TECHNICAL UNIVERSITY OF LIBEREC
Faculty of Textile Engineering

# STUDY ON THE THERMAL PROPERTY OF TEXTILE EXPERIMENTALLY AND NUMERICALLY

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SUMMARY OF THE THESIS

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|---|---|
| **Title of the thesis:** | **Study on the thermal property of textile experimentally and numerically** |
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| **Field of study:** | Textile Materials Engineering |
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| **Department :** | Department of material engineering |
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The dissertation is available at the study department for doctoral studies.

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# Abstract

Thermal property of non-woven and other textile fabrics is one of most important aspects for their applications in protective clothing, sleeping bags and related technical textiles. The thermal property of textiles can be influenced by many factors, such as thermal property of materials, structure of textiles in forms of fiber, yarn, and fabric, surrounding conditions including temperature, humidity, and air movement. And the different surrounding conditions would result in different heat transfer mechanisms (heat conduction, heat convection, and heat radiation) and moisture transfer. Therefore, a lot of work has been doing in thermal property of textile in the following aspects: (1) design and improve testing devices for evaluating the thermal property of textiles under various conditions; (2) deeply understand the heat transfer process in textiles; (3) predict the thermal property of textile more accurately by analytical model; (4) design and apply the textile products to meet various applications, and utilize the resources in an economically efficient way. Even though a lot of the testing instruments which are available to evaluate the thermal property of textiles under conductive heat transfer. There still has no any commercial instrument for measuring the thermal property of textile under convective heat transfer, which happens almost everywhere in daily life. And it is well known that the performances of one material would be quite different when it is under different conditions. Besides, the lack of testing instrument and the complexity of textile structure increase the difficulty to deeply understand the heat transfer process in textiles. On the other hand, very few work reported in heat release when the textile absorbs liquid/moisture, which could be also one important factor influencing the thermal property of textiles. In theoretical research, there are several analytical models for predicting the effective thermal conductivity of textiles, but all of the models simplified the structures of yarn and fabric/non-woven fabric, ignored the convective transfer heat in textiles, and ignored the temperature dependent thermal conductivity. Based on the above problems, the performances of textiles in thermal property still cannot be precisely predicted, and plenty of experimental work is still needed for optimizing the products or for meeting various applications.

Therefore, some of the above problems were studied in this work in order to understand more about thermal property of textiles. This dissertation consists of seven chapters. Chapter one introduced the three heat transfer mechanisms (conduction, convection, and radiation) in textile, presented the measurements of thermal conductivity/resistance of textile in forms of fiber and fabric, introduced the experimental and theoretical research work has done in thermal property of textile, and the aim of this work. Chapter two studied the effect of some parameters which are pore shape, pore size, distribution of pores, major-axis length of pore, and the contact area on thermal conductivity of porous materials/textiles by numerical simulation owing to the difficulty in finding suitable samples and the reliable results from numerical method; and also compared the thermal conductivity of textiles from some existing analytical models and from numerical simulation to know about the difference among them. Chapter three evaluated the thermal conductivity of nonwoven fabrics with very high porosity (>95%) under heat conduction, investigated the effect of porosity, pore size and thickness on thermal conductivity, and also determined the ratio of heat transfer causing by conductive, convective, and radiative. Chapter four studied the air permeability and thermal resistance of textile under convective heat transfer, for which one self-designed device was constructed; investigated the effect of porosity, pore size and pore's area ratio to total sample's area on air permeability and thermal resistance. Chapter five studied the impact of structure on the thermal resistance of fabric under heat convection numerically. The local temperature distributions, local heat flux distributions, local/average heat transfer coefficients, and local Nusselt numbers of fabrics taken as plate and porous material under conductive and convective heat transfer were investigated.

Chapter six and chapter seven gave the conclusions and the future work.

**Keywords:** heat transfer; heat conduction; heat convection; thermal conductivity; thermal resistance; numerical simulation

# Anotace

Tepelné vlastnosti netkaných textilií a jiných textilních materiálů jsou jedněmi z nejdůležitějších vlastností pro jejich použití jako ochranné oděvy, spací pytle a další podobné technické textilie. Tepelné vlastnosti textilií mohou být ovlivněny mnoha faktory jako např. tepelné vlastnosti samotného materiálu, struktury vlákna textilie, příze a látky, okolní podmínky jako teplota, vlhkost a pohyb vzduchu. Různé okolní podmínky mohou vést k různým mechanismům přenosu tepla (vedením, sáláním a zářením) a přenosu vlhkosti. Práce byla zpracována v mnoha oblastech (1) návrh a vylepšení testovacího zařízení pro hodnocení tepelných vlastností textilií za různých podmínek; (2) hlubší porozumění přenosu tepla v textiliích; (3) přesnější predikovaní tepelných vlastností textilií na základě analytického modelu; (4) návrh a použití textilních produktů v souvislosti s jejich použitím včetně ekonomicky výhodného využití zdrojů. Ačkoliv je na trhu mnoho měřících a testovacích zařízení pro zjišťování tepelných vlastností textilií, není v nabídce žádný, který by nabízel měření textilií během každodenního přenosu tepla sáláním. Je také dobře známo, že každý materiál se za různých podmínek chová jinak. Navíc absence testovacího zařízení a komplexnost textilní struktury stěžovala hlouběji porozumět přenosu tepla v textiliích. Na druhou stranu velice málo prací se zmiňovalo o vlhkých textiliích uvolňující teplo, což by mohl být jeden z ovlivňujících faktorů. V teoretickém výzkumu existuje několik analytickým modelů pro odhad tepelných vlastností textilií, ale všechny tyto modely jsou zjednodušené pro struktury příze, látka/netkaná textilie ignorující přenos tepla sáláním a závislost tepelné vodivosti na teplotě. Na základě výše uvedených problémů nemůže být správně odhadnuto chování textilií z hlediska tepelných vlastností a je zapotřebí ještě dalšího výzkumu v optimalizaci produktů v souvislosti s jejich použitím.

Proto byly v této práci výše zmíněné problémy studovány pro lepší porozumění tepelných vlastností textilií. Tato dizertační práce obsahuje sedm kapitol. První kapitola uvádí čtenáře do problematiky přenosu tepla v textiliích (vedením, sáláním a zářením), předkládá měření teplotní vodivosti/odporu textiliích ve formě vlákna a textilie. Je v ní uveden provedený experimentální a teoretický výzkum disertační práce, což byl hlavní cíl. Druhá kapitola se zabývá vlivy na některé parametry, jako je tvar a velikost pórů, distribuce pórů, délka hlavní osy póru a kontaktní plocha pro tepelnou vodivost porézního materiálu/textilie pomocí numerických simulací zatížené náročným hledáním vhodných vzorků a spolehlivých výsledků numerických metod. Také je v této kapitole porovnána tepelná vodivost textilií z již existujících analytických modelů a jiných numerických simulací ke zjištění rozdílů mezi nimi.

Třetí kapitola hodnotí tepelnou vodivost netkaných textilií s vysokou pórovitostí (nad 95%) pod vlivem sálajícího tepla. Je zkoumán vliv porozity, velikost a tloušťka pórů na tepelnou vodivost a také je stanoven poměr přenosu tepla vedením, sáláním a zářením. Čtvrtá kapitola studuje prodyšnost a tepelný odpor textilií během přenosu tepla sáláním, pro které bylo sestrojeno samostatné měřící zařízení.  Pátá kapitola se zabývá numericky vlivem struktury na tepelný odpor textilie během sálání tepla. Dále je zde řešena distribuce lokální teploty, lokálního tepelného proudu, lokálního/průměrného koeficientu přenosu teplat a lokálních Nusseltových čísel textilie a porézního materiálu za působení přenosu tepla vedením a sáláním. Šestá a sedmá kapitola shrnuje výsledky práce do závěru a dalšího bádání.

**Klíčová slova:**

Přenos tepla; vedení tepla; tepelná vodivost; tepelný odpor; numerické simulace.

# Content

# 1 Introduction

Textiles have been being one part of people's daily life, are widely used for clothing, protection, fashion statement, and technical applications [1-2]. In order to apply textiles properly, a lot of properties of textile are needed to be evaluated. Among them, thermal property of non-woven and other textile fabrics is one of most important aspects. Under the conditions of comfort, the mind is alert and the body operates at maximum efficiency. In contrast, serious physiological disorders or even death may occur if the temperature rises or falls to extreme levels. Besides, textiles are used for the thermal protection and insulation applications in order to conserve the thermal energy due to their excellent thermal insulation property. Therefore, the effective thermal conductivity/resistance of textiles has been studying in order to deeply understand the heat transfer process in fibrous structure materials, in order to predict, design and apply the textile products to meet various applications, and utilize the resources in an economically efficient way.

The thermal conductivity/resistance of textiles have been studied both in theoretical and experimental work. In theoretical aspect, the textiles are taken as porous materials (fibers and air), and their thermal conductivity/resistance under conductive heat transfer is the effective combined value of each components. However, a lot of experimental results revealed that there was a big difference between experimental results and predicted values if only considering the porosity and heat conduction[3-15]. On the other hand, almost all of the thermal conductivity of textiles is evaluated under heat conduction[2-4,8,16-18] due to the limitation of existing testing instruments and the difficulties of producing one instrument to meet various real conditions in human's daily life (temperature range, convection conditions, and humidity, etc.).

Besides, moisture transmission through a textile material is not only associated with the mass transfer processes, but also related to heat transfer. During the transmission of water molecules through textile materials, they are absorbed by fiber molecules due to their chemical nature and structure. With an increase in humidity, the heat transfer efficiency of the material increases. And the adsorption of moisture/liquid of textiles is inevitably accompanied by exchange of heat or energy, which will cause temperature changes of textiles at the same time[19-21]. It makes the small environment between human body and cloth system more complicated. The increased temperature due to the production of heat on the surface of the material led to the decrease of the rate of moisture vapor transmission [22-24].

Although the most reliable information about a physical process is often given by actual measurement, however, it would take plenty of time and labor force to carry out measurements for evaluating, designing and optimizing a product. In addition, there are serious difficulties of measurement in many situations, and the measuring instruments are not free from errors. In contrast, a theoretical prediction works out the consequences of mathematical models rather than those of an actual physical process. In a theoretical calculation, both the realistic conditions and ideal conditions can be simulated in a very short time comparing with practical experiments. Besides, more detail information can be provided by computer. And numerical method has been widely used in every area due to its reliable accuracy, flexibility for both realistic conditions and ideal conditions, and more detailed information. The use of numerical simulations to study effective thermal is very common by using finite element method. Carson[25] and Dasgupta [26] stated that the numerical simulation for heat transfer had good agreements with the experimental results.

# 2 Purpose and the aim of the thesis

The aim of this work includes:

(1) Investigate the factors which would influence the thermal conductivity of textiles under conductive and convective heat transfer by numerical method;

(2) Study the effect of structure on the effective thermal conductivity of highly porous textiles;

(3) Study the factors of thermal resistance of textiles under convective heat transfer;

(4) Investigate the temperature changes of textile during the adsorption process.

# 3 Overview of the current state of the problem

Two principles, which are guarded hot plate principle[27-28] and photopyroelectric technique[29-31], are widely applied for determining the thermal conductivity/resistance of textiles even though various instruments come out in market.

However, almost all of the thermal conductivity of textiles is evaluated under heat conduction[2-4,8,16-18] due to the limitation of existing testing instruments and the difficulties of producing one instrument to meet various real conditions in human’s daily life (temperature range, convection conditions, and humidity, etc.). Theoretically, if only consider the conduction mechanism in textiles or porous materials, thermal conductivity should decrease continually with decreasing bulk density, finally approaching the conductivity of the gas filling the void spaces. However, nonwoven fabrics typically show first a decrease and then an increase in the apparent thermal conductivity with decreasing bulk density. This suggests that other heat transfer mechanisms must contribute appreciably to the apparent thermal conductivity of these materials[32]. Esra[3] reported that the thermal conductivity of fabrics made of hollow fiber and solid fiber from the experiment didn't demonstrate significant difference because the porosity of fabric played a more important role than the porosity of fibers. Lizak[4] stated that the thermal conductivity of fabric from hollow fibers got lower thermal conductivity than the fabric from solid fibers, but the difference was not significant. Stuart and Holcombe[7] have published data for polyester and polypropylene nonwovens showing an increased role in fiber conduction at high solidities. Heather[8] investigated the thermal insulation of three type of fibers (solid fiber, hollow fiber and grooved fiber) in terms of various denier, interstitial void fractions, interstitial void media, and orientations to the applied temperature gradient to evaluate their applicability. And their results indicated that the best conductive insulation is achieved for a high-void-fraction configuration with a grooved fiber cross section, aerogel void medium, and the fibers oriented normal to the heat flux vector. The experiments of Hager and Steere[9] showed that fiber conduction accounts for only 0.3% of the total heat transfer in high porosity fibrous structure. Strong[33] studied glass fiber systems, found that solid conduction could account for 6-7% of the total, but they obtained these results with highly compressed samples (solidities 10-19%), and so a large degree of fiber-fiber contact might be expected. Monika Baczek investigated the thermal conductivity of nonwoven fabrics; found that the ratio of thermal conductivity by radiation to conduction was about 15%[16]. Therefore, there appears to be a consensus that heat flux passing through textile or a porous medium may in general be represented by several mechanisms: conduction through solid fibers, conduction through air in the interfiber spaces, free and forced convection, and radiation[34]. However, there is no instrument for evaluating the thermal conductivity/resistance of textiles under heat conduction, heat convection and heat radiation simultaneously. Fortunately, some kinds of heat transfer mechanisms can be ignored in some cases, for instance, the convective heat transfer can be ignored when the speed of air flow is very small, and the convective and the radiative heat transfer can be ignored when the temperature difference is small. Based on heat transfer in conduction, some analytical models were proposed to predict the thermal conductivity of textiles.

The first analytical model for predicting the thermal conductivity of textiles was reported by Bogaty[10]. In his model, the volume fraction of air and textile material, the orientations (the heat flow is parallel and perpendicular to the fiber) of fibers, and also the percentage of fibers in parallel and series arrangement are taken considerations. For simplified cases, this model can be applied if all the fibers are parallel to the heat flow or perpendicular to the heat flow. But for real structures of textiles or nonwovens, it is very difficult to determine the orientations of fibers as well as the percentages of fibers in parallel and series arrangement. Therefore, this model cannot be widely used. Since the difficulties from Bogaty's model, Militky[11] simplified the model by assuming that the parallel and series arrangements of fibers have the same quantity in textiles, therefore, the average value of the parallel and the series models can be used for the thermal conductivity of textile. Faleh[35] stated one polynomial predicting model which needs to get the coefficient from every practical experiment for evaluated the thermal conductivity of fiber in composites. Maxwell-Eucken model[13-14] was used for materials with continuous phase and dispersed phase. It assumes a dispersion of small spheres within a continuous matrix of a different component, with the spheres being far enough apart so that the local distortions to the temperature distributions around each of the spheres do not interfere with their neighbors' temperature distributions. Wang[12] deduced a mathematical expression for co-continuous structural materials based on Maxwell-Eucken model, but his model also can be expressed by the series and parallel models. Levy's[15] gave a model based on the Maxwell-Eucken model, but levy's model was derived solely by algebraic manipulation, with no stated physical basis. Ismail[36] developed a mathematical model for predicting the effective thermal conductivity of plain woven fabric containing circular warp yarns and elliptic weft yarns. In this model, the fractional concept is adopted, which means the thermal resistances of solid parts and gas parts are calculated separated first, and then the total thermal resistance according to the combinations of solid and gas parts can be obtained. But this model is only convenient for simple structures. Even these analytical models are available, all of them assumed that the air in textiles is stagnant, no heat loss/thermal resistance happens in contact area, the pore size and pore shape don't have influence in thermal resistance. And according to the literature research, there lacks of analytical model for thermal conductivity of textiles under convective heat transfer and radiative heat transfer. Kothari[6] proposed a model for prediction of thermal resistance of woven fabrics by using thermal electrical analogy technique. Yoshihiro[17] developed structural models of yarns, plain weave fabrics and plain weave fabric/resin composites and theoretical formulas for the effective thermal conductivity which were derived from these models. Zhu[37] developed a fractal effective thermal conductivity model for woven fabrics with multiple layers. Das[38] developed a mathematical model for prediction of thermal resistance of multilayer clothing in non-convective media. Matusiak[39] developed a model of thermal resistance of woven fabrics and considered cross-section of yarn as square shape. But the prediction models for special-shaped fibers and yarns are missing.

On the other hand, moisture transmission through a textile material is not only associated with the mass transfer processes, but also related to heat transfer. During the transmission of water molecules through textile materials, they are absorbed by fiber molecules due to their chemical nature and structure. With an increase in humidity, the heat transfer efficiency of the material increases. And the adsorption of moisture/liquid of textiles is inevitably accompanied by exchange of heat or energy, which will cause temperature changes of textiles at the same time[19,21,40]. It makes the small environment between human body and cloth system more complicated. The increased temperature due to the production of heat on the surface of the material led to the decrease of the rate of moisture vapor transmission[22-24]. King and Cassie[40] observed that in a textile material, immersed in a humid atmosphere, the time required for the fibers to come to equilibrium with the atmosphere is negligible compared with the time required for the dissipation of heat generated and absorbed by the fibers when regain changes. On the other hand, this kind of heat would be helpful for moisture evaporation and would provide a much warmer condition for human body in a period of time. In other cases, the heat of liquid absorption could result in the deterioration of textile's qualities when the textiles packed and the heat cannot dissipate quickly. And this kind of heat also could be one reason for spontaneous combustion of warehouse where stored a lot of textiles. Therefore, it is very important to investigate the temperature change of textiles when they are absorbing moisture/liquid.

# 4 Used methods, study material

## 4.1 Numerical simulation

### 4.1.1 Heat conduction

The governing equations used in numerical simulation for heat conduction are,

$$[C(T)]\{\dot{T}\}+[K(T)]\{T\}=[Q(T)] \tag{4.1}$$

Where $\{T\}$ represents temperature matrix, $[C]$ represents specific heat matrix, $[K]$ represents thermal conduction matrix, $[Q]$ represents heat flux vector matrix, $\{\dot{T}\}$ is the derivative of the temperature with respect to time.

Therefore, the equation for steady- state thermal analysis is

$$[K]\{T\}=\{Q\} \tag{4.2}$$

Where $\{Q\}$ is the heat flux vector at nodes.

The boundary conditions are given in figure 4.1.

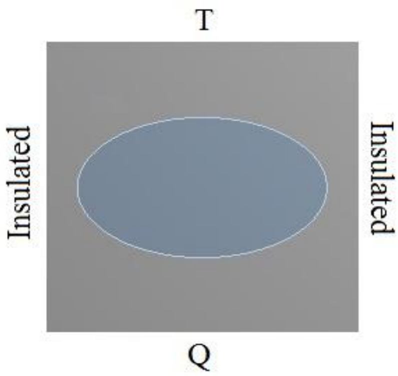



Figure 4.1 Geometrical model and boundary conditions

### 4.1.2 4.1.2 Conjugate heat conduction and heat convection

The governing equations for calculation are given as follows. The heat conduction equation for the solid part is:

$$\nabla\cdot\left(\lambda_s\nabla T_s\right)=0 \tag{4.3}$$

The mass, momentum and energy equations as well as the ideal gas equation of state are given by:

$$\nabla \cdot (\rho U) = 0 \tag{4.4}$$

$$\nabla \cdot (\rho U U) = -\nabla p + \nabla \cdot \left( \mu \left( \nabla U - \frac{2}{3} \nabla \cdot U I \right) \right) \tag{4.5}$$

$$\nabla \cdot (\rho U H) = \nabla \cdot \left( \lambda_f \nabla T_f \right) \tag{4.6}$$

$$p = \rho R T \tag{4.7}$$

Where $\lambda_s$ is thermal conductivity of solid ($W \cdot m^{-1} \cdot K^{-1}$), $\lambda_f$ is Thermal conductivity of fluid ($W \cdot m^{-1} \cdot K^{-1}$), $I$ is the unit tensor.

The boundary conditons are: the temperature contacting with human body was 310K, the temperature of air flow above fabric was 273K at a velocity (5m/s). From the above known information, the following useful information for simulation can be obtained:

The Mach number

$$M_a = u_0 \big/ \sqrt{k R T_0} \tag{4.8}$$

The total pressure

$$\frac{p_t}{p_b} = \left[ 1 + \frac{k-1}{2} M_a^2 \right]^{k/(k-1)} \tag{4.9}$$

The pressure drop

$$\Delta p = p_t - p_b \tag{4.10}$$

## 4.2 Experimental part

### 4.2.1 Materials

#### *4.2.1.1 Nonwoven fabrics*

The polyester hollow fiber, supplied by the Sinopec Yizheng Chemical Fibre Company Limited (Suzhou of China), was used to prepare nonwoven fabrics in a carding machine and a needle-punching machine. The specifications of nonwoven fabrics are given in table 4.1. The nonwoven fabrics were conditioned in a constant temperature and constant humidity box for 24 hours before measurements.

Table 4.1. Specifications of nonwoven fabrics

| Thickness (mm) | Porosity (%) | Pore diameter(mm) |
|---|---|---|
| 6.25±0.04 | 97.87±0.026 | 1.66±0.02 |
| 6.9±0.04 | 97.87±0.026 | 1.66±0.02 |
| 7.59±0.05 | 95.32±0.022 | 0.76±0.012 |
| | 96.12±0.021 | 0.91±0.013 |
| | 97.07±0.023 | 1.21±0.017 |
| | 97.87±0.026 | 1.66±0.02 |
| | 98.35±0.021 | 2.14±0.022 |
| | 98.83±0.025 | 3.01±0.028 |
| 8.01±0.05 | 97.87±0.026 | 1.66±0.02 |
| 8.53±0.07 | 96.99±0.023 | 1.17±0.016 |
| | 97.32±0.027 | 1.32±0.019 |
| | 97.64±0.028 | 1.5±0.018 |
| | 97.87±0.026 | 1.66±0.02 |
| | 98.07±0.027 | 1.83±0.023 |
| | 98.16±0.028 | 1.92±0.027 |
| | 98.30±0.027 | 2.08±0.029 |
| | 98.33±0.028 | 2.12±0.03 |
| 9±0.06 | 97.87±0.026 | 1.66±0.02 |

#### *4.2.1.2 Woven fabrics*

Plain woven fabrics from different materials with various pore sizes were applied since the aim of this work is to investigate the effect of structure (porosity, pore size, and pore area) on the air permeability and thermal resistance under heat convection. Besides, it is not easy to find the fabrics with various pore sizes from one kind of material. The specifications of samples are given in table 4.2.

Table 4.2 The specifications of samples

| Samples | Areal density ($g/m^2$) | Thickness (mm) | Bulk density ($kg/m^3$) | Density of fiber ($kg/m^3$) | Porosity | Pore size ($mm^2$) | η % |
|---|---|---|---|---|---|---|---|
| PA | 142.77±2.60 | 0.36±0.012 | 396.58±7.22 | 1150 | 0.66±0.006 | 0 | 0 |
| PES | 85.36±0.56 | 0.28±0.009 | 304.88±1.99 | 1370 | 0.78±0.001 | 0.0015±0.0008 | 0.82 |
| Visc | 85.38±1.16 | 0.19±0.007 | 449.37±6.11 | 1500 | 0.70±0.004 | 0.009±0.0003 | 1.57 |
| Co45 | 198.17±5.03 | 0.80±0.01 | 247.71±6.29 | 1540 | 0.84±0.004 | 0.044±0.0166 | 13.16 |
| PP | 177.66±2.87 | 0.82±0.013 | 216.66±3.50 | 946 | 0.77±0.004 | 0.096±0.0078 | 12.79 |
| Co20 | 82.11±2.51 | 0.56±0.01 | 146.64±4.48 | 1540 | 0.90±0.003 | 0.188±0.0554 | 35.88 |

*Note: PA represents polyamide, PES represents polyester, Visc represents viscose, Co45 represents cotton fabric by using 45 Tex cotton yarn, PP represents polypropylene, Co20 represents cotton fabric by using 20 Tex cotton yarn , η represents the ratio of pore's area to sample's area.*

### 4.2.2 Methods

The thermal conductivity of fiber was evaluated by measuring the thermal conductivity of composites including fibers and polymer[35]. In this work, a bundle of hollow fibers were put into PEO solution in which the air bubbles were removed by a vacuum pump. After drying, the thermal conductivity of composite was measured, and the thermal conductivity of fiber could be calculated.

The thermal conductivity of composites and nonwoven fabrics were measured by an Alambeta instrument, which enables quick measurements of both steady-state and transient-state thermal properties. The temperature difference between the upper and bottom heating plates which were directly contact with the both sides of nonwoven fabric was constant (10°C or 40°C), and then the instrument directly measured the stationary heat flow density and the sample thickness under a pressure of 200Pa or 1000Pa pressure[27].

The air permeability of samples was measured by air permeability tester FX3300, which measures airflow rate under constant air pressure drop. The morphology of samples was observed by Dino-elite digital microscope, which is able to measure the dimensions and areas of sample and pores. The porosity of sample can be calculated by equation $p = 1 - (\rho_{fabric}/\rho_{fiber})$, $P$ is porosity, $\rho_{fabric}$ and $\rho_{fiber}$ are the densities of fabric and fiber, respectively.

The schematic diagram of self-designed testing device for evaluating thermal resistance of textile under heat convection is shown in figure 4.2. This device consists of one heater which provides hot air flow going through the testing sample, an air flow channel, a sample holder which is in the air channel, two anemometers for recording the speed of air flow, three thermocouples for recording the temperature on the both sides of sample, one data acquisition module which connects the thermocouples with laptop and collect the data from thermocouples, and one laptop which is able to save and read data. The output of heater was 42.35°C, velocity was 4.86m/s, and the heating time duration was 5s.

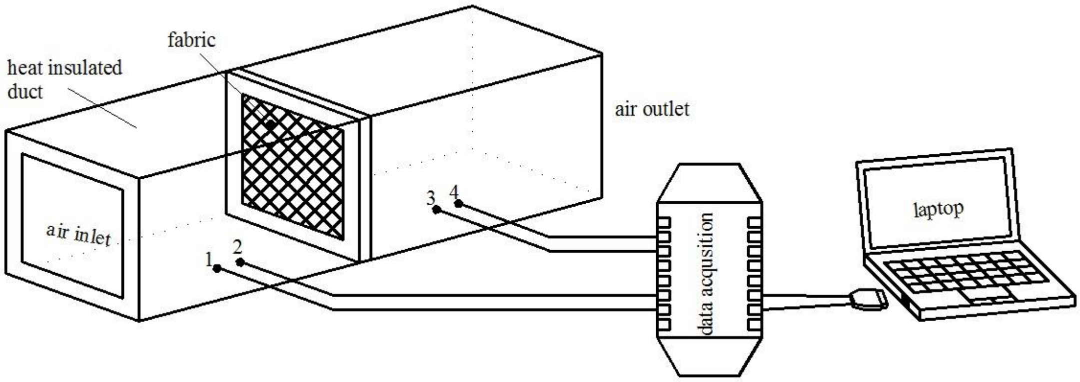
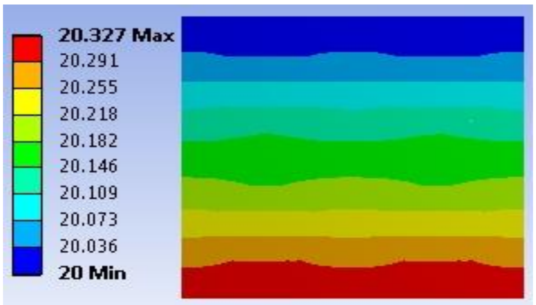


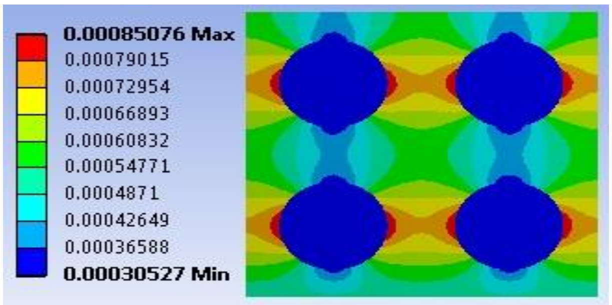

Figure 4.2. Schematic diagram of testing device. (1,4 are anemometers; 2,3 are thermocouples)

# 5 Summary of the results achieved

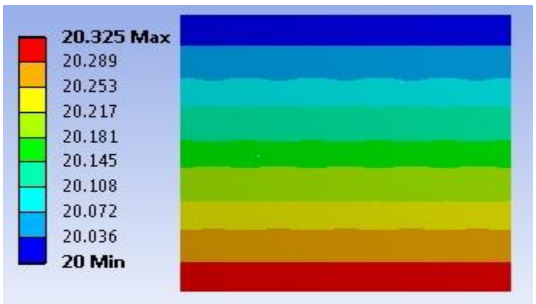
## 5.1 Results from numerical simulation



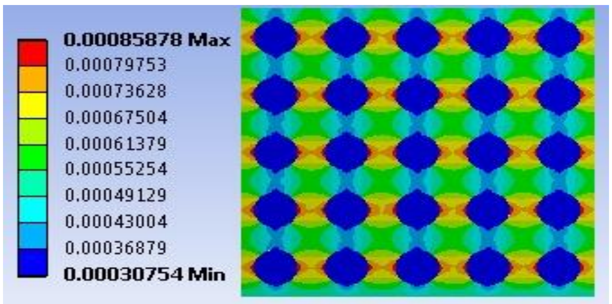

(a) temperature distribution of sample with 4 pores



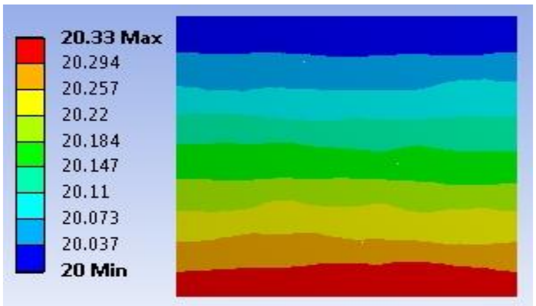

(b) heat flux distribution of sample with 4 pores



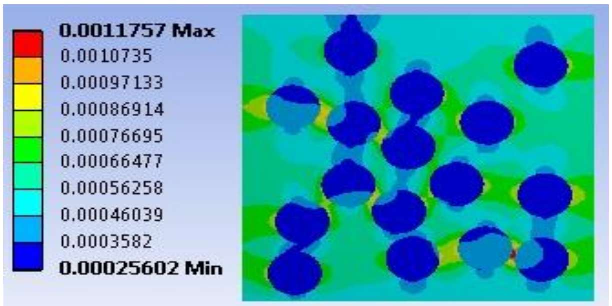

(c) temperature distribution of sample with 25 pores



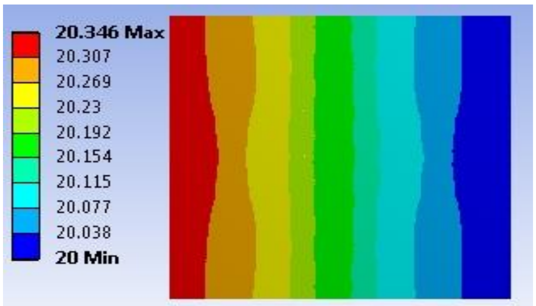

(d) heat flux distribution of sample with 25 pores



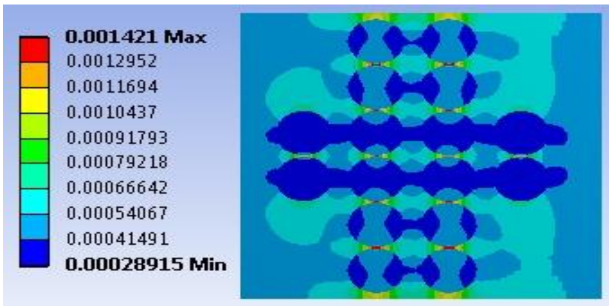

(e) temperature distribution of sample with random distribution 4 of pores



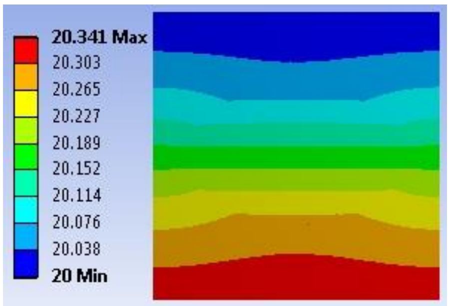

(f) heat flux distribution of sample with random distribution 4 of pores



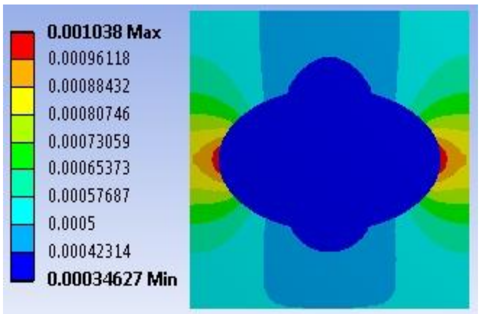

(g) temperature distribution of sample with random distribution 6 of pores



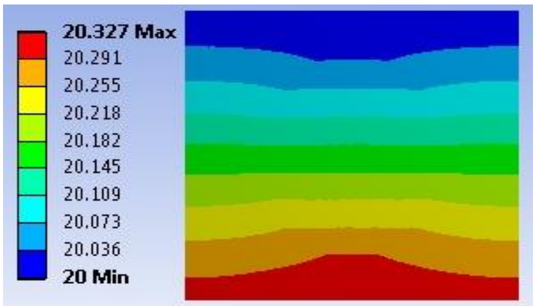

(h) heat flux distribution of sample with random distribution 6 of pores



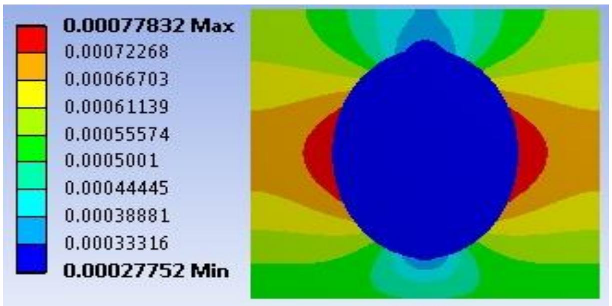

(i) temperature distribution of sample with larger major axis length



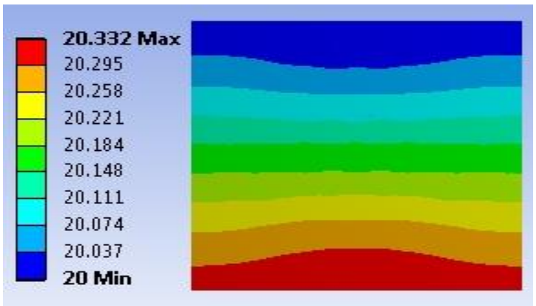

(j) heat flux distribution of sample with larger major axis length



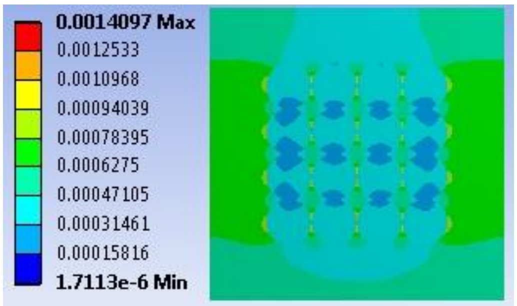

(k) temperature distribution of sample with smaller major axis length



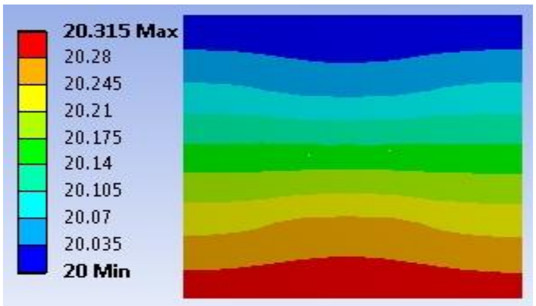

(m) heat flux distribution of sample with smaller major axis length



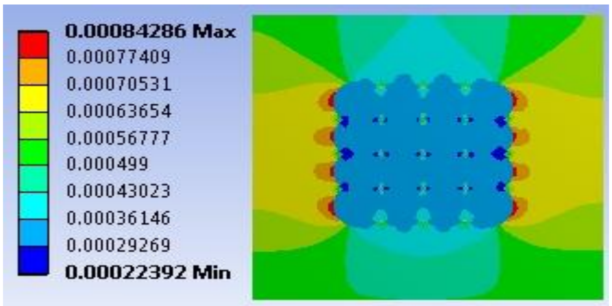

(n) temperature distribution of sample with smaller contact area




(l) heat flux distribution of sample with smaller contact area




(o) temperature distribution of sample with larger contact area




(p) heat flux distribution of sample with larger contact area

Figure 5.1 Temperature distrubtion and heat flux distribution of samples from numerical simulation

Table 5.1 Thermal conductivity of samples including different porosity and pore shape from analytical models and simulation

| Pore shape | Thermal conductivity ($W \cdot m^{-1} \cdot K^{-1}$) | | | | | | |
|---|---|---|---|---|---|---|---|
| | Porosity (%) | Fourier's law | From simulation | PSM1 | ME model | Levy's model | PSM2 |
| square | 10 | 0.8984 | 0.9091 | 0.9048 | 0.9143 | 0.9212 | 0.9157 |
| | 20 | 0.8205 | 0.8278 | 0.8246 | 0.8364 | 0.8473 | 0.8408 |
| | 30 | 0.753 | 0.753 | 0.7548 | 0.7652 | 0.7784 | 0.7731 |
| | 40 | 0.6924 | 0.6868 | 0.6925 | 0.7 | 0.7138 | 0.711 |
| | 50 | 0.6361 | 0.6265 | 0.6357 | 0.64 | 0.6533 | 0.6532 |
| | 60 | 0.5837 | 0.5721 | 0.5831 | 0.5846 | 0.5964 | 0.5988 |
| | 70 | 0.5344 | 0.523 | 0.5339 | 0.5333 | 0.5429 | 0.5469 |
| Rectangule | 10 | 0.9318 | 0.916 | 0.9048 | 0.9143 | 0.9212 | 0.9157 |
| | 20 | 0.8636 | 0.8361 | 0.8246 | 0.8364 | 0.8473 | 0.8408 |
| | 30 | 0.7955 | 0.7622 | 0.7548 | 0.7652 | 0.7784 | 0.7731 |
| | 40 | 0.7273 | 0.6964 | 0.6925 | 0.7 | 0.7138 | 0.711 |
| | 50 | 0.6591 | 0.6345 | 0.6357 | 0.64 | 0.6533 | 0.6532 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | 60 | 0.5905 | 0.5747 | 0.5831 | 0.5846 | 0.5964 | 0.5988 |
| | 70 | 0.5227 | 0.5176 | 0.5339 | 0.5333 | 0.5429 | 0.5469 |
| circle | 10 | 0.8964 | 0.9124 | 0.9048 | 0.9143 | 0.9212 | 0.9157 |
| | 20 | 0.816 | 0.8305 | 0.8246 | 0.8364 | 0.8473 | 0.8408 |
| | 30 | 0.7458 | 0.7553 | 0.7548 | 0.7652 | 0.7784 | 0.7731 |
| | 40 | 0.6822 | 0.6868 | 0.6925 | 0.7 | 0.7138 | 0.711 |
| | 50 | 0.6232 | 0.6234 | 0.6357 | 0.64 | 0.6533 | 0.6532 |
| | 60 | 0.568 | 0.5643 | 0.5831 | 0.5846 | 0.5964 | 0.5988 |
| | 70 | 0.516 | 0.5081 | 0.5339 | 0.5333 | 0.5429 | 0.5469 |
| ellipse | 10 | 0.8752 | 0.8803 | 0.9048 | 0.9143 | 0.9212 | 0.9157 |
| | 20 | 0.7858 | 0.7987 | 0.8246 | 0.8364 | 0.8473 | 0.8408 |
| | 30 | 0.7182 | 0.7331 | 0.7548 | 0.7652 | 0.7784 | 0.7731 |
| | 40 | 0.6654 | 0.6757 | 0.6925 | 0.7 | 0.7138 | 0.711 |
| | 50 | 0.6228 | 0.6234 | 0.6357 | 0.64 | 0.6533 | 0.6532 |
| | 60 | 0.5876 | 0.5695 | 0.5831 | 0.5846 | 0.5964 | 0.5988 |

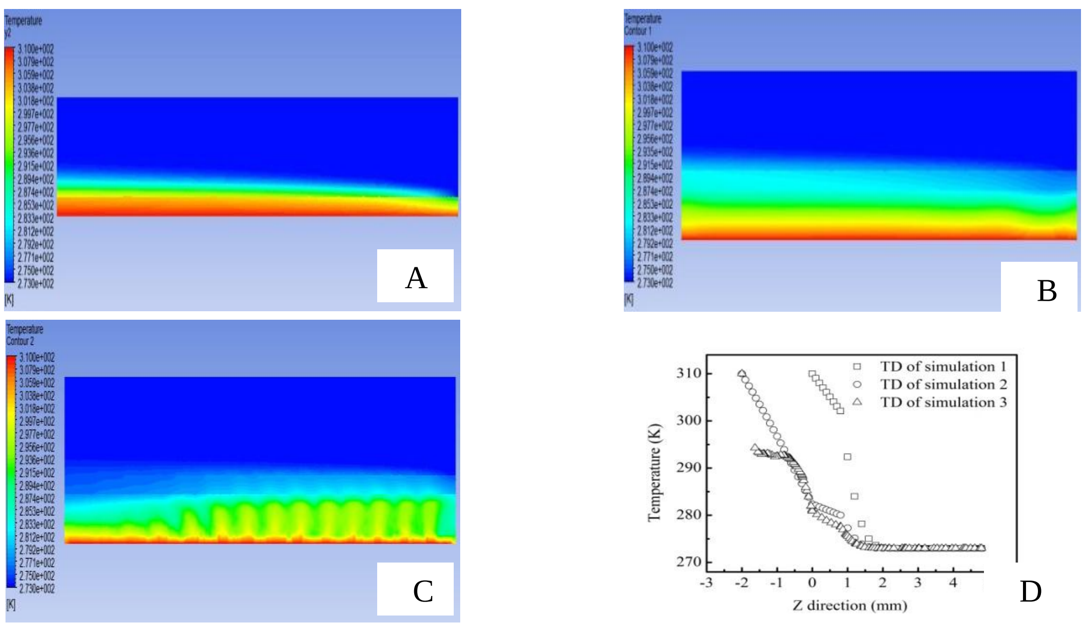



Figure 5.2 Temperature distribution in xz-plane (A) Temperature distribution of simulation 1 in xz-plane at y=2mm; (B) Temperature distribution of simulation 2 in xz-plane at y=2mm; (C) Temperature distribution of simulation 3 in xz-plane at y=2; (D) Temperature distributions of simulations in xz-plane at x=15mm and y=2mm.

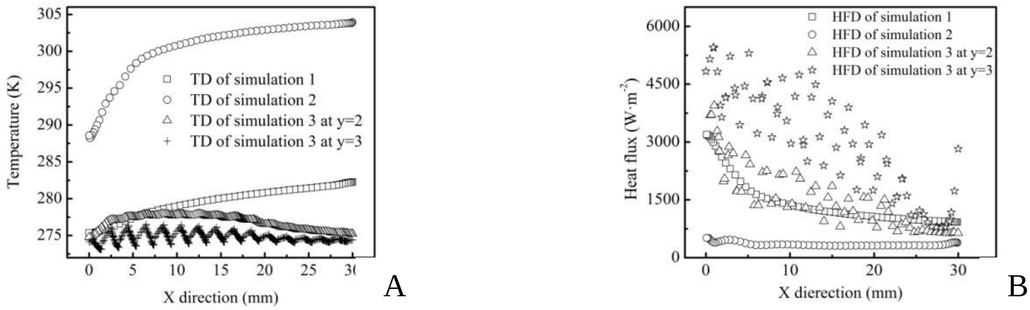



Figure 5.3. Comparison of temperature and heat flux distributions (A) Temperature distributions of simulations in xy-plane at y=2mm and z=0 (upper surface of fabric); (B) Heat flux distributions of simulations through fabric

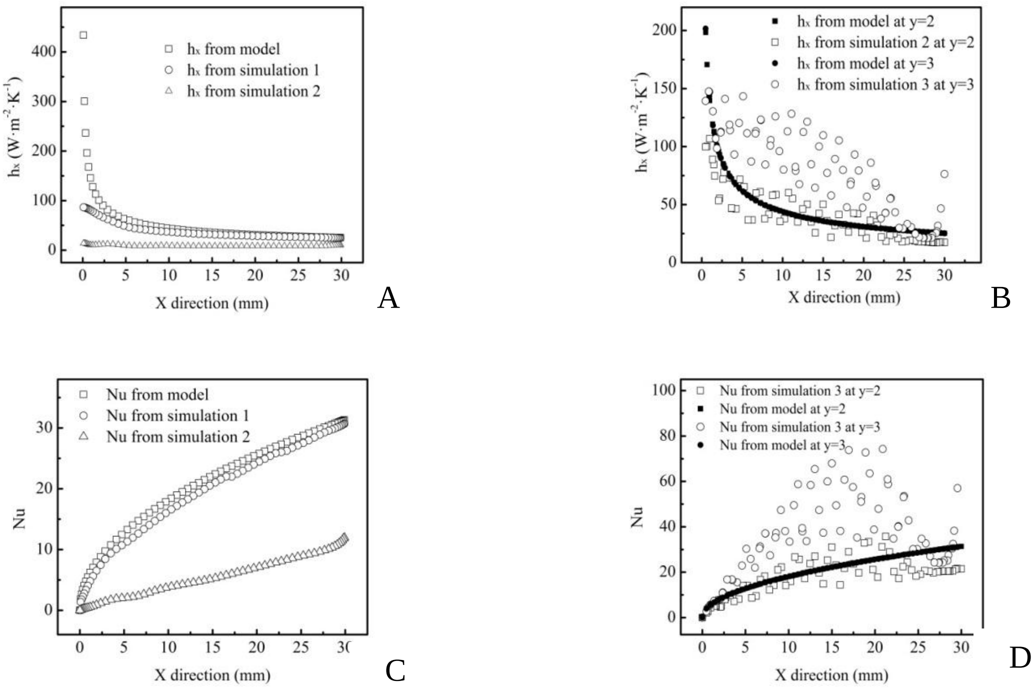



Figure 5.4. comparison of local heat transfer coefficients and Nusselt numbers (A) comparison of local heat transfer coefficient of model and simulation 1 and 2; (B) comparison of local heat transfer coefficient of model and simulation 3 at y=2 and y=3; (C) comparison of local Nusselt number of model and simulation 1 and 2; (D) comparison of local Nusselt number of model and simulation 3 at y=2 and y=3.

In addition, the average heat fluxes through fabrics were obtained by area-weight average method. There were 1346.9 $W \cdot m^{-2}$, 342.3 $W \cdot m^{-2}$, and 2520.4 $W \cdot m^{-2}$ for simulation 1, simulation 2, and simulation 3, respectively. Then, the average heat transfer coefficients of simulations were 36.4 $W \cdot m^{-2} \cdot K^{-1}$, 9.25 $W \cdot m^{-2} \cdot K^{-1}$, and 68.12 $W \cdot m^{-2} \cdot K^{-1}$, respectively. Therefore, the thermal insulation of fabric will be much better when there has air gap between fabric and skin. And the porosity will have a negative effect on thermal insulation when there has air flow motion and the air flow penetrates the fabric.

## 5.2 Results from experiment

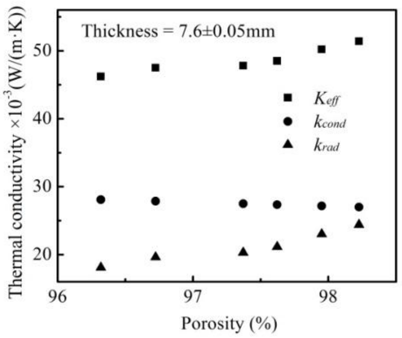



Figure 5.5. Effect of porosity on thermal property of nonwoven fabrics

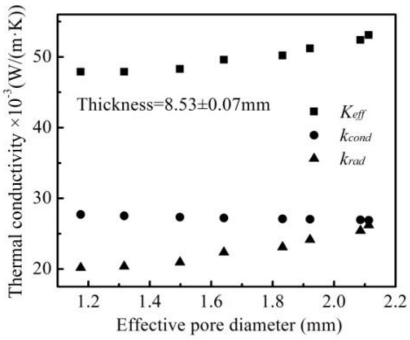



Figure 5.6. Effect of effective pore diameter on thermal property of nonwoven fabrics

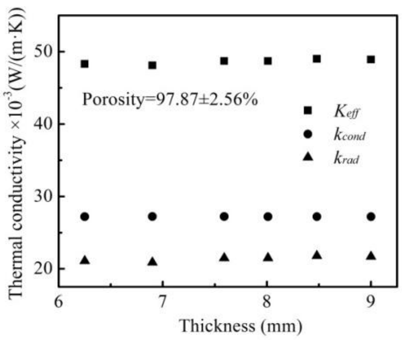



Figure 5.7. Effect of thickness on thermal property of nonwoven fabrics

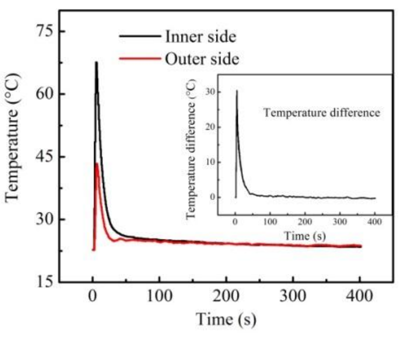
Table 5.2 Air permeability of woven fabrics under different pressure

| Samples | 10Pa (mm/s) | Slope | 20Pa | Slope | 30Pa | Slope |
|---|---|---|---|---|---|---|
| PA | 5.74±0.103 | 0.574 | 12±0.187 | 0.6 | 17.02±0.22 | 5.67 |
| PES | 18.82±0.258 | 1.882 | 36.4±0.69 | 1.82 | 52.48±1.19 | 1.75 |
| Visc | 24.5±1.45 | 2.45 | 45.96±1.87 | 2.3 | 60.3±1.53 | 2.1 |
| Co45 | 61.3±6.35 | 6.13 | 119±13.28 | 5.95 | 174.6±25.26 | 5.82 |
| PP | 133.2±12.29 | 13.32 | 214±8.746 | 10.7 | 316±24.36 | 10.53 |
| Co20 | 740±22.34 | 74 | 1204±51.76 | 60.2 | 1592±31.14 | 53.07 |

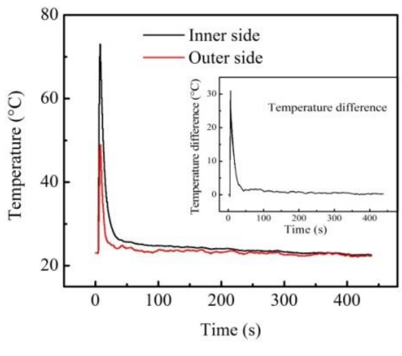
*Note: slope is the quotient of air permeability and pressure gradient, the smaller difference between slopes for the same fabric, the better direct proportional relation between pressure gradient and air permeability.*

Table 5.3 Thermal property of woven fabrics

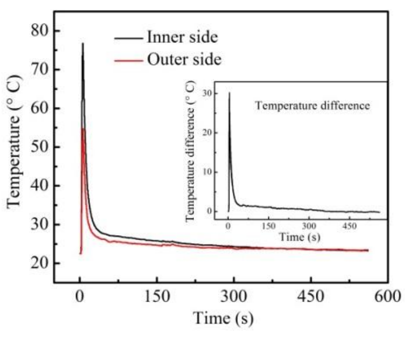
| Samples | Thermal conductivity of fabric $\times10^{-3}$ (W/(m·K)) | Thermal resistance of fabric $\times10^{-3}$ (K/W) | Thermal diffusivity of fabric $\times10^{-6}$ ($m^2$/s) | Thermal conductivity of fiber $\times10^{-3}$ (W/(m·K)) |
|---|---|---|---|---|
| PA | 40.18±1.46 | 8.99±0.829 | 0.0435±0.0024 | 95.16 |
| PES | 31.93±1.32 | 8.77±1.78 | 0.0843±0.02 | 76.67 |
| Visco | 31.25±0.61 | 6.08±0.933 | 0.0413±0.0095 | 55.83 |
| Co45 | 41.19±1.45 | 19.42±2.01 | 0.1132±0.0125 | 214.03 |
| PP | 42.8±0.758 | 18.92±1.03 | 0.1081±0.019 | 162.05 |
| Co20 | 34.56±0.647 | 16.4±1.19 | 0.1613±0.01282 | 211.85 |



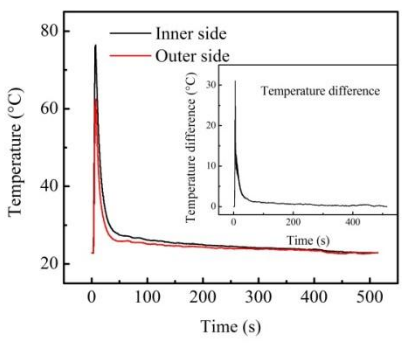
A



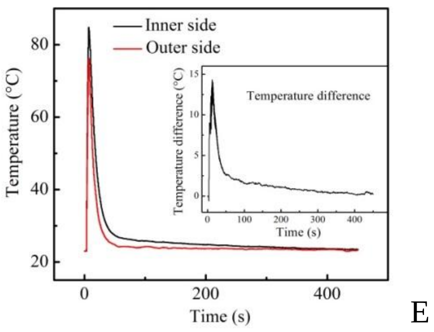
B



C



D



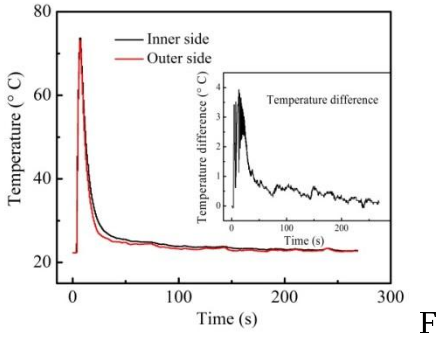




Figure 5.8. Temperature distributions on the both sides of samples (A: PA; B: PES; C: Visc; D: Co45; E: PP; F: Co20)

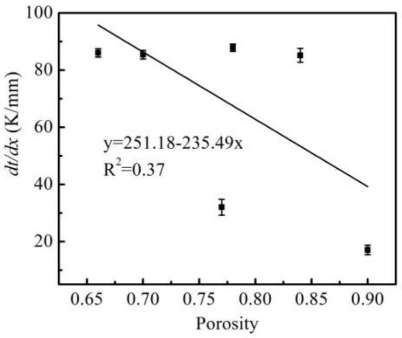



Figure 5.9. Effects of porosity on thermal property of samples

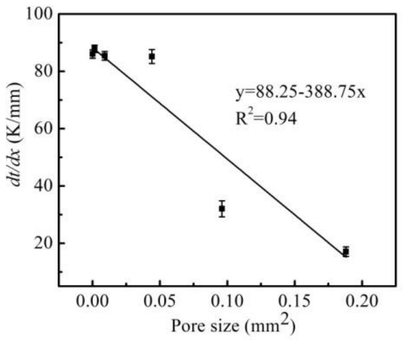



Figure 5.10. Effects of pore size on thermal property of samples

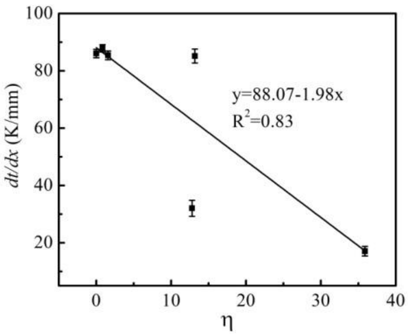



Figure 5.11. Effects of pore's area ratio on thermal property of samples

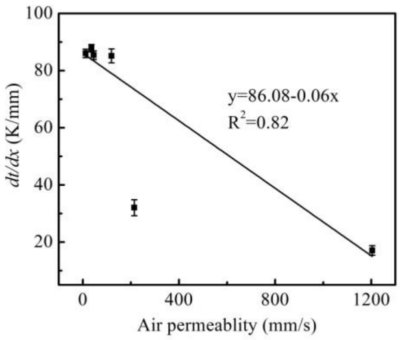



Figure 5.12. The relationship between air permeability and thermal property

# 6 Evaluation of results and new findings

The main contribution of this work is to investigate the thermal property of textiles, which consists of four parts,

(1) Comparison of some widely used analytical models for predicting the thermal conductivity of textiles under conductive heat transfer, and investigation of the factors influencing the thermal conductivity of textiles by numerical method, and some conclusions can be obtained,

Analytical models can provide accurate prediction when the structure of samples is simple; the numerical simulation can provide more accurate results than analytical models', and is more flexible for any complicated structures; the effective thermal conductivity of textile will be lower as the increase of porosity, pore size, and major-axis length, as the decrease of contact area; and also the distribution of pores will influence the thermal conductivity of textiles; therefore, a more delicate model is needed for predicting the thermal conductivity of textile.

(2) Investigation of structure influencing the thermal property of textiles under conductive, convective and radiative heat transfer, and some conclusions are as follows,

Both porosity and pore size influenced the thermal conductivity of textile having very high porosity (>95%) under heat conduction; the effective thermal conductivity of textile was contributed by conductivity heat transfer and radiative heat transfer, and the ratio of radiative heat transfer reached up to 50% to the total heat transfer in some cases.

(3) Investigation of the effect of structure (porosity, pore size, and pore's area ratio) on the air permeability and thermal property of textile under convective heat transfer,

The structure of samples has a big influence in air permeability and thermal property; the pore size and pore's area ratio have more significant effect on air permeability and thermal property then porosity; air permeability is directly proportional to thermal property under convective heat transfer.

(4) Investigation of the impact of structure on the thermal resistance of textile under heat convection numerically,

The numerical simulation of flow and conjugate heat transfer through fabric can be an accurate and reliable method according to the good agreement between the simulation results and a well-known analytical model; the stagnate air gap between fabric and skin plays a positive role in increasing the thermal insulation, and the porosity of fabric has an negative impact on increasing thermal insulation; the local heat transfer coefficients and Nusselt numbers of porous fabrics have big difference, and the skin would have difference thermal feeling at different local area. In addition, more work is needed to be studied in order to investigate the effect of pore size, pore's distribution, the angle between air flow and fabric, and the air flow velocity on the thermal insulation of fabric.

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37. Zhu, F.; Li, K., Determining Effective Thermal Conductivity of Fabrics by Using Fractal Method. *Int J Thermophys* 2010; 31 (3): 612-619.
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39. Matusiak, M., Modelling the thermal resistance of woven fabrics. *J Text I* 2012; 104 (4): 426-437.
40. G, K.; Cassie, A., propagation of temperature changes through textiles in humid atmospheres. part 1: rate of absorption of water vapor by wool fibers. *Trans Faraday Soc* 1940; 36: 445-453.

# 8 List of papers published by the author

## 8.1 Publications in journals

1. **Guocheng Zhu**, Jiri Militky, Yan Wang, Bele Vijay Sundarlal, Dana Kremenakova, study on wicking property of cotton fabric, Fibres & Textiles in Eastern Europe, 2015, 23, 2(110): 137-140.

2. **Guocheng Zhu**, Dana Kremenakova, Yan Wang, Jiri Militky, Study on air permeability and thermal resistance of textile under heat convection, Textile research journal, DOI: 10.1177/0040517515573407.

3. **Guocheng Zhu**, Dana Kremenakova, Yan Wang, Jiri Militky, Study on the thermal property of high porous nonwoven fabrics, industria textila. (accepted)

4. **Guocheng Zhu**, Dana Kremenakova, Yan Wang, Jiri Militky, Temperature change of cotton fabric during liquid adsorption process, International Journal of Clothing Science and Technology. (accepted)

5. **Guocheng Zhu**, Dana Kremenakova, Yan Wang, Jiri Militky, Air permeability of polyester nonwoven fabrics, Autex Research Journal, DOI: 10.2478/aut-2014-0019.

6. **Guocheng Zhu**, Dana Kremenakova, Yan Wang, Jiri Militky, Buyuk Mazari Funda, An anslysis of effective thermal conductivity of heterogeneous materials, Autex Research Journal, vol 14(1), (2014), pp.14-21.

7. R. Mishra, J. Militky, V. Baheti, J. Huang, B. Kale, M. Venkataraman, V. Bele, V. Arumugama, **G. Zhu** & Y. Wang, Textile Progress: The production, characterization and applications of nanoparticles in the textile industry, 2014, Taylor & Francis.

8. **Guocheng Zhu**, Jiri Militky, Yan Wang, Juan Huang, Dana Kremenakova, Comparison of Effective Thermal Conductivity of Hollow Fibers by Prediction Models and FE Method, *Applied Mechanics and Materials,* Vol 440, (2014), pp.3-8.

9. **Guocheng Zhu**, Sayed Ibrahim, Dana Kremenakova, Yan Wang, Simulation of airflow motion in jet nozzle with different geometric parameters, *Advanced Materials Research,* Vol 683 (2013), pp.869-876.

10. Jiri Militky, **Guocheng zhu**, Dana Kremenakova, selected properties of functional materials (charpter 16), 1st ed, ops, czech republic, (2013), pp.207-215.

11. Yan Wang, Jacob Wiener, **Guocheng Zhu**, Langmuir isotherm models applied to the sorption of dyes from effluent onto polyamide nanofibers, AUTEX RJ, vol 13(6), (2013), pp.95-98.

12. **Guocheng Zhu**, Sayed Ibrahim, Dana Kremenakova, The optimization of experimental parameters for Jet-ring spinning, *Vlakna a Textil*, Vol 19 (2012), pp.60-67.

13. **Guocheng Zhu**, Sayed Ibrahim, Dana Kremenakova, Optimization application of air-jet nozzle in ring spinning system, *world journal of engineering*, Vol 9 (2012), pp.455-461.

## 8.2 Contribution in conference proceeding

1. **Guocheng Zhu**, Dana Kremenakova, Yan Wang, Huang Juan, Mohanapriya Venkataraman, Jiri Militky, Evaluation of thermal conductivity of hollow fiber padding by experiment, TexSci 2013, Sept. 23-25, Liberec, Czech Republic. (ISBN 978-80-7372-989-9)

2. **Guocheng Zhu**, Jiri. Militky, Yan Wang, Lukasova V., Dana Kremenakova, Prediction of hollow fibers effective thermal conductivity, STRUTEX 19, December 2012, Liberec, Czech Republic. (ISBN 978-80-7372-913-4).

3. **Guocheng Zhu**, Dana Kremenakova, Jana Grabmullerova, Mazari Adnan Ahmed, Yan Wang,Thermal property of nonwoven fabrics from different testing methods, ICCE-22 July 13-19, 2014, Malta.

4. **Guocheng Zhu**, Jiri Militky, Yan Wang, Dana Kremenakova, Study on wicking property of cotton fabric, the fiber society spring, May 21-23, 2014, liberec.

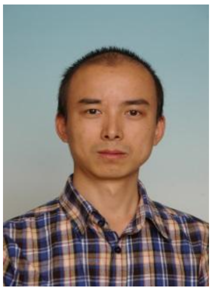
5. **Guocheng Zhu**, Dana Kremenakova, Air permeability and thermal resistance of textile under heat convection, september 16-19, 2014, Světlanka.

6. **Guocheng Zhu**, Dana Kremenakova, Yan Wang, Jiri Militky, Numerical simulation of coupled fluid flow and heat transfer of fabric, December 1-2, 2014, Liberec.

## 8.3 Quotation

Eventual citation of the leading citation databases (Web of Science, Scopus).

# Curriculum Vitae




| | |
|---|---|
| Name | Guocheng Zhu |
| Gender | Male |
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| | |
|---|---|
| Ph.D. Degree | in Textile Material engineering (02/2011- present), Technical University of Liberec, Liberec, Czech Republic |
| MSc. Degree | in Textile Material and Design (09/2007-06/2010), Wuhan Textile University, Wuhan, China |
| B.S. Degree | in Machinery Design, Manufacturing and Automation (09/2003-06/2007), Wuhan Textile University, Wuhan, China |

**Honor and activities**

1. Excellent Graduates of Wuhan Textile University in 2010
2. Three University Scholarship Awards during 2008-2009
3. The Bachelor Thesis titled “The Pinprick Structure Design of Nonwovens Needle Machine” was awarded the third prize in Hubei province in 2007
4. Instructed six undergraduates who accomplished their graduation thesis, and five of them were honored with distinguished paper.

# Brief description of the current expertise, research and scientific activities

Heat and moisture transfer in fibrous structure textiles, nanomembrane filtration, and composites;

Numerical simulation in fluid dynamic, static/dynamic mechanic, conjugate flow and heat transfer.

**Doctoral studies**

| | | |
|---|---|---|
| Studies | Textile Engineering | |
| | Textile Materials Engineering. | |
| Exams | Theory of Spinning Processes | 3. 1. 2011 |
| | Theory of Yarn | 11. 10. 2011 |
| | Numerical Methods | 5. 3. 2012 |
| | Heat and Mass Transfer in Porous Media | 15. 6. 2012 |
| SDE | State Doctoral Exam completed on | 13. 3. 2014 |
| | with the overall result passed | |

## Record of the state doctoral exam

TECHNICKÁ UNIVERZITA V LIBERCI
Fakulta textilní

# ZÁPIS O VYKONÁNÍ STÁTNÍ DOKTORSKÉ ZKOUŠKY (SDZ)

*Jméno a příjmení doktoranda:* **Ing. Guocheng Zhu**

*Datum narození:* **18. 12. 1984**

*Doktorský studijní program:* **Textilní inženýrství**

*Studijní obor:* **Textilní materiálové inženýrství**

*Termín konání SDZ:* **13. 3. 2014**

**prospěl** ~~**neprospěl**~~

*Komise pro SDZ:*

| | | *Podpis* |
|---|---|---|
| Předseda: | prof. Ing. Jiří Militký, CSc. | |
| Místopředseda: | prof. Dr. Ing. Zdeněk Kůs | |
| Členové: | prof. Ing. Jaroslav Šesták, DrSc., Dr.h.c. | |
| | Ing. Blanka Tomková, Ph.D. | |
| | Ing. Petra Komárková, Ph.D. | |

V Liberci dne 13. 3. 2014

*O průběhu SDZ je veden protokol.*

# Recommendation of the supervisor

## Opinion of the dissertation supervisor

## Topic: Study of thermal property of textile

## Author: Zhu Guocheng, MSc.

Dissertation contains review which is specified by the definition and the main goals of this work. It includes the study of thermal conductivity of textiles by numerical method, thermal property of highly porous nonwoven fabrics, air permeability and thermal resistance of textiles under heat convection and 3D simulation of laminar flow and conjugate heat transfer through fabric. Chapter "Investigation of the temperature changes of textiles during the adsorption process" mentioned in main goals is not included. Dissertation is supplemented by list of symbols, list of figures and list of tables. Each chapter is thoroughly discussed and results are summarizes in conclusion and future work is described, too. 106 references and 15 self-citations were used during creation of dissertation work. The Czech translation of the abstract should be preceded by the word "proudění" and not "sálání".

Definition of the thermal conductivity of textiles by heat conduction, convection and radiation, their measurement methods and numerical simulation methods are described in review. There should be other methods for measurement of textile thermal conductivity as Togmeter, Sweating guarded hotplate, PSM, Thermal manikin, etc. included in review. Textile thermal comfort unit "clo" and its connection with thermal conductivity and resistance should be mentioned.

In second part of dissertation effective thermal conductivity of textiles under heat conduction by numerical method was simulated and compared with result based on Fourier´s law and with results obtained by analytical methods. Influence of volume and pores shape, size, major axis length, distribution and contact area on the thermal conductivity was described. A very good prediction of thermal conductivity under heat conduction by series/parallel model and simulation method was found, maximum difference between them was 8,45%. It is known that there is strong correlation between the volume porosity and the thermal conductivity, but this work showed, that other pore parameters must be considered to this study. Pore distribution should be mathematically described in this part.

In third part of dissertation, thermal conductivity of high porous nonwoven fabrics created from hollow fibers is discussed. It is discussed that contribution of heat transfer not only by conduction, but also by convection and radiation, and effective thermal conductivity is important to be calculated. For measurement of fiber thermal conductivity, composite samples with fiber bundles were used. Influence of fabric porosity, pore size and thickness on the effective thermal conductivity was studied. This part could be more clearly described. It is well known that thickness plays most important role in relation with thermal resistance. Citation of equations are not in order, the equations no (7) and (8) are not included in the text.

In fourth chapter new method for measurement of thermal resistance of textiles under heat convection is proposed. Influence of volume and areal porosity, pore size and air permeability on the thermal difference measured on the both sides of samples was evaluated. There should be repeatability and reproducibility of measurement evaluated. Group of textiles was created from different materials and with different construction. Description of some yarns and fabrics parameters and technology is missing. Relationship between volume and areal porosity of woven fabric should be described. What is the porosity of the fabrics created with the same construction and made from various types of fibers, e.g. cotton and polypropylene?

In the last chapter 3D numerical simulation of laminar flow and conjugate heat transfer through fabric was described. Heat transfer coefficient and Nusselt number of fabrics in different conditions under heat convections was investigated. Comparison between simulation methods and analytical models were described. (General equation for Nusselt number (5.3) is second time described see chapter 1, equation(1.7).).

In conclusion I can say that in this dissertation work, simulation models were created describing particularly the transfer of heat (thermal conductivity / resistance) by conduction and convection through the chosen textile structures and these models were compared with the analytical models. New methodology for measuring convective heat transfer was proposed and investigated. In this work the main parameters of fabrics that affect the specified thermal properties were found and discussed.

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The dissertation work meets the specified objectives and I am recommending it for positive defense realization.

19th April 2015

Assoc. prof. Dana Kremenakova, PhD.

# Rewievs of the opponents

*Prof.* ***Jaroslav Šesták****, MEng., PhD., DSc, dr.h.c..*
*Senior Scientist, the Czech Academy of Sciences in Prague*
*Program Auspice, West Bohemian University, Institute of Interdisciplinary Studies*
*Visiting professor, New York State University, Business School in Prague*

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Technická universita v Liberci
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*Prague April 10$^{th}$, 2015*

**Subject**: The opponent report on the dissertation work by **MSc. Guocheng Zhu** **"Study on the thermal property of textile experimentally and numerically"**.

The dissertation consists of 99 pages and CD of data files containing 15 self-citations and 106 references. The text is written clearly and the author shows a good overview of the concept of the current state of solution problematic, which in the recent years acquired a considerable amount of theoretical work and moreover experimental results revealing the leading position of the TUL university.

The work is written in English (which gives it the necessary internationalist character, which I do welcome in general), is suitably designed and straightforward readable though the text is somehow demandable to be fully understood in details. Besides the conclusion I am missing at the dissertation a Czech and English written end-summary as well as discussion needed on the definition of dissertant personal opinion for the processes optimization, including estimates of the prospects for further development, which is not enough in the paragraph of future work. The list of symbols, abbreviations and figures is usually reserved at the ending position.

At my review opening I have to admit that I am not an expert in the entire field of textiles but I found some resemblance with my experience in the study of thermal properties of some extreme materials such polymeric foams and inherent micro- and nano- specificity of heat transfer. Theoretical basis of material's micro-behavior as the area of expertise stays thus factually analogous to various resources.

The textile properties lays on the boundary between macro- and micro-perform thus the inherent heat transfer in micro-scale (i.e.: Volz S, Micro-scale and Nano-scale Heat Transfer. Springer, Heidelberg 2007) can vary from that in a classically assumed macro-scale (i.e.: H.S. Carslaw, J.C. Jeager. Heat Conduction in Solids. Cleradon, London 1959) becoming dependent on other phenomena such as ballistic effects, scattering, thermal photon tunneling, and relative heat transfer in participating media, stationary versus dynamic heat conductivity and finally even impact of Brownian motion many of which may be of theoretical and numerical interest.

Measurement of thermal conductivity in textiles bears it specificity and tradition (e.g. Hess, correct ref. 2). Potentiometry testing looks for a thermal gradient along a sheet which can be questioned of its rather complex setup while a periodic tester provides the measurement of diminishing amplitude. Whatsoever, investigated materials habitually involve non-equilibrated states where the inherent heat treatment may affect the minute material properties. Most wanted procedure would be a joint determination of threefold data such as specific heat, $c_p$, thermal diffusivity, a, and thermal conductivity, $\lambda$, but mostly a single parameter is resolved and then the crucial problem of consequent data consistency from different sources must be solved. A thermometric procedure, which is quite similar to the convenient relaxation calorimetric method for measuring heat capacities are thus the pulse-heating technique.

Heat pulse or laser flush method for the determination of diffusivity was well inspected by Slovak Kubičár (L. Kubičár. Pulse Methods of Measuring Basic Thermophysical Parameters. Elsevier, Amsterdam 1990) and commercially produced apparatuses by the German Netzsch instruments are available at different laser flush modes (LFA 427, 437 or 447) using various measuring set ups and sample arrangements. This contact-less and non-destructive method is of a simple geometry, with easy sample preparation and wide range of temperature applicability, employing different (even very small) sample size of a range of conductivity down to isolators..

Let me present some further remarks and inquiries.

In pulse or periodic heating tests the inserted heat is not absorbed by the sample immediately but gets its inertia due to the material thermal capacity. Can you explain it?

Would be a commercially available pulse technique (see above) applicable in the business of textiles?

Would be the micro-scale properties (see above) of your interest in the domain of nano-textiles?

In the world of structured polymers the relative conductivity of porous foams plotted against the apparent porosity exhibit a concave figure at one upper side of lower porosity it is decisive conduction while at the other upper end become dominant radiation. Can you extrapolate it to textiles? (see Figs. 2.9 to 2.12).

Despite a numerous citations there are many other sources, for example and for further eventual interest

J. Krempaský Measurements of Thermophysical Quantities, VSAV, Bratislava 1969

R. Černý, P. Rovaníková. Transport Processes. SponPress, London 2002

J. Kosek etal. Modeling of Transport and Transformation Processes in Porous and Multiphase Bodies. *Advances in Chemical Engineering,* Volume 30, 2005, 137–203

J. Kosek etal. Conduction-radiation Heat Transfer in Closed-cell Polymer Foams. http://avestia.com/HTFF2014_Proceedings/papers/162.pdf

J. Kosek etal. Mathematical Modeling of Coupled Conductive and Radiative Heat Transfer in Polymeric Foams
http://www.esco2014.femhub.com/docs/ESCO2014_Book_of_Abstracts.pdf#page=78

V. Novák , P. Kočí , F. Štěpánek , and M. Marek. Integrated Multiscale Methodology for Virtual Prototyping of Porous Catalysts. *Ind. Eng. Chem. Res.*, Vol. 2011, *50* (23), pp 12904–12914

In conclusion I am satisfied with the presented text and its scientific and expert contents ranking the dissertation in the standard average of comparable presentations within similar material specializations.

The work meets the requirements for a doctoral thesis specifiled both by the Ministry of Education, Sport and Young (MSMT) and the Technical University in Liberec, and therefore recommending the work for an appropriate support and positive defense realization as well as the dissertant to be granted by a PhD degree.

Best regards,

Yours

Jaroslav Šesták
Section of Solid-State Physics
Institute of Physics, v.v.i., AV CR

**Technical University of Liberec**

**Ph.D. Thesis Review for the degree of Doctor of Philosophy**

**Opponent Report**

**Ref. No.: TUL-15/4814/005245**

**Candidate: Guocheng Zhu, MSc.**

**Tutor: Doc. Dr. Ing. D. Křemenáková**

**Subject: Textile materials engineering**

This opponent review was based on the formal invitation letter of the dean of the faculty Ing. Jana Drašarová, Ph.D. ref. no. TUL-15/4814/005245 dated 23.2.2015.

Please comment on:

1. The nature and the scope of the investigation:

The thesis presented deals with interesting scientific and technical problem of the simulation and experimental verification of the thermal properties of textile materials. Thesis has both the experimental as well as the theoretical background, however the second theoretical orientation was dominant. Different theoretical simulation approaches were employed to allow the comparison of logically selected both the pore size distributions as well as pore shape distribution patterns.

2. The contribution made to the subject field, including the extent to which the thesis contains original, publishable work or merit:

Obtained results are the original contribution to the studied problem of non-destructive characterization of polymer composites and fabrics. Author in his thesis has vigorously analysed and compared theoretical modelling of thermal properties and has correlated them with the experimental results obtained on homemade heat transfer measuring apparatus and compared the results with the structural arrangements of the tested fabrics as well as the composites. His results brought a new valuable knowledge to the applied materials science and engineering study field which might be later published in scientific journals.

3. The quality of the submission and, where appropriate, of the investigative work described:

Current version of the Ph.D. thesis is relatively well written with minimum English language style as well as grammar errors. However there were found sometimes minor stylistic errors in the text, e.g. p. 48 … due to the small <u>different</u> of thermal … etc. For readers not working in the area of simulation and data processing should be more appropriate to describe more in detail the orientation of the samples, the direction of fibres in the material etc., to make it clear also for not a very professionally skilled reader in this subject. With respect to the fact, that Chapter 2 is comparing different selected models and modes of calculation of the thermal properties, the conclusion (1) of the Chapter 2.5 given by the applicant should be verified by the experimental testing.

As mentioned above, more precise and in detail description of the graphs, charts and schemes should be needed to allow easy understanding of the message given by the author, e.g. p.36 missing description of the colours meaning of the individual circles, p. 64. Fig. 4.3 missing right hand y-axis description and units, p.65 figs. 4.4 to 4.6 missing materials sample identification, pp. 71-72 not clear legends with proper samples identification in figs. 4.8 to 4.11 and finally need of more precise conclusions specification in Chapter 4.4 will be more appropriate and expected than ones which are being offered by the author. With respect to the references cited in the text, the total 106 references were cited, majority relevant to the subject.

I have checked the publication activity of the applicant in the WOS as well as in SCOPUS databases, where in the first case I have found 2 records and in the second case 5 records, thus confirming relatively high publication activity of the applicant. In combination with the declared submitted/accepted manuscript, the overall publication activity of the applicant is exceeding the average, and can be ranked as the highly active excellent grade.

I have not found any other formal as well as any logical or knowledge based errors in the thesis.

That is why I am fully supporting submission of the thesis as a base for final examination/defence. Ph.D. thesis presented according to my meaning fulfils the highest quality requirements for PhD thesis.

Signed: Prof. Ing. Lubomír Lapčík, PhD. Date: March 16, 2015