Indian Journal of Fibre & Textile Research
Vol 46, March 2021, pp. 15-21

Development of relative contact area model for prediction of thermal absorptivity of single-layer cotton woven fabrics

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Received 30 April 2020; revised received and accepted 1 August 2020

A semi-empirical model of the relative contact area of woven fabrics has been developed. Its output is implemented into a multiple linear regression model of thermal absorptivity of 100% cotton woven fabrics as a predictor, together with open area, areal density, thickness and fabric density. Validation of the thermal absorptivity model shows that the contribution of the relative contact area and its interaction term with areal density generates lowest values of the mean and maximum percentage errors, indicating good predictability of the thermal contact feeling. The model is not applicable for nonwovens.

Keywords: Alambeta, Fabric comfort, Relative contact area model, Semi-empirical model, Thermal absorptivity, Woven fabric

1 Introduction

Comfort is an important property that consumers are seeking more and more nowadays. It can be classified as sensorial, thermo-physiological, optimal fit and psycho-aesthetic. These terms deal with the contact feeling of clothing with the skin, the body thermo regulation, body movement freedom and aesthetic appeal and the current fashion trend of society, respectively[1]. The thermal contact feeling of a fabric when it touches the skin affects the customers' first impression, and most probably decision of purchase. Thermal absorptivity of a woven fabric is defined as a measure of the warm-cool feeling when the fabric touches the human skin for a short period of time, normally less than two seconds[2,3]. The concept of thermal absorptivity was first introduced by Hes and Dolezal[4]. Since the thermal contact between the textile material and the human skin is transient, the fabric was assumed to be a semi-infinite body characterised by a thermal capacity (ρc, Jm^{-3})[2]. The difference of temperatures between the human skin (t_1) and the fabric (t_2) stimulates the heat flow (q) through the textile material during time τ, where b is the thermal absorptivity, as shown in following equation[2,3]:

$$q = \frac{b(t_1 - t_2)}{\pi\tau^{0.5}} \qquad \dots (1)$$

Hes[5] developed an equation to measure objectively the thermal absorptivity of textile materials, with thermal conductivity (λ), density (ρ) and specific heat (c) as predictors. Thermal absorptivity does not depend on either the temperature difference or on the time elapsed during measurement[2]. The developed equation is given below:

$$b = \sqrt{\lambda\rho c} \qquad \dots (2)$$

With higher thermal absorptivity, cooler effect is felt. The values of thermal absorptivity vary from 20 $Ws^{0.5}m^{-2}K^{-1}$ which corresponds to dry lofty knits made of micropolyester texturised filaments to 900 $Ws^{0.5}m^{-2}K^{-1}$ for highly wet cotton or wet viscose fabrics[6].

Fabric structural parameters are known to affect the thermal contact feeling of a textile material when it touches the skin. Afzal *et al.*[7] have reported that an increase in the areal density of double layer interlock knitted fabrics increases the thermal absorptivity due to the high number of contact points between the human skin and the textile material. The thermal absorptivity is found to depend on the fabric surface profile[2, 8-9].

Smoother surface generally leads to more contact between the human skin and the textile material. The area of contact between two adjacent bodies promotes the flow of heat through conduction. Higher contact area will increase the thermal absorptivity through enhanced heat transfer. Matusiak *et al.*[10] have

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reported that the weave pattern affects the thermal sensation of fabrics. Assuming yarn linear density is constant, plain woven fabrics give cooler feeling than twill when in contact with the human skin.

Woven fabric structure is such that only certain segments of the interlaced yarns will make contact with a surface when lying flat on it. This fabric property has been characterised in this work by the relative contact area (CA_{Rel}), which is defined as the ratio of fabric area in contact with a surface to the projected area of the fabric. A statistical model of thermal absorptivity was developed for 100% cotton single-layer plain woven fabrics and woven fabrics involving floats, with the relative contact area, open area (*OA*), areal density (*AD*), thickness (*Th*) and fabric density (*FD*) as potential predictors.

2 Materials and Methods

The fabric samples with various constructions in ready to apparel conditions were chosen. These samples undergo standard finishing treatments, such as singeing, desizing, scouring, bleaching, mercerising, dyeing and calendering.

Thermal absorptivity was measured on the Alambeta non-destructive testing instrument [4]. It satisfies the ISO 8302, under a varying contact pressure of 200Pa. The instrument has a temperature control system that keeps the upper measuring plate at 32°C (human skin temperature). The bottom plate, on which the fabric is placed, was kept at an ambient temperature of 20±2°C. A heat power sensor measures the heat transferred from the upper plate to the fabric within a low time constant of 0.2s, when it gets into contact with the textile material under a contact pressure adjustable from 200Pa to 1000Pa.

The fabric thickness was also measured on the Alambeta under a pressure of 200Pa. Areal density of each fabric sample was measured according to ASTM D3776/D3776M-09a (2017) using a sensitive electronic balance, Mettler AE 200. The fabric open area was measured using image processing and analysis techniques. The microscopic RGB image of the fabric samples (× 4 magnified) of 2048 × 1536 resolution was taken on Motic digital microscope. It was converted into a binary image with black and white pixels, representing the fibrous material and fabric openness respectively. Yarn hairiness, which is characterised by the quantity of freely moving fibre ends or fibre loops protruding from the yarn core, is a common feature in the cotton fabric. For the evaluation of exclusively the two-dimensional open area, without the yarn hairiness effect, morphological operations were performed on the images (Dilation, followed by Erosion). Thus, the open area (OA) was calculated as a percentage of the ratio of the sum of individual pore areas in the fabric (A_{IP}) to the whole fabric area (A_F), as shown below:

$$OA = \frac{\sum A_{IP}}{A_F} \times 100\% \quad \ldots (3)$$

The fabric density (FD) was calculated according to following equation, where areal density (AD) and thickness (Th) are in grams per metre square and millimetres respectively:

$$FD(g/cm^3) = \frac{AD}{Th} \times 10^{-3} \quad \ldots (4)$$

The multiple linear regression models of thermal absorptivity (b) were developed on the IBM SPSS Statistics package using 54 fabric samples.

2.1 Geometrical Derivation of Relative Contact Area

The racetrack cross-section proposed by Kemp[11] was chosen for interlaced yarns because it allows the evaluation of a contact surface area. Circular and elliptical cross-sections make tangential contact with a flat surface and therefore produce contact points transversely and contact line longitudinally (Fig. 1). However, racetrack cross-section produces contact segments transversely resulting in flat rectangular contact surfaces along the yarn axis. This allows the evaluation of contact areas between the fabric and flat surfaces.

While developing the relative contact area model, the following three assumptions were made, viz. (i) human skin was a flat surface; (ii) free-yarn was of circular cross-sectional shape; and (iii) cross-sectional area of the yarn remained constant after deformation from circular to racetrack shape. The free yarn major axis (*X*) comprises the length of the rectangle and the radius of each semicircle. The minor axis (*Y*) is the width of the rectangle which is equivalent to the diameter of the semicircle (Fig. 2).

The circular yarn diameter (D) was calculated according to Peirce's formula from the yarn linear density (tex), specific volume (φ) and fibre density

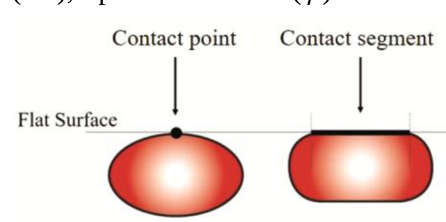

Fig. 1 — Flattened yarn contact with flat surface

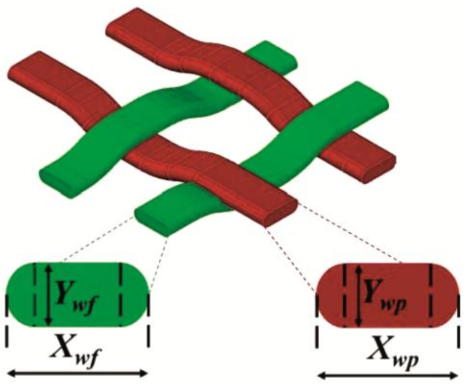

Fig. 2 — Plain woven fabric with racetrack cross-section of yarns

(ρ_f). Since the fabric samples are made up of 100% cotton, φ and ρ_f were taken as 0.65 and 1.52g/cm^3 respectively. Following equation was used to calculate circular yarn diameter:

$$D\ (cm) = \frac{\sqrt{tex}}{280.2\sqrt{\varphi\rho_f}} = \frac{\sqrt{tex}}{280} \quad \dots (5)$$

The length of the major axis of the flattened interlaced-yarn (X) is calculated from the circular free-yarn diameter and the interlaced-yarn flattening factor. The interlaced-yarn flattening factor was determined by comparing measurements of major diameters of warps and wefts, respectively, on fabric images with the theoretical circular diameter of free yarns. The established interlaced-warp flattening factor and the interlaced-weft flattening factor were found to be 1.4 and 1.6 respectively. The experimental values of the length of interlaced-yarn major axis were compared to those obtained using the interlaced-yarn flattening factor (calculated). An average percentage error of 6 was obtained for both threads, with a maximum value of 11% and 14 % for the warp and weft yarns respectively. Interlaced-yarn flattening factor was calculated using the following equation:

$$\text{Interlacedyarn flattening factor} = \frac{\text{Interlaced length of yarn major axis}}{\text{Circular free yarn diameter}} \quad \dots (6)$$

The minor axis of the interlaced-yarn can thus be calculated as its major axis (X) and the circular cross-sectional yarn diameter are known [Eq. 7]. Assuming that the circular free-yarn cross-sectional area is equivalent to the racetrack flattened yarn cross-sectional area, the minor diameter of the racetrack section can be defined as follows:

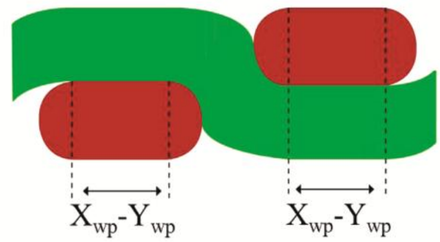

Fig. 3 — Plain weave contact segments

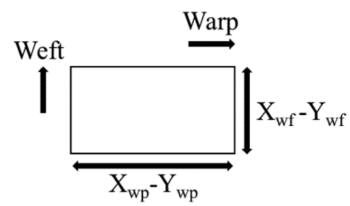

Fig. 4 — Rectangular surface of plain contact segment

$$Y(X-Y) + \pi\frac{Y^2}{4} = \pi\frac{D^2}{4}$$
$$Y(X-Y) = \frac{\pi}{4}(D^2 - Y^2)$$
$$X = \frac{\frac{\pi}{4}(D^2-Y^2)}{Y} + Y \quad \dots (7)$$

2.2 Plain Weave

In the case of plain woven fabrics, the number of contact segments where the yarns intersect in one square centimetre of the fabric was calculated as the product of warp sett (S_{wp}) and weft sett (S_{wf}), as shown below:

$$n^P = S_{wp} \times S_{wf} \quad \dots (8)$$

The plain weave contact segments are shown in Fig. 3. The area of contact was considered to be a rectangular surface with dimensions as shown in Fig. 4. The difference between the major and minor axes of the warp and weft gives the length and the width of the contact region respectively. Consequently, the contact area at one segment (C^P) was computed using the following equation:

$$C^P(cm^2) = (X_{wp} - Y_{wp}) \times (X_{wf} - Y_{wf}) \quad \dots (9)$$

The zone of contact between the textile material of area one centimetre square and the human skin is characterised by the relative contact area (CA_{Rel}). It is the product of the number of yarn intersections in one centimetre square and the area at one contact segment, as shown by the following relationship:

$$CA_{Rel} = N^Y \times C^P \quad \dots (10)$$

2.3 Woven Structures Containing Floats

The surface profiles of woven structures, other than plain weaves, have been viewed to be made up of two distinct types of yarn segments, viz. (i) plain segments, where the surface yarn is inclined downwards from the vertical axis on both sides of the single yarn underneath and (ii) float segments, where the surface yarn lies straight on top of two or more consecutive underneath yarns and is inclined downwards from the vertical axis on the outermost sides of the yarns underneath (Fig. 5).

In this work, it was observed that for a fabric made up of warps and wefts of given linear densities and yarn setts, the contact areas of all plain segments will be the same. The contact areas of floats will depend on the float length, and may therefore vary depending on the fabric design. In the derivations that follow, suffixes wp, wf, P, F and f have been used to represent warp, weft, plain segment, float segment and float number respectively.

In a fabric repeat consisting of J warps and I wefts, the contact area made by plain segments of the jth warp is given by the following equation:

$$A_j^{wp^P} = n_j^P \times C^P \quad \text{… (11)}$$

where n_j^P is the number of plain segments in jth warp; and C^P, the contact area of one plain segment.

The contact area made by plain segments of all warps in the repeat is

$$CA_{wp}^P = \sum_{j=1}^{J} A_j^{wp^P} = \sum_{j=1}^{J} n_j^p \cdot C^P = C^P \sum_{j=1}^{J} n_j^P \quad \text{… (12)}$$

The contact area made by float segments of the jth warp is given by the following equation:

$$A_j^{wp^F} = \sum_{f=1}^{n_j} C_{jf}^{wp} \quad \text{… (13)}$$

where C_{jf}^{wp} is the contact area made by the fth float of the jth warp; and n_j , the number of floats in the jth warp.

The contact area made by float segments of all warps in the repeat is

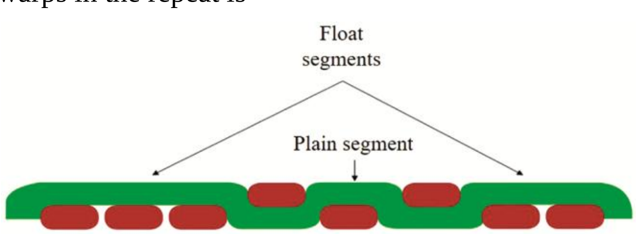

Fig. 5 — Surface profiles of woven structures

$$CA_{wp}^F = \sum_{j=1}^{J} \sum_{f=1}^{nj} C_{jf}^{wp} \quad \text{… (14)}$$

Hence, the total contact area made by the J warp yarn in repeat is

$$CA_{wp} = CA_{wp}^P + CA_{wp}^F = C^P \sum_{j=1}^{J} n_j^P + \sum_{j=1}^{J} \sum_{f=1}^{n_j} C_{jf}^{wp} \quad \text{… (15)}$$

Likewise, the total contact area made by the I weft yarns in the repeat will be given by

$$CA_{wf} = CA_{wf}^P + CA_{wf}^F = C^P \sum_{i=1}^{I} n_i^P + \sum_{i=1}^{I} \sum_{f=1}^{n_i} C_{if}^{wf} \quad \text{… (16)}$$

Therefore, the overall contact area, CA^Tmade by the plain and float segments of all warps and wefts in the $I \times J$ repeat can be computed as

$$CA^T = CA_{wp} + CA_{wf} = C^P\left(\sum_{j=1}^{J} n_j^P + \sum_{i=1}^{I} n_i^P\right) + \sum_{j=1}^{J} \sum_{f=1}^{n_j} C_{jf}^{wp} + \sum_{i=1}^{I} \sum_{f=1}^{n_i} C_{if}^{wf} \quad \text{… (17)}$$

Hence, the relative contact area is given by

$$CA_{Rel} = n^r \cdot CA^T \quad \text{… (18)}$$

where n^r is the number of weave patterns in one centimetre square of fabric and is computed as

$$n^r = \frac{S_{wp}}{n_{wp}} \times \frac{S_{wf}}{n_{wf}} \quad \text{… (19)}$$

where S is the yarn sett; and n, the number of yarns in weave pattern.

3 Results and Discussion

In this work, statistical models of thermal absorptivity of 100% cotton woven fabrics have been successfully developed. The fabric structural parameters, namely relative contact area, open area, areal density, thickness and fabric density are investigated as potential predictors. The arithmetic specifications of the data used to establish the thermal absorptivity equations are given in Table 1.

Each predictor's relationship with the thermal absorptivity has been investigated (Fig. 6). The open

Table 1 — Statistics of thermal absorptivity database

Property	Mean	Minimum	Maximum
Thermal absorptivity (b), $Ws^{0.5}m^{-2}K^{-1}$	201	133	301
Open area (OA), %	3.72	0.01	16.25
Areal density (AD), g/m^2	155	71	476
Relative contact area (CA_{Rel})	0.33	0.10	0.90
Thickness (Th), mm	0.38	0.15	1.03
Fabric density (FD), g/cm^3	0.41	0.20	0.61

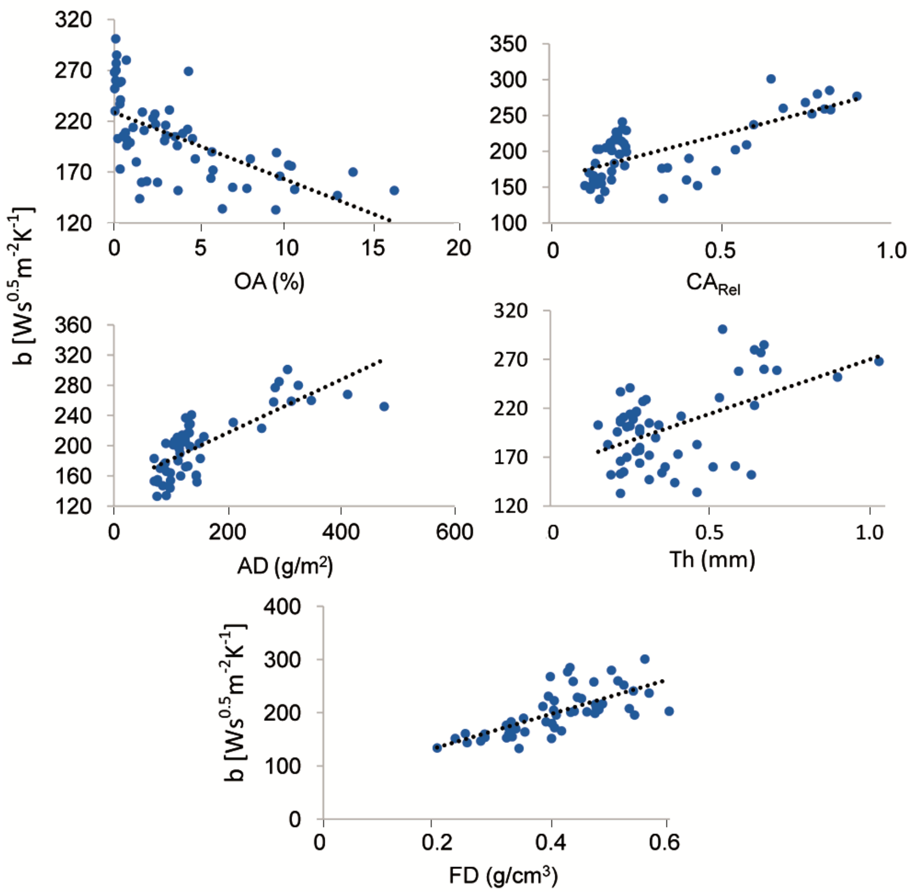

Fig. 6 — Thermal absorptivity (b) correlation with open area (OA), areal density (AD), relative contact area (CA_{Rel}), thickness (Th) and fabric density (FD)

area of textile material is characterised by the ratio of fibres to fabric at its surface. Therefore, low values of the open area show that the number of cotton fibres per unit area is greater. There is a tendency of the thermal absorptivity decreasing with an increase in open area (Fig. 6). Since the thermal conductivity of cotton fabrics (0.050 $Wm^{-1}K^{-1}$) is higher than that of air (0.026 $Wm^{-1}K^{-1}$), instantaneous heat transfer will happen when the portion of yarn is greater than that of the pores. As reported by Afzal *et al.*[7], there is direct relationship between fabric areal density and thermal absorptivity; higher areal density increases the contact points for fabrics of same order of thickness, resulting in intensified thermal absorptivity. Increase in the relative contact area leads to an increase in the thermal absorptivity. The results are in line with those reported by Mangat *et al.*[2] and Rengasamy *et al.*[9], who stated that as the area of textile materials in contact with the human skin becomes larger, it stimulates the heat flowing from one medium to the other, thus a cooler effect is felt. Thermal absorptivity has a tendency to rise with an increase in fabric thickness. This is due to the increase in fibre weight per unit area, which creates more contact points, as described by Afzal *et al.*[7]

Four combinations of the independent variables have been investigated for the development of thermal absorptivity multiple linear regressions. Each model is tested for generalisation and validation with new fabric samples. The fabric structural parameters of the testing samples are input into the developed thermal absorptivity. The predicted thermal absorptivity data (b_{pred}) of each testing sample are compared to that of the experimental values (b_{exp}) by calculating the percentage error, as shown in the following equation:

$$\%\ \text{Error} = \frac{|b_{pred} - b_{exp}|}{b_{exp}} \times 100 \qquad \ldots (20)$$

The mean and maximum percentage errors of each model are presented in Table 2. The predicted thermal absorptivity data of each sample tested of each model

Table 2 — Results of thermal absorptivity of plain and weave structures with floats fabrics multiple linear regression models

Model	Adjusted R^2	Parametar	p-value	Equation	Average error, %	Max error, %
A	0.66	Constant	0.000	$b = 171 - 3.25OA + 0.28AD$	5.51	12.13
		OA	0.002			
		AD	0.000			
B	0.66	Constant	0.000	$b = 168 - 2.99OA + 0.22AD + 32.84CA_{Rel}$	5.60	9.14
		OA	0.005			
		AD	0.001			
		CA_{Rel}	0.163			
C	0.70	Constant	0.000	$b = 140 - 2.29OA + 0.31AD + 191CA_{Rel} - 0.43(CA_{Rel} \times AD)$	5.03	8.72
		OA	0.049			
		AD	0.042			
		CA_{Rel}	0.033			
		AD* CA_{Rel}	0.203			
D	0.84	Constant	0.039	$b = 74 - 1.08OA + 0.15AD + 35.79CA_{Rel} + 16.18Th + 222FD$	6.19	11.88
		OA	0.194			
		AD	0.351			
		CA_{Rel}	0.029			
		Th	0.819			
		FD	0.003			

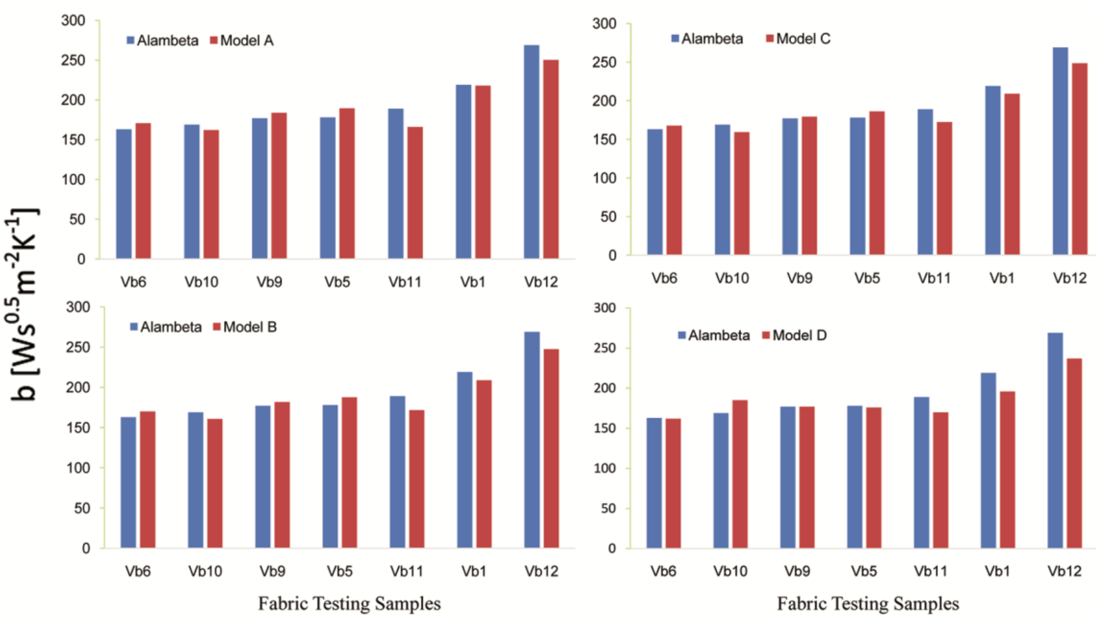

Fig. 7 — Thermal absorptivity (Alambeta) and MLR thermal absorptivity data of the models developed

are presented in Fig. 7, together with the values obtained experimentally using Alambeta. It can be observed that the coefficient of determination is higher for model D (0.84) in which all the fabric structural parameters are used as predictors. However, the model C which includes the relative contact area, open area and areal density, together with the product of areal density and relative contact area shows the least percentage average and maximum errors. This reveals that the generalisation of model C is better than that of model D. In addition, these results show that the prediction of the thermal absorptivity improves with the inclusion of the relative contact area data obtained from the geometrical model developed in this work. A decrease in the mean and maximum percentage errors of 8.7% and 28% respectively is observed, when models A and C are compared.

4 Conclusion

The warm-cool feeling of a woven fabric, measured by the thermal absorptivity, influences the consumer’s sensorial comfort. When the fabric touches the skin, only part of the textile material will come into thermal contact with the skin surface. Thus, a geometrical model of the relative contact area has been developed in this work, assuming a racetrack yarn cross-section. A predictive model of thermal absorptivity of 100% cotton woven fabrics is developed with open area, areal density, relative contact area, thickness and fabric density as potential predictors. It is observed that with the inclusion of the relative contact area, and its interaction term with areal density, the mean and maximum percentage error of the predicted thermal absorptivity of the samples tested is decreased by 8.7% and 28% respectively. The results validate the relative contact area as a major property influencing the thermal absorptivity of fabrics. Additionally, the semi-empirical relative contact area model can be further consolidated by inclusion of experimental surface roughness data of woven fabrics. Moreover, to make the thermal absorptivity model widely applicable for the textile industries, we are actively engaging in developing models of different materials such as wool, polyester, acrylic, etc., as well as, different fabric structures such as nonwovens.

Acknowledgement

The authors gratefully acknowledge the financial support by Higher Education Commission, Mauritius, for this research.

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