sun. Clothing must act as an engineered system which can impart the net heat balance towards the direction necessary so as to maintain a comfortable heat flow as mentioned above.

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The role of various design parameters of clothing on the thermal comfort and protection provided by clothing ensemble has been the topic of scientific research for a reasonable time. For example, the effects of apertures, air gaps and reflective layers have been studied experimentally[2-7]. Manikins are generally used for such purpose. A number of empirical models for clothing comfort has been proposed as well. Only a few of them have discussed the role of radiation and hot climate on the overall heat-mass transfer through clothing. Shkolnik *et al*[8]. reported their studies on the effect of different dress styles and colours on the net heat transferred through the clothing to skin surface under real conditions in a desert. They concluded that both white and black robes used by Arabic tribes (Bedouins) give almost same net heat transfer from outside to skin in a standing upright condition. They ascribed this due to either a bellows action or a chimney effect. According to their study, these robes were better insulators than the army uniform or a semi-nude condition. Lotens[9] developed a generic model for heat and mass transfer in clothing and showed that the model framework could be used to analyse the problem when the environment is hot and dry. Another study[10] has discussed the possible role of the chimney effect in the narrow long gap between the outer fabric and the body in case of the Bedouin robes. However, the design of the dress for such hot-dry climates has not been discussed in terms of optimization or improvement over the existing solutions. It is generally assumed that the existing design has been optimised naturally during the long history of its use.

It is also a tradition in many regions of the world to use head gear which can provide large shadows over the body to protect it from the exposure to direct sunlight. Thus Mexican ‘Sombrero’, or the Vietnamese ‘Nón lá’ or the Assamese ‘Jaapi’ all have a distinctive common feature,such as a large diameter of its span which extends far from the borders of the skull. Typically such head gears are used by farmers, fishermen or people who have to work for long periods under the hot Sun.

In this study, the role of such shades over human skin under solar radiation has been investigated analytically and the results are verified experimentally. A novel device has been set-up which acts as a physical simulator of human skin and a high power halogen bulb is used to simulate source of equivalent solar radiation[11]. Direct measurement of heat flux at the simulated skin surface is done at various angles of the incident radiation. Small rectangular thin strips or fins of various opaque materials are used close to the simulated skin to generate small shadow on the sensor area. A mathematical analysis of the set-up is done to relate the heat-flow with the various adjustable parameters. Effects of those parameters on heat flow at skin surface are studied. The findings indicate that such thin inclined fins on the clothing can effectively improve the comfort under hot and dry outdoor conditions. This study, therefore, offers a new design concept to engineer the clothing surface to reduce heat load under dry hot radiation and the mathematical model forms a basic framework for analytical modelling the heat-mass transfer in such systems.

2 Analytical Model

The theoretical analysis of the situation was done with several simplifying assumptions. Only the case of a single fin with its major axis kept horizontal has been considered in the following analysis as shown in Fig. 1. It is expected that by having parallel fins, the overall area covered by the shadow will be multiplied, but the mechanism of heat and mass transfer will remain same.

The radiation from the source falls on the outer surface of the fin and increases its temperature. Since the temperature of the fin surface becomes higher than ambient, it starts to effectively radiate and this radiation falls on the vertical surface of the skin. A convection heat transfer due to the wind is considered parallel to the fin and vertical skin surface. Since the

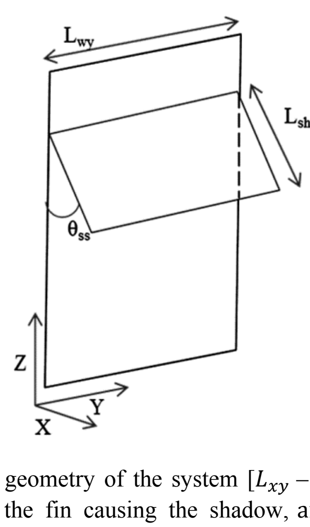

Fig. 1 — Basic geometry of the system [L_{xy} – width of the fin, L_{sh} – length of the fin causing the shadow, and θ_{ss} – angle of inclination of the fin with respect to vertical Z axis]

vertical skin surface is wet with profuse sweat, it causes evaporative cooling. Therefore, the net heat flux at the skin surface is a result of addition of all these components. The radiation heat transfer between the inclined bottom surface of the fin and the vertical surface of the simulated skin requires calculation of the view factor of the system. The situation is depicted in Fig. 2.

Denoting radiosity of surface i by J_i, area of surface i by A_i, emissive power of black body at the same temperature as surface i as E_{bi} and the view factor for fraction of radiation leaving surface i that is intercepted by surface j as F_{ij}, where ε_i is the emissivity of the i-th surface and the enclosure has three surfaces , i.e., $i, j \in \{1,2,3\}$, we have the standard equation for the enclosure[12] shown in Fig. 2 as

$$\frac{E_{b2}-J_2}{{(1-\varepsilon_2)}/{\varepsilon_2.A_2}} = \frac{J_2-J_1}{{1}/{A_2.F_{21}}} + \frac{J_2-J_3}{{1}/{A_2.F_{23}}} \quad \ldots (1)$$

In this case,

$$J_3 = E_{b3} = \sigma.T_a^4,$$
$$E_{b2} = \sigma.T_{sk}^4$$

where T_a (K) and T_{sk} (K) are the temperatures of ambient and skin respectively; and σ, the Stefan-Boltzmann constant. From the property of reciprocity of view factors, we have $A_2.F_{21} = A_1.F_{12}$. Here F_{ij} is the view factor of i-th surface from the j-th surface. Now for standard values of the angle θ_{ss}, the values of the view factor F_{12} can be obtained from standard tables available in open source for different values of enclosure dimensions L_{sh}, L_{sk}, W_L and L_a.

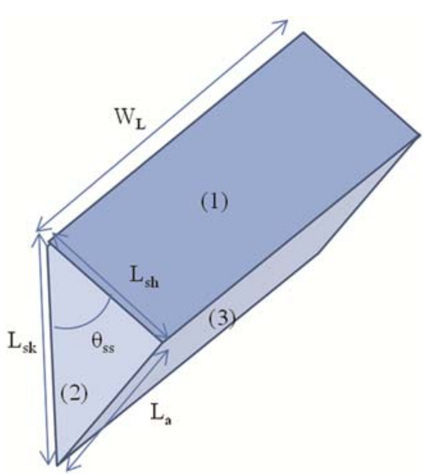

Fig. 2 — Schematic diagram of enclosure for radiation view factor [W_L – Width of enclosure, L_{sk}, L_{sh}, L_a – lengths of boundaries on skin, fin and open area of the enclosure respectively, (1) area bound by the fin, (2) area bound by skin, and (3) area bound by opening]

Considering the radiation balance for surface 2 (Fig. 2), we have from Eq. (1):

$$\frac{\sigma.T_{sk}^4-J_2}{{(1-\varepsilon_{sk})}/{\varepsilon_{sk}}} = \frac{J_2-J_1}{{1}/{F_{21}}} + \frac{J_2-J_3}{{1}/{F_{23}}} \quad \ldots (2)$$

And for the heated shade bottom (surface 1), it follows from Eq. (1):

$$\frac{\sigma.T_{sh}^4-J_1}{{(1-\varepsilon_{sh})}/{\varepsilon_{sh}}} = \frac{J_1-J_2}{{1}/{F_{12}}} + \frac{J_1-\sigma.T_a^4}{{1}/{F_{13}}} \quad \ldots (3)$$

where T_{sh} is the temperature (K) of the shade; σ, the Stefan-Boltzzmann constant (W. m^{-2} .K^{-4}); ε_{sk}, the emissivity of skin surface; and $\varepsilon_{sh,}$ the emissivity of shaded surface Since $F_{13} = 1 - F_{12}$, $F_{23} = 1 - F_{21}$, $F_{21} = \frac{L_{sh}}{L_{sk}}.F_{12}$; and values of σ, ε_{sk}, ε_{sh}, T_a are known, the value of F_{12} can be obtained from suitable tables, and Eqs (2) and (3) can be solved simultaneously for J_1 and J_2 if T_{sk} and T_{sh} are known.

The net heat balance equation (for dry heat transfer), in steady state, of the inclined fin is obtained as

$$q_{rb}.\varepsilon_{sh}.\sin\varphi_{rs} - \varepsilon_{sh}.\sigma.\left(T_{sh}^4 - T_a^4\right) = 2 \times 0.664 \left(\frac{\rho u_x c_p}{L}\right)^{1/2} \left(\frac{\lambda^4}{\mu}\right)^{1/6} (T_{sh} - T_a) + \frac{\sigma.T_{sh}^4-J_1}{{(1-\varepsilon_{sh})}/{\varepsilon_{sh}.L_{sh}.W_L}} \quad \ldots (4)$$

where q_{rb} is the heat flux incident (W.m^{-2}) due to radiation from bulb; φ_{rs}, the angle (deg) of incidence of radiation on the outer side of the skin; ρ, the density of air (kg m^{-3}); u_x, the velocity of air (m.s^{-1}); c_p, the specific heat of air at constant pressure (kJ.kg^{-1}.K^{-1}); λ, the thermal conductivity of fin material (W.m^{-1}.K^{-1}) and μ, the dynamic viscosity of air at the average temperature (kg.m^{-1}s^{-1}); and W_L, width of enclosure (m).

In the above equation, the left hand side is the net radiative heat flux incident on the outer surface (the first term is incident heat flux from the halogen bulb, the second term is the radiation lost from the outer surface to surroundings) and the right hand side is the net convective and radiative heat transfer from the bottom surface of the fin.

When the skin is wet, evaporation will take place and this will cause evaporative cooling apart from the dry heating as discussed above. In order to find a mathematical expression for this at steady state, the following assumptions are made:

(i) Evaporation takes place in an uniform and homogeneous manner from all over the vertical skin surface

(ii) A film of water of negligible thickness is always present on the skin surface irrespective of quantity of evaporation (infinite source of water in the film area) and this film is not affected by the evaporation.

In addition to the above, as a first approximation, we consider that the properties of air with moisture are same as that of dry air.

In this case, using the Chilton-Colburn analogy we can use the following equation:

$$\frac{\bar{h}_{sk,conv}}{h_m} = \rho . c_p . Le^{2/3} \quad \ldots(5)$$

where h_m is the coefficient of mass transfer; $\bar{h}_{sk,conv}$, the convective heat transfer coefficient for the skin surface; and Le the Lewis number. For air-water vapour mixture, $Le = 0.872$ and since Lewis number is relatively insensitive to temperature variations, we can use the Lewis relation as shown below:

$$\bar{h}_{sk,conv} = \rho . c_p . h_m \quad \ldots(6)$$

The net heat balance equation for the wet skin surface is obtained as

$$q_{sk} = \frac{\sigma . T_{sk}^4 - J_2}{(1-\varepsilon_{sk})/\varepsilon_{sk}.L_{sk}.W_L} + \bar{h}_{sk,conv}.(T_{sk} - T_a) - \frac{\bar{h}_{sk,conv}}{\rho . c_p . R_u / M_w} . \left(\frac{P_{vsat,T_{sk}}}{T_{sk}} - \frac{\varphi_{T_a} . P_{vsat,T_a}}{T_a} \right) . L_v \quad \ldots(7)$$

where q_{sk} is the heat flux at skin surface (W.m^{-2}); $P_{vsat,T_{sk}}$, the saturation vapour pressure of air (Pa) at temperature T_{sk}; P_{vsat,T_a}, the saturation vapour pressure of air (Pa) at temperature T_a; L_v the latent heat of evaporation of water (kJ.kg^{-1}); R_u the universal gas constant (kJ.kmol^{-1}.K^{-1}); and M_w, the molecular weight of water (kg.kmol^{-1}).

In the above equation, the first two terms on the right hand side are the components due to gain of heat by radiation and convection respectively and the third term is due to loss of heat by latent heat of evaporation. The above equations can be solved numerically using the initial and boundary conditions as per the system under consideration.

3 Materials and Methods

3.1 Materials

A 100% cotton poplin fabric of thickness 0.18 mm and area mass density 96.6 g.m^{-2} was used as the base fabric material for this study. Table 1 gives relevant description of the three textile samples, used as inclined fins attached to the base material.

3.2 Methods

The experimental set-up is shown schematically in Fig. 3. A halogen bulb was used to simulate solar radiation. It was found that the incident radiation in this case was about 450 W/m^2, which is still about 250 – 300 W/m^2 lower than the expected solar radiation under real desert conditions. Therefore, while the results of the experiments were to be interpreted, this difference in real and simulated situations was taken into consideration.

The vertical skin simulator consists of a metal vessel containing 10 L of water. A stirrer continuously keeps the water stirred for homogeneous distribution of temperature and a heating element of maximum heating power of 1000 W is used to keep the water warm, if required. An electronic controller is used to control the actual heating power to adjust the temperature of the metal surface at a desired temperature in the range 20-90°C. This vertically mounted metal tank simulates the torso of a human body. A thin heat flux sensor is mounted in the middle of the height of the simulator on one flat vertical surface. Its output voltage is measured with an Almemo 2290-S millivoltmeter and multiplied by the calibration constant to get the respective thermal flux levels. A small fan is mounted on one side of the table on which the vertical skin simulator is standing, in such a way that the air is blown almost parallel

Table 1 — Fabric samples (woven twill) used as fins to provide shadow

Sample No.	Material	Thickness mm	Mass per unit area, g.m^{-2}	Colour
1	Polyester	0.74	243.3	Black
2	Cotton	0.50	228.3	Black
3	Cotton	0.48	208.3	White

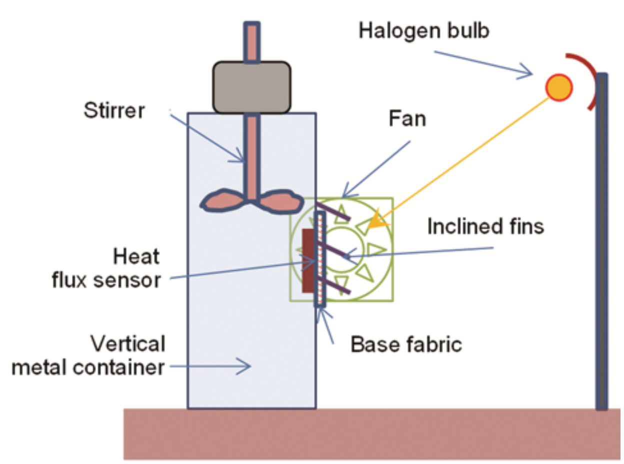

Fig. 3 — Schematic description of experimental set-up[5]

over the sensor surface. The speed of the fan can vary so as to obtain a desired wind speed near the temperature surface. The wind speed was adjusted to be 1 m/s (walking velocity) and this was done with the help of a portable digital anemometer at the beginning of installation of the measuring system. The halogen bulb has a small tubular shape and it was kept with its axis horizontal and parallel to the flat surface of the vertical skin simulator. The height of the bulb was adjusted by mounting it on an adjustable holder.

The base fabric under test was mounted covering the entire heat flux sensor and it was fixed at its edges by quick-drying adhesives. Care was taken to ensure that the fabrics have good contact with the sensor surface. The base fabric was kept wet during the test by adding water drops to it till the surface is completely wet, and when the water has stopped dripping. The measurement time was short (few seconds) and it was assumed that the wetness of the fabric did not change much during the short time of measurement. The high thermal capacity of the metallic container with water ensured that the measurement was done in isothermal conditions. A special holder was designed using stiff cardboard to mount the thin fins at desired angles on the test region. Two different angles could be adjusted. One was the angle that its base line made with horizontal line and the other was the angle that the fin surface made with respect to the sensor surface. In practice, three sets of such fins, each parallel to the other, were used to make sure that the entire sensor surface area can be covered by their shadows at certain specified angle that was used in this study, while using a small span of the fin. The geometry is schematically explained in Fig. 1.

In typical hot arid climate, the temperature of the air may range from 35°C to even higher. Considering human skin temperature under such condition to be at 35°C, it may be said that a typical climate condition would be when the difference between skin temperature and air temperature is zero, if not negative (i.e., skin temperature ≤ air temperature). Occurrence of 35°C and less than 40% humidity is quite common in summer in many countries including India. Analogically, this condition was met during the tests by keeping the temperature of the water in the metal container at ambient conditions. All measurements were done at 22°C air temperature and 37% relative humidity.

4 Results and Discussion

Three different fabrics (Table 1), were used to prepare the fins and they were tried at different angles of inclination over the base fabric. Figure 4 shows the cooling heat flux obtained for each of these fin materials with respect to angle of inclination. Expectedly, the higher heat fluxes are obtained at the angles which provide more shadow area over the base material. Interestingly the figure also shows that the fin material itself may have important influence on the cooling heat flow. The black polyester which is thicker and denser shows slightly better cooling flux in nearly all cases than the cotton fabrics. The colour of the fabric used in the fins, on the other hand, does not show consistent influence on the cooling heat flux.

Table 2 shows the values of various input parameters used for the numerical calculation. This exercise has been done to check the effectiveness of the analytical model.

Considering the wet skin, we observed that since in this case $T_{sk} = T_a$, there will be zero convective heat transfer. Hence the total heat flux at skin will be the positive heat gain due to the net radiation and the negative heat gain due to evaporation. Considering that at normal air pressure and at $T_a = 293\text{K}$, the saturation vapour pressure is found $P_{vsat,T} = 2339$ Pa. Hence, considering relative humidity as 37%, i.e. $\varphi_T = 0.37$, we have following relationship from Eq. (2):

$$q_{sk}(\mathrm{W.m^{-2}}) = 2.85 \times 10^{-8} + 0 - \frac{17.28623}{1.205\times1.005\times8.314/_{18}} \times \left(\frac{2339}{293} - \frac{0.37\times2339}{293}\right) \times 2260 = -351.25$$

The net heat flux at skin can also be calculated for the case without any shadow. The results of the calculated and experimental values are given in Table 3. Since

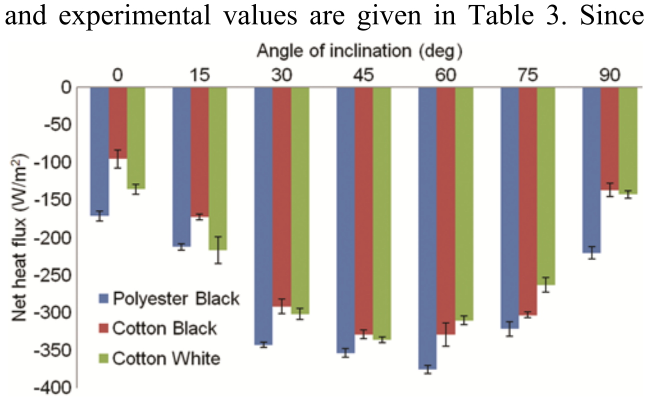

Fig. 4 — Cooling flux with radiation and convection of 1 m/s with three different fabric fins

Table 2 — Values of different input parameters used for numerical calculation

Parameter	Value
Ambient air temperature (T_a)	293 K
Skin surface temperature (T_{sk})	293 K
Heat flux from the bulb (q_{rb})	450 W.m^{-2}
Emissivity of shade (ε_{sh})	0.95
Emissivity of skin (ε_{sk})	0.68
Acceleration due to gravity (g)	9.8 m.s^{-2}
Stefan-Boltzmann constant (σ)	5.670373 x 10^{-8} W. m^{-2} .K^{-4}
Universal gas constant (R_u)	8.314 kJ.kmol^{-1}.K^{-1}
Molecular weight of water (M_w)	18 kg.kmol^{-1}
Latent heat of vaporization of water (L_v)	2260 kJ.kg^{-1}
Dynamic viscosity of air at ambient temperature (μ)	1.983 x 10^{-5} kg.m^{-1}s^{-1}
Density (ρ)	1.205 kg.m^{-3}
Specific heat of air at constant pressure (c_p)	1.005 kJ.kg^{-1}.K^{-1}
Thermal conductivity of fin material (λ)	0.0257 W.m^{-1}.K^{-1}
Width of fin (L_{wy})	0.05 m
Spn of fin (L_{sh})	0.015 m
Angle of inclination of fin (θ_{ss})	45°
Angle of solar radiation (α)	45°
Air speed (u_y)	1 m.s^{-1}
Relative humidity fraction (φ_T)	0.37

Table 3 — Comparison of experimental and numerical results of heat flux

Parameter	Heat flux, W/m^2	
	Experimental	Numerical
Without fins	-135.9	-134.8
With fins	-335.6	-351.3

the emissivity of the poplin sample is not known, a white unsized paper with known emissivity is used for the experimental evaluation. The emissivity of this paper is 0.68 (ref. 13) and this value is used for the numerical calculation.

It is evident from the above results that the simple analytical model is able to describe the experimental situation. Therefore such model can be further used to optimize the design for a desired heat flow. It is also clear from above results that the introduction of the fins drastically reduces the heat load on the skin surface. This is a well-known experience that the shades are much more comfortable than under direct sunlight in hot climates. The model, therefore, is also applicable to most kinds of inclined shades such as large hats ('Sombrero') or umbrella etc. The wedge shaped air between the fins and the base material is very important as it gives the opportunity for evaporative cooling under forced convection. It must be mentioned here that the larger reserve of cooling flow (~300 W/m^2) is necessary under the present set-up as the heat flux obtained from the halogen bulb used here is less by about 300 W/m^2 than the real solar radiation encountered in desert regions.

Fig. 5 — Artist's imagination of how inclined fins may be incorporated in dress

The present study does not consider the other degree of freedom for attaching the fins, viz. the angle of the line connecting the fin with the base with respect to the horizontal line. Such inclination may facilitate free convection as well as a component of the flow under the fins can then move effectively upwards. Therefore, the model may further be developed to study this possibility. The air temperature in real desert may be even higher than skin temperature and the effectiveness of the fins in such condition needs to be evaluated experimentally as well as by the analytical model. The practical implementation of this effect is another step for future. Figure 5 gives an outline of an artist's imagination about how such small fins may be endorsed by fashion designers in garment outer surfaces[14]. Empirical measurements with such designs would be interesting.

5 Conclusion

In this study, the effectiveness of generating small shadow on the outer dress material for improving comfort in hot dry climate has been discussed. This is already experienced in tropical and hot regions where people use large hats or umbrella which provides shadow over most part of the body. According to the novel design concept used in this study, small thin fabrics may be used as fins which are attached at their top edge with the base material and are kept at an inclination so that a wedge of air is present between the fin and the base fabric. This fin provides the small shadow on the base and multiple such fins may be used to cover a larger area of the base. It is found that the fin material may have important influence over the net heat-mass transfer. The white and black colours of same material do not show consistent difference. The angle of inclination of these fins is most important for getting optimum comfort. The study shows that the fins are most effective with inclinations from 45° to 60°. A simple analytical model has been developed using fundamental equations of convection and radiation. The view factor is considered for such analytical model. The possibilities of improving this approach further have been discussed and a design concept of using this study to develop improved clothing for hot dry climates has been given.

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