Investigating the effective thermal conductivity of moist fibrous fabric based on Parallel-Series model: a consideration of material’s swelling effect

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Abstract
The aim of this work reported in the paper is to investigate the influence of moisture content on the effective thermal conductivity (ETC) of non-hygroscopic Polyethylene terephthalate (PET) and hygroscopic Viscose (VC) fabrics using Parallel-Series (P-S) thermal-electrical analogy method and TPS measurement. An equivalent porosity for hygroscopic fabric was first proposed to preserve the validity of the P-S model. The equivalent porosity is characterized by reasonably eliminating the absorbed moisture effects partly, which is embodied in enhancing heat conduction, endothermic reaction and swelling. Calculated values of the effective thermal conductivity of the two kinds of fabrics had been compared with experimental measurements. Results show that the P-S model incorporated with equivalent porosity is found to yield higher prediction accuracy than that of P-S model with parent porosity. The calibrated model can also provide a robust tool for predicting the global effective thermal conductivity of moist hygroscopic fibrous porous media.

Nomenclature

P-S Parallel-Series
ETC Effective thermal conductivity
ΔP pressure difference
r pore-throat radius
|| parallel
⊥ series
T temperature
Lc characteristic length
Kn Knudsen number
D diameter
f solid fraction ratio
MR moisture regain
MC moisture content
MAS moisture absorbing saturation
k correction coefficient

Greek symbols
λ thermal conductivity
ϕ porosity

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1. Introduction

Moisture absorbed by fabric material in a humidity environment or liquid water penetration into fabric will exact a significant impact on heat transport of clothing, which in turn influence comfort sensation of a wearer in practical wear situations [1, 2]. Most textile materials are typically porous materials composed of plenty of macro- or meso-pore, and micro-pores [3]. In general, liquid water may easily penetrate into these pores and water vapor could be also adsorbed onto fiber and condense in the pores or voids. Therefore, moisture content within the porous fabric can be categorized into three aspects depending on the pore size and fiber hygroscopicity: absorbed water, capillary water and bulk water [4]. Heat transfer or thermal protection capacity of the porous fabric is governed by thermo-physical properties such as the effective thermal conductivity (ETC) and heat capacity. Thermal conductivity is generally the most used parameters to describe heat transfer, especially when relating to insulating materials. Simultaneously, the knowledge of their thermal transmissivity in the presence of atmospheric humidity under various conditions is required in the utilization of fabric in many applications.

Experimental work has been carried out on the thermal properties of porous media including fibrous fabrics with the varying moisture content. Earlier, Black and Matthew [5] investigated the common fabrics (wool, cotton and linen fabrics) at different levels of moisture content and found that as the moisture content increased from 0 to 75% of the dry weight, the thermal insulation of fabric reduced markedly. Also, the thermal protective performance of firefighting suit could vary due to the introduction of moisture inside the porous fabrics in an exposure of high heat flux [6, 7]. For example, moisture content coming from human body perspiration showed dual effect on evaporative cooling and thermal protection of protective clothing. Perspired moisture penetrating into the hydrophobic fiber can increase evaporative cooling and decrease radiant heat gain concurrently, yet sweating under the condition of hydrophilic fabric would result in higher radiation heat gain than heat dissipation [8].

Moisture content within the porous insulating materials greatly affect thermal insulation and energy efficiency. Ochs et al [9] measured thermal conductivity data of (bulk) insulation including inorganic artificial and natural products at high temperature and at elevated moisture content and provided the conclusions that the ETC of insulation materials increases with increasing temperature and moisture content. The relationship between the experimental ETC values and the moisture content within some fibrous insulating building
materials can be expressed as a non-linear fit [10] or linear fit [11] at a specified operating temperature. Other studies have also shown that the presence of these moisture contents leads to the increase ETC of moist fibers to a great extent from their drying state [12, 13], and therefore to the decrease of their insulation capacity. This can be explained by the fact that moisture occupying the encloses air in the sample leads to heat transfer by conduction hence increase in the thermal conductivity values with increase in time [14]. Lately, the influence of moisture content on insulating performance of moist silica aerogel was studied by Chen et al [15]. They observed that the increase of thermal conductivity of moist silica composite material with water uptake increment is linear at the same temperature.

On the other hand, many theoretical prediction studies are also encountered in the literature about the ETC of two (solid matrix and air or solid matrix and saturated liquid water) or three-phase (solid matrix, air and water) porous systems. Singh et al [16] made n successive small dispersion of a particular phase in the effective continuous media and predicted the ETC of moist soils using a lattice-type dispersion in saturated (two phase) and unsaturated (three-phase) soils. The study provides a change in the thermal conductivity of porous material as the phase composition changes. Bouguerra [17] introduced a new parameter, named liquid-liquid contiguity parameter into the unit cell based model to account for the effect of micro-pore structure on the transmission of heat transfer the continuous liquid phase. Hollies and Bogarty [18] proposed a succinct formula

$$\lambda_{eff} = (1 - \phi_w) \lambda_{eff, d} + \phi_w \lambda_w$$

in which $\lambda_{eff, d}$ is the over-all conductivity of the air dry assembly, $\lambda_w$ is the water thermal conductivity and $\phi_w$ is the volumetric fraction of water. This similar calculated formula in parallel combination of thermal resistance was applied in numerically modeling heat and moisture transfer within porous fabric considering the effect of water content [19]. For example, Hes and Loghin [20] modeled heat and moisture transfer through wet woven fabric based on the weighted summed up related conductivity of fabric and water. For porous plain knitted fabric, Dias and Delkumburewatte [21] developed a theoretical model to estimate the thermal conductivity of knitted structure. This structure model for thermal conductivity includes the porosity model, which demonstrates the variation of porosity with the variation of fabric structural parameters. It is noticed that most of these published thermal conductivity models are based on four basic structure unit models: the Parallel, Series, Maxwell-Eucken and Effective Medium Theory (EMT) equations. The equivalent structural method is one of the widely used approach by deriving its effective thermal conductivity based on the known structure parameters. The Parallel and Series models, which are the two basic models, represent a layered structure with the characteristics of its components (fiber) aligning either parallel or perpendicular to the heat flow [22]. A series-parallel hybrid models (\(\|\|\)) which assumed a cubical geometry were also developed by Krischer-Kroll [23]. In the hybrid model, volume fraction \(\psi\) of layers oriented perpendicular to the direction of heat flow is arranged in series with the complementary fraction \((1 - \psi)\) of layers oriented parallel to the direction of heat flow. The hybrid model has found successful predictions in fibrous moist building materials and unsaturated soils of layers oriented parallel to the direction of heat flow. The hybrid model has found successful predictions in fibrous moist building materials and unsaturated soils [10, 24, 25].

To our best knowledge, although theoretical work has been done on the thermal conductivity of different porous media with different content, there is less information on modelling the effect of fiber’s swelling on the heat conduction of hygroscopic fibrous fabrics. Water saturation results in swelling of the hygroscopic fibrous fabrics, which is a dimensional change due to breaking of inter- and intramolecular hydrogen bonds and will further complicates the microstructure of fabric [26]. Okubayashi et al [27] experimentally investigated the moisture sorption and desorption kinetic on lyocell fibers and concluded that with increasing water uptake the fiber structure gets looser and at higher water vapor pressures water molecules can easily invade the structure. The swelling will also complicate the kinetics of the sorption process [28] and increase the average distance between the water molecules [29]. Therefore, the effect of swelling on thermal conductivity should be included in the P-S theoretical model. However, it is a difficult task for measuring the overall porosity of a moist hygroscopic fabric using mercury intrusion porosimetry method. Therefore, both experimental and modeling efforts will be made to address the swelling effect in the present work. First, the variation of the ETCs for fabric samples with MC will be measured through transient plane source (TPS) method. Subsequently, the Parallel-Series (P-S) model will be employed to compare the predicted values with experimental results. At last, the the validity of the P-S model will be also checked by introducing an equivalent porosity parameter for calculating the ETC of hygroscopic fabrics with varying MC. The change of porosity due to absorbing moisture is taken into account in the model, and then the determination procedure of the proposed method for computing the ETC of hygroscopic fabrics with different MC is also presented. The improved method can also find potential applications for reliable numerical modeling of coupled heat and mass transfer within thermal functional clothing.
2. Theoretical methodology

2.1. Effective thermal conductivity model of moist fibrous fabrics

This section will introduce the derivation process of the effective thermal conductivity based on the Parallel-Series structural model. In general, the convection heat transfer within a porous material may be neglected when the pore diameter is less than 4 mm [30]. Moreover, thermal radiation contribution to heat transfer plays a small role when the temperature of material is under 200 °C and radiation heat transfer can be also ignored since the liquid water only exists in the range of 0 °C–100 °C [15]. Therefore, only conduction heat transfer is considered in this work. For one-dimensional (1D) heat conduction, the conduction heat transport through fibrous assembly can be calculated by using Fourier’s law. Figures 1(a) and (b) show the real structure and an equivalent structure of moist fibrous material. Using the thermo-electrical analogy technique, the solution of heat conduction problem for fibrous medium can be obtained by decomposing the complex fibrous structure into a network consisting of a set of series/parallel structural elements (figure 1(c)) [24, 31]. Thus, in the study, the Parallel-Series model [23, 32], which is a combination of the series \( \lambda_s \) and the parallel \( \lambda_p \) models, was applied to predict the ETC of fabric sample at different moisture content state as follows

\[
\lambda_{\text{eff}} = \frac{1}{\tau_{\text{av}}} \cdot \lambda_p + \frac{\tau_{\text{av}} - 1}{\tau_{\text{av}}} \cdot \lambda_s
\]  

(1)

Where \( \tau_{\text{av}} \) is the average tortuosity of pore channels, which can be determined by the following equation [33]

\[
\tau_{\text{av}} = 0.8(1 - \phi) + 1
\]  

(2)

Where \( \phi \) is the fabric porosity, which can be measured by the Mercury intrusion porosimetry analysis method.

The P-S models suppose that the fluid (including air and liquid water) and solid phase are thermally parallel or perpendicular to the heat flux direction. Therefore, the ETC \( \lambda_p \) and \( \lambda_s \) of the fluid and solid phase in parallel and series can be written as, respectively [34]

\[
\lambda_p = (\phi - \phi_w) \lambda_f + \phi_w \lambda_w + (1 - \phi) \lambda_f
\]  

(3)
The effective thermal conductivity of liquid water \( \lambda_w \) and gas \( \lambda_g \) can be represented by a third-order polynomial equation described as \[ \lambda_w = 0.557 + 0.0022T - 1.051 \times 10^{-5}T^2 + 1.081 \times 10^{-8}T^3 \] where \( T \) is the temperature in °C. At 27 °C, the thermal conductivity of liquid water \( \lambda_w \) is equal to 0.609 W m\(^{-1}\) K\(^{-1}\). However, the effective gas thermal conductivity \( \lambda_g \) at macroscopic scale is related to the Knudsen number (\( Kn \)), which is defined as the ratio of molecular mean free path \( \kappa_m \) and some characteristic length of considered structure \( L_c \): \( Kn = \kappa_m / L_c \). In a microscale space, gas molecules collide between and with both sides of the fiber skeleton interface. Generally speaking, a continuum gas regime takes place when Knudsen number is less than 0.01, and gas flow belongs to free-molecular regime when Knudsen number is greater than 10. The interval 0.01 < \( Kn < 10 \) is described as a transition regime, where both intermolecular and molecule-fiber collision processes can occur. Furthermore, the gas molecular mean free path can be calculated by

\[ \kappa_m = \left( \frac{\sigma T}{\sqrt{2} D_g^2 P} \right) \] and \( L_c \) is given by

\[ L_c = \frac{\pi D_f}{4 f_v} \]

Where \( \sigma \) is the Boltzmann constant, \( P \) the absolute pressure, \( D_g \) the gas collision diameter, \( D_f \) the fiber diameter and \( f_v \) the fiber solid fraction ratio (\( f_v = 1 - \phi \)).

In the atmospheric pressure, the Knudsen numbers for the PET fabric and VC fabric calculated from the equation \( Kn = \kappa_m / L_c \) based on fiber diameter data (12 \( \mu \)m for PET fiber and 14 \( \mu \)m for VC fiber, see figure 2) are 0.0007 and 0.0005. The gas flow falls in continuum gas regime. The gas conductivity is then related to the Knudsen number and the conductivity at ambient pressure by

\[ \lambda_g = \frac{\lambda_g^*}{1 + 2\beta Kn} \]

Where \( \beta \) is a parameter equal to 1.5 for air. \( \lambda_g^* \) is gas thermal conductivity at atmospheric pressure, which is dependent of temperature, and can be evaluated using the expression

\[ \lambda_g^* = 0.0237 + 6.41 \times 10^{-5}T_g \]

Where \( T_g \) is the gas temperature in °C.

### 2.2.2. The equivalent thermal conductivity of solid phase

For non-hygroscopic medium (PET fabric sample), the thermal conductivity of fiber parent material \( \lambda_f^* \) is regarded as the equivalent thermal conductivity of solid phase \( \lambda_f \) without consideration of geometrical orientation and contact of the fibers, because the contact points among these fibers are rather less and the medium’s internal geometrical structure is abstracted as Parallel-Series layered structure. The equation is written as

\[ \lambda_f = \lambda_f^* \]

Where \( \lambda_f \) is the thermal conductivity of fiber parent material.

### 2.2.3. Equivalent porosity \( \phi_{eq} \) for absorbent fabric

In terms of hygroscopic fiber (VC fabric sample), the absorbing moisture onto or into the fiber will change its size and swelling occur. When the ambient humidity increase or decrease, the hygroscopic fiber materials absorb or desorb water vapor until moisture absorbing saturation (MAS) state reach. The process is also regarded as a saturation state and can be characterized by water vapor sorption kinetics obtained by plotting mass gain or loss percentage as function of time. An equivalent porosity \( \phi_{eq} \) for hygroscopic fabrics with saturation regain is
proposed in the work to reasonably eliminating the absorbed moisture effects. The determination procedure for the equivalent porosity of saturated fabric \( \phi_{eq} \) can be divided into the follow steps:

(1) The moisture regain \( MR_{eq} \) at atmospheric pressure: a measurement was made by oven-drying with ambient and pre-conditioned in standard environment.

(2) The \( \lambda_{eff,eq} \) of VC fabric at the moisture absorbing saturation (MAS) state were tested by MIP and TPS approach. For hygroscopic fiber assembly, \( \phi_{eq} = \phi \). Then, based on the two phase typical structure model, the equivalent porosity \( \phi_{eq} \) of wetted fiber mat at MAS state can be calculated by the following equation [38]

\[
\lambda_{eff,eq} = k_w \cdot \lambda_f \left( 1 - \phi_{eq} \right) \cdot \lambda_g \phi_{eq} = \lambda_{eff,eq}
\]

Where \( k_w \) is the correction coefficient which is related to the energy transformation due to moisture migration. It is dependent on material type and can be obtained by comparing the measuring values from TPS and steady guarded-hot-plate (GHP) methods.

(3) The MAS fabric was processed further to introduce more moisture content into the fabric. The fabric was soaked into distilled water for 30 min and squeezed to certain moisture content. Then, the sample was kept at the room temperature with its weight frequently monitored until its moisture naturally decreased to destined moisture content \( MC_1 \). The sample was then immediately sealed with a thin plastic film to keep its moisture content. So, non-absorption moisture content \( MC_2 \) (capillary water or bulk liquid) can be calculated from

\[
MC_2 = MC_1 - MR_{eq}
\]

Subsequently, the volumetric fraction \( \phi_{w,eq} \) of non-absorption moisture content within the whole fabric was defined by the following formula.
\[ \phi_{w,eq} = (\rho_{fab,d} \cdot MC_2) / \rho_{\text{liquid}} \]  
(13)

Where \( \rho_{fab,d} \) is the density of dry fabric and \( \rho_{\text{liquid}} \) is the density of liquid water.

It is noteworthy that the volumetric fraction \( \phi_w \) for non-hygroscopic PET fabric would be calculated by equation (14)

\[ \phi_w = (\rho_{fab,d} \cdot MG) / \rho_{\text{liquid}} \]  
(14)

Finally, according to three-phase structural model, the ETC of the moist fabric sample at moisture content \( MC_2 \) can be calculated by the P-S model (equation (1)), as described above. The equations (3) and (4) can be rewritten as

\[ \lambda_p = (\phi_{eq} - \phi_w) \lambda_g + \phi_w \lambda_w + (1 - \phi_{eq}) \lambda_f \]  
(15)

\[ \lambda_\perp = \frac{1}{(\phi_{eq} - \phi_w) / \lambda_g + \phi_w / \lambda_w + (1 - \phi_{eq}) / \lambda_f} \]  
(16)

3. Materials and methods

3.1. Materials

Two types of different fiber groups were used: hygroscopic viscose (VC) nonwoven fabric (bulk density 0.21 g cm\(^{-3}\)) and non-hygroscopic Polyethylene terephthalate (PET) nonwoven fabric (bulk density 0.26 g cm\(^{-3}\)). Both the two kinds of fabrics are needlepunched type nonwoven fabrics. Needle punching are techniques used to give a web of fibers sufficient cohesion by mechanical bonding, respectively. Spunbonding fabrics are not used in the study since the fiber surface and cross section will be destructed and become coarse in the thermally bonding process in the spunbonded fabrication.

3.2. Moisture conditioned

In this study, the hygroscopic VC fabric, dried in an oven at 80 °C with 6 h, was selected and then was preconditioned in the moist environment of 21 °C and 65% RH until reaching constant weight. Moisture absorption saturation (MAS) of fabric sample reached when the weight gain of sample was less than 0.01 g. The moisture regain (MR) of hygroscopic fabric under the condition of hygroscopic equilibrium can be measured by the following equation

\[ MR(\%) = \frac{m_{eq} - m_d}{m_d} \]  
(17)

Where \( m_{eq} \) is the fabric wet weight at the MAS state, \( m_d \) is the fabric weight at the dry state. For non-hygroscopic fiber, it is assumed that the MR is equal to 0. Above the MAS state, MR is called as moisture content (MC) and equation (6), where wet weight is referred as \( m_{\text{wet}} \), is utilized to calculate MC values for hygroscopic and non-hygroscopic materials.

\[ MC(\%) = \frac{m_{\text{wet}} - m_d}{m_d} \]  
(18)

In order to set MC value for the sample, the fabric was soaked into distilled water to allow water absorption by capillary effect for 60 min and squeezed. Then, the sample was kept at the room temperature for drying with its weight frequently monitored until its moisture naturally decreased to destined moisture content. Four moisture content levels of 0%, 25%, 50% and 75% were used in the thermal conductivity experiments. After each drying step and the determination of moisture content following the above described procedure, the ETCs of the moist and drying sample were measured.

3.3. Measurements

3.3.1. SEM

Scanning electron microscopy (SEM) images were obtained on a field emission scanning electron microscope (FEI Quanta 250FEG) operated at an acceleration different voltage of 5, 10 and 15 kV. Figure 2 shows the SEM images of the fibrous structure of the studied materials. The insets are the higher-magnification SEM images (5000 ×). From the figure it can be seen that the average diameters for PET fiber and VC fiber are 12 μm and 14 μm, approximately.
3.3.2. MIP

In order to further analyze the pore structure and pore size distribution, a measurement by mercury intrusion porosimetry (MIP) analysis method was conducted. MIP tests were performed by using a Micrometritics Autopore IV 9500 instrument (Micrometitics, USA). The MIP technique is a well known technique based on the property of a non-wetting liquid (like mercury) of not being spontaneously absorbed on the surface of solid or inside their pores itself because of the surface tension, but can be forced by applying external pressure. According to Washburn’s equation, pore-throat radius \( r \) can be calculated by assuming contact angle \( \theta \) and liquid Hg surface tension \( \gamma \), the following relationship equation between pressure and pore size can be obtained as

\[
\Delta P = -\frac{2\gamma \cos \theta}{r}
\]  

(19)

Where \( \Delta P \) is the pressure difference across the curved mercury interface, \( \theta \) is the wetting angle of mercury (equal to 141°) and \( \gamma \) is the surface tension of mercury (0.48 N m\(^{-1}\)). The measurements were conducted by incrementing the pressure up to 30 MPa on a sample immersed in the non-wetting mercury.

Figure 3 shows pore size distribution (PSD) curves between 5 nm and 58 \( \mu \)m. The measurement of the large pores with diameters >58 \( \mu \)m is not included due to technical restriction. It can be observed that the PSD curves of nonwoven fabrics are clearly one-modal, which is very characteristic of traditional nonwoven fabric materials. Rutledge [39] characterized the pore parameters of electrospinning fiber mats and found that MIP suffer from deformation due to the increasing pressure to intrude mercury into the smallest pores, which are one or two orders of magnitude smaller in diameter than the traditional fabric. The deformation should be considered under the condition of the fiber diameter below 10 \( \mu \)m. The fiber diameters of investigated sample in the study are 12 \( \mu \)m and 14 \( \mu \)m. For simplicity, mechanical deformation under the pressures attained in the Mercury porosimetry experiment was not included in the calculation of pore parameters. The calculated porosities from MIP for PET and VC nonwoven fabrics are 0.83 and 0.80, respectively.

3.3.3. TPS measurements

A transient approach, the transient plane source (TPS) technique was adopted to measure the ETC of both dry and moist non-woven fabric samples through Hot Disk TPS-2500 thermal constants analyzer at room temperature. Measurement of thermal conductivity by means of the TPS approach has been demonstrated elsewhere [40, 41]. The standardized TPS technique offers its advantage in simultaneously determining thermal conductivity, thermal diffusivity and specific heat capacity from a single measurement, with marginal effort on sample preparation. The basic technique principle of the approach is that a plane film acts both as temperature sensor and heat source. The sensor will be placed between two pieces of identical samples to be investigated. Both sensor faces in tightly contact with the two sample surfaces by applying a constant force of about 30 N between the two samples in order to reduce the thermal contact resistance. To make sure of the experimental accuracy, each experiment is repeated three times and the average value is acquired. Parameter estimation would be applied to analyze the temperature measurement uncertainty using least-squares procedure [42].

4. Results and discussion

4.1. Variations of experimental ETC with moisture content

The samples were tested at four different levels of moisture content by using the above TPS technique described above. The ETCs of the moist fabrics were taken as the averages of the three measurements under the same conditions. Results of thermal conductivity measurements are illustrated in figure 4 with respect to moisture content. In previous literature, it was assumed that the ETC has an approximately linear relationship with the MC under low MC range conditions. Building porous materials are the cases like mercury

\[
\rho_p(t) = \frac{\lambda_{ps} - \lambda_{uw}}{\lambda_p} \rho_{ps} + \lambda_{uw}
\]

(20)

incrementing the pressure up to 30 MPa on a sample immersed in the non-wetting mercury. The ETCs of the moist fabrics were taken as the averages of the three measurements under the same conditions. Results of thermal conductivity measurements are illustrated in figure 4 with respect to moisture content. In previous literature, it was assumed that the ETC has an approximately linear relationship with the MC under low MC range conditions. Building porous materials are the cases like mercury

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4.2. Comparisons between experimental and predicted results

The comparisons between the experimental evolution of the ETC with moisture content and those calculated by the proposed P-S model are illustrated in figure 5. As a whole, these predictions for sample basically agree with experimental data at drying state, but are deviated from experimental data at moist state. In describing the thermal conductivity model, the radiation contribution to heat transfer has been ignored. For fibrous media

Figure 3. Pore diameter distribution from mercury intrusion porosimetry. ((a) PET fabric; (b) VC fabric).
Table 1. Fitting parameters and formula for fabric sample.

| Sample No. | Correlation | Coefficient of correlation, $R^2$ |
|------------|-------------|----------------------------------|
| PET fabric | $\lambda = -0.03947 \cdot \exp\left(-\frac{MC}{11.76138}\right) + 0.0618$ | 0.9755 |
| VC fabric  | $\lambda = -0.09393 \cdot \exp\left(-\frac{MC}{20.0642}\right) + 0.11947$ | 0.9551 |

Figure 4. Best-fit exponential relationship of experimental data versus moisture content. (a) PET fabric; (b) VC fabric.
with long cylinder fibers, the radiative thermal conductivity $\lambda_{\text{rad}}$ at drying state can be calculated by the following equation [45]

$$\lambda_{\text{rad}} = C \cdot \sigma T^4 \frac{D_f}{\varepsilon \cdot f_v}$$

(20)

Where $\sigma$ is the Stephan-Boltzmann constant, $D_f$ is the fiber diameter, $\varepsilon$ is the emissivity, and $C$ is the constant.

The radiative thermal conductivities of PET and VC fabrics obtained from equation (18) are 0.00018 Wm$^{-1}$K$^{-1}$ and 0.00023 Wm$^{-1}$K$^{-1}$. The experimental and predicted values of ETC from equation (2) in the P-S model are 0.022 33 Wm$^{-1}$K$^{-1}$ and 0.027 98 Wm$^{-1}$K$^{-1}$ for PET fabric, 0.023 42 Wm$^{-1}$K$^{-1}$ and 0.02664 Wm$^{-1}$K$^{-1}$ for VC fabric. Analysis of these data indicates that thermal radiation plays relatively little role in heat transfer and the predicted value is a little higher than measured results. Possible explanation for the overestimation is related to the defects of the highly porous structure with different types of pores. The porosity evaluated by MIP technique only determines the percentage of open pores or channels that were Hg accessible. The closed pore, micro-pores or meso-pores cannot be measured [46]. This would result in lower measured porosity than actual one. For example, the viscose fiber can be visualized as having longitudinal cracks, crevices, or grooves from surface morphology (figure 6, 5000×). The dead trapped air inside these mesopores, microvoids or grooves will not flow, which contribute to high heat insulation [47]. Another intriguing example for strengthening thermal insulation by the micro-porous structure of micro-channels is the polar bear hair [48]. However, these factors aren’t considered in the P-S model, which in fact exist in the experimental fibers. Consequently, the ignorance of microvoids or grooves in the fiber skeleton is the cause of overestimation of the
ETC of dry VC sample. But, these microvoids or pores were occupied by moisture content when the fiber absorbs liquid water through capillary effect. The heat insulated effects provided by micropores become weaker or disappear when the fabric are wetted.

Go to the wet VC fabric, the predicted results are deviated considerably with those obtained by experiments. In general, this can be explained by three reasons for doing contributions to heat transfer:

1. Enhanced heat conduction: Viscose fiber belongs to the hygroscopic material, and the thermal conduction of the fiber skeleton during humidifying process is greatly enhanced due to high thermal conduction of absorbing moisture. However, the previous study about the thermal transmissivity data for cellulose fiber [49] revealed that the thermal conductivity of a single hygroscopic fiber vary little though it is water-absorbed. Therefore, the impact of absorbed moisture on the thermal conductivity of a single fiber can be ignored when modelling thermal conductivity of hygroscopic fabric.

2. Absorbed heat: the hygroscopic viscose fiber will hydrate in the transient heating test process (TPS). The dehydration is accompanied by an endothermic reaction and something of the energy can be involved. Hygroscopic fibers such as wool, linen and cotton absorb moisture vapor from ambient air when the humidity rises, releasing heat [50].

3. Swelling: Water absorption could induce a volume increase (swelling) of the fibers inside the fabric sample. For example, In an aramid fibers, it is suggested that the absorbed water is mainly located inter-or intra-fibrillar microvoids and larger core defects. The width of the microvoids increases with the increase of the fiber moisture regain. From the view of macroscopical morphology, the swelling phenomenon occurs. The expansion of a plant fibers (consisting of cellulose, semi-cellulose and lignin) results from occupied space between the microfibrils by the water molecular absorbed onto the cell wall of a plant fiber [51]. The swelling of the fibers will lead to smaller pore channels within the fabric sample, which will also generate more internal water bridge (figure 9(d)) between adjacent frameworks. This will be beneficial to heat transfer due to high thermal conduction of water. It is rather complex to quantitatively evaluate the influence of hygrothermal reaction on the total heat transfer of porous fabric through the P-S model though much experimental work has been done [52, 53]. Also, relating the ETC with the pore change due to fiber swelling is a difficult task if only measuring porosity of fabric through MIP tests. In the next section, the validity of the proposed equivalent porosity for P-S model is evaluated.

4.3. Consideration of hygroscopic swelling effect

In this section, the relative prediction error (RPE), which indicates the average ratio of the absolute value of the predication error and the measured values, is used to compare predication accuracy. The RPE, $\eta_i$ at ith moisture content level, was calculated by $\eta_i = |\lambda_p - \lambda_{m_i}|/\lambda_p$. A RPE of 0.3 means a difference of 30% from the measured data and a smaller RPE is an indicator of more accurate prediction. A direct comparison among these RPEs for PET and VC fabrics, as shown in figure 7, indicates that larger RPE were noted for the moist VC fabric sample. As above mentioned, the absorbing moisture by fiber hydrosopic group will lead to fiber swelling and enhancing heat conduction within the fiber assembly. Therefore, the effect of fiber water absorbing on thermal conduction should be considered in the P-S model for predicting the ETC of moist VC fabric.

Here, another generalized calculated procedure based on the P-S model was proposed, which was constructed by firstly determining the equivalent porosity of hygroscopic fiber mats at moisture-saturated state by typical two-phase system model, and then calculating the ETC of the fibrous assembly through the three-phase system model from the equivalent porosity (see methodology part 2.2.2).
In the previous work, it was concluded that moisture content bears a little quantitative influence on the thermal transmissivity of a single hygroscopic fiber. That is to say, the thermal conductivity \( \lambda_f \) of parent fiber, which is commonly used in a large majority of two phase models (solid + gas), can be employed in the predicted three phase model at different levels of moisture content. Here, the equivalent porosity \( f_{eq} \) for wetted fibers within the porous materials was proposed to consider water absorbing effect, including swelling inducing decrease of gas porosity, the humidity liquid bridge conduction on heat transfer. But the heat of wetting was not contained. The specific comparisons between actual values measured and predicted ETCs using different porosities are illustrated in figure 8. The blue triangles denote these thermal conductivity data predicted from P-S model by using equivalent porosity \( f_{eq} \). By contrast, the predication accuracy of P-S model with equivalent porosity is higher than that of P-S model with measured porosity by MIP approach. The fact confirms the validity of the basic consideration on the effect of absorbed moisture on swelling of hygroscopic fiber assembly.

However, it should be notified that under the saturation state, the equivalent porosity, which is used to characterize the water absorbing effect, is difficult to predict only through the two-phase structure model. This is
because swelling occur intra-fibers until reach moisture-saturated state. This can be further explained by the various absorptive phase, shown in figure 9 [54]. Unlike wood fiber, which expands in the moisture content above equilibrium moisture content, but below fiber saturation point [55], VC fiber swells once be humidified even if from dry state. Simultaneously, the nonlinear relationship between the ETC and moisture content could be also interpreted by water distribution within the fibers and fabrics. So, the ETC of VC fabric under the level of moisture content 18% (10% moisture content in this calculation) is not presented in the improved P-S model (figure 8).

5. Conclusion

In this work, the experimental determination and P-S modeling of the ETC of a moist fibrous porous fabric with different moisture contents were reported. To improve the testing accuracy and repeatability, the TPS approach was applied to obtain the ETC of fabric in a rapid manner. This avoids consistent moisture evaporation during the test. It is showed that the ETC increases with increasing the moisture content and the relationship between them at a specified operating temperature was established. Comparisons have been also made between the predicted and experimental values by existing P-S model. It is found that there is comparatively larger discrepancy between experimental and calculating results. In order to reduce the relative prediction error, an equivalent porosity was proposed to calibrate the existing P-S model for predicting thermal conductivity of hygroscopic fabric. By contrast, the improved P-S model produces closer estimates. To a certain degree, the equivalent porosity can offset the enhanced conduction effect from swelling, increasing bridge points and lessen disagreement between experiment and prediction though.

At present, the improved model presented in this work is only valid for the moist, hygroscopic fabric with regain above the saturation state. In addition, the hygrothermal reaction of hygroscopic fiber during moisture evaporation process will absorb heat in the TPS experiment. Moisture content inside the fabrics redistribute itself and distillation. These factors should be considered in the future work for P-S model. Though some discrepancy, this validated result is good basis for future work. Further improvement, the calibrated P-S model is a useful tool for estimating the ETC of a moist, hygroscopic fabric used in thermal functional clothing.

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