Thermal Insulation of High Performance Fibrous Materials

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SUMMARY OF THE THESIS

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Abstract

This research was an endeavor to study the thermal insulation behavior of high performance fibrous materials. Based on the objectives set for this research, a detailed literature review was conducted on existing literature. The literature review provided necessary theoretical background, baseline data and insights into similar research conducted in the past. It assisted in understanding the gaps and limitations of the past research. The objectives were crystallized to add to this knowledgebase and also address a few of the identified gaps and limitations. The broad objectives of this research were to analyze the thermal measurement techniques used for insulation materials at different temperatures; to conduct a comparative analysis of thermal properties of different types of insulating materials; explore new techniques to conduct thermal measurements by fabricating new instruments; correlate results from conventional and unconventional experimental methods; study and analyze convective heat transfer through insulation material; study thermal behavior of electrospun PUR and PVDF nanofibrous layers embedded with silica aerogel; modeling and simulation of heat transfer by convection for aerogel treated nonwoven fabrics for the research conducted. A range of samples made of different materials, composition and thicknesses were chosen. Polyester and polyethylene nonwoven composite fabrics of varying thicknesses embedded with amorphous aerogel, struto nonwoven fabrics and a few commercially available insulation materials were used as samples. The type of aerogel used was hydrophobic amorphous silica aerogel which was most suitable for application in textile material. Flexible electrospun nanofibrous layers embedded with silica aerogel was produced via electrospinning process. The aerogel particles were also added during thermal bonding of standard non-woven web. The struto nonwoven structure was produced in the laboratory. Thermal properties of the electrospun nanofibrous layers embedded with SiO_2 aerogel were analyzed. These studies were carried out under subzero temperature conditions and differ widely from commonly used conditions. Various conventional and unconventional techniques were used in additional to fabrication of new devices for thermal measurements. The data generated from the experiments were validated against established theories and found to adhere to theoretical principles. The data was statistically analyzed and various conclusions were drawn based on the results.

Keywords: Thermal measurement, Insulation materials, Heat transfer, Aerogel, Electrospinning.

Abstrakt

Oblečení chrání lidstvo před extrémními projevy přírody. Kromě poskytování ochrany, je také nutné, aby textilie zajišťovaly fyziologické komfort. Typ a uspořádání vláken v textiliích, vlastnosti okolního vzduchu a fyziologické projevy nositele jsou hlavní složky tepelné pohody. Základní konstrukční parametry vícevrstvého oblečení jsou tloušťky, plošné hmotnosti a hustoty vláken jednotlivých vrstev. Různé tkaniny a povrchové úpravy by měly být studovány za účelem optimalizace tepelných vlastností vysoce výkonných textilií. Aerogel na bázi oxidu křemičitého, objevený Kistlerem v 1930, je pevná látka s nízkou hustotou, nízkou optickou indexem lomu, nízkou tepelnou vodivostí, nízkou rychlosti šíření zvuku, vysokou měrnou povrchovou plochou a nízkou dielektrickou konstantou. Vzhledem ke svým super-izolačním vlastnostem a speciálním přenosem tepla v komplexní nanoporézní struktuře, jde o velmi slibný materiál pro vysoce funkční textilie. Měření tepelných vlastností textilních materiálů je důležité pro vyhodnocení použitelnosti textilií v extrémních povětrnostních podmínkách. Zařízení používaná pro měření tepelných vlastnosti textilií však pracují na základě různých fyzikálních principů a různých podmínek, což limituje možnosti jejich přímého porovnání. Cílem tohoto výzkumu bylo porovnání různých metod měření tepelných vlastnosti textilií pro různé kombinace textilních materiálů a povrchových úprav; prozkoumání možností nové metody pro měření tepelných vlastností textilií při různých teplotách a popis výsledků s ohledem na jednotlivé typy (zejména vedení a proudění) přenosu tepla. Pro tepelná měření byly vybrány různé typy tepelně izolačních textilií, připravených v laboratorním měřítku nebo volně přístupných na trhu. Byly porovnány tepelné vlastnosti těchto materiálů s ohledem na tepelně izolační vlastnosti při extrémních klimatických podmínkách (teploty pod bodem mrazu). Byly připraveny speciální měřicí systémy pro měření za těchto nestandardních podmínek. Do studie bylo zahrnuto zkoumání mechanismů přestupu tepla přes vláknité izolační vrstvy, kde je průměr vláken je menší než 1 mikrometr. Tento výzkum je příspěvkem k selekci měřicích technik a nalezení vhodných izolačních struktur vhodných pro tyto extrémní podmínky. Zjištění uvedená v této studii jsou zajímavá jak pro další výzkum, tak i pro praktické aplikace. Mohou být použita pro další výzkum v oblasti aerogelem ošetřených netkaných textilií, přenosu tepla přes porézní média, výrobu nestandardních měřicích zařízení využívající alternativních technik pro tepelná měření a v neposlední řadě pro realizaci simulačních výpočtů pomocí různých matematických a výpočetních modelů.

Klíčová slova: Měření tepelných projevů, Izolační materiály, Přenos tepla, Aerogel, Elektrostatického zvlákňování.

Summary

1 Introduction

Textile materials have found a range of applications in the field of thermal insulation. Thermal insulation is an important factor for estimating physiological comfort for the application area. Combination of different types of fabrics, with various coatings and treatments, are being studied to understand and improve the effectiveness of textile materials as thermal insulators. In extreme cold applications, the role of the middle layer in multilayer clothing is to protect the human body against chilling. Different kinds of fibrous materials such as traditional nonwovens are used as the middle thermal insulating layer. Nonwoven fabrics are important components for good thermal insulation of the body from the surroundings, and they offer both space and weight savings [1]. The important constructive parameters are thickness, weight per unit area and packing fraction p.f., which is the ratio between the bulk density of fibrous structure samples and of the same sample if it was made up wholly from the same polymer [2]. Thermal insulation properties are determined by the physical parameters of fibrous structures as well as the structural parameters [3]. Heat transfer from the man's body to the environment is not just a simple conduction through a thick layer of material of constant insulation value. Moisture plays a very prominent role in the transfer of the energy, and a role that changes with activity. In addition to transfer of latent heat by diffusion through the spaces of various materials, water vapor may be absorbed by the fibers giving rise to a further exothermic change, and the thermal conductivity of the wet fibers then becomes very different from that of the dry fibers. When the human ceases the activity which caused sweating, they lose heat more rapidly through the wet insulation, than through the same insulation when dry, and this may cause chilling. These problems with moisture are difficult to deal with while designing efficient cold weather clothing. Inspite of improvements made in cold weather clothing over the past two decades, users at extreme environments still suffer from lack of comfortable and effective clothing at affordable cost. Therefore, an alternative solution must be found. To achieve this, a close examination of heat and moisture transfer mechanism is required. A thorough understanding of these mechanisms is essential before advances can be made in materials and clothing design. The materials of good thermal insulating properties as used for cold weather clothing, review the methods of measuring the equations for the effect of variables on the heat and moisture transfer mechanisms [4]. Heat is a form of energy that can cross the boundary of a system. Heat can, therefore, be defined as “the form of energy that is transferred between a system and its surroundings as a result of a temperature difference”. Heat is usually referred to in thermodynamics through the term “heat transfer”, which is consistent with the ability of heat to raise or lower the energy within a system. There are three different modes of heat flow in porous media are conduction, convection and radiation. All three modes of heat flow rely on a temperature difference for the transfer of energy to take place. The greater the temperature difference the more rapidly will the heat be transferred. Conversely, the lower the temperature difference, the slower will be the rate at which heat is transferred. When discussing the modes of heat transfer it is the rate of heat transfer Q that defines the characteristics rather than the quantity of heat. Although two, or even all three, modes of heat flow may be combined in any particular thermodynamic situation, the three are quite different and will be introduced separately [5].

Silica aerogel is a low-density, highly porous material, known for its super-insulating characteristics. Heat transfer phenomenon in silica aerogel is associated with its complex nanoporous structure [6, 7]. Heat flow in porous media is the study of energy movement in the form of heat which occurs in many types of processes. The transfer of heat in porous media occurs from the high to the low temperature regions. Therefore a temperature gradient has to exist between the two regions for heat transfer to happen. It can be done by conduction (within one porous solid or between two porous solids in contact), by convection (between two fluids or a fluid and a porous solid in direct contact with the fluid), by radiation (transmission by electromagnetic waves through space) or by combination of the above three methods. Electrospinning is a simple and low-cost method for making polymer and ceramic fibers with superfine diameters [8-10]. In recent years, it has attracted an increasing interest in the electrospinning technique owing to the promising properties of the electrospun nanofibers. Various structured and assembled nanofibers have been developed via electrospinning. Recent advances in the technology of producing nanofibers have revealed a gap in our knowledge about the heat transfer behavior of low-density nanofibrous layers. Understanding heat transfer through nanofiber structures will allow us to exploit the unique properties of polymer nanofibers for applications such as cold weather clothing and hand wear, sleeping bags, and tent liners, food service refrigeration and storage equipment [4].

2 Purpose and the aim of the Thesis

The purpose of this research is to study the thermal behavior of high performance textiles. This was expected to be done by studying various combinations of insulation materials, battings and coatings, explore new methods to measure thermal measurements at various temperatures and seek further understanding of conductive heat transfer. Compare the thermal properties of insulating materials to identify the one best suited for thermal insulation applications at subzero temperature. The research could help in identifying the best insulation material and the best means to measure its efficacy. The major objectives of this research are as follows:

2.1 Comparative Analysis of Thermal Measurement Techniques

To analyze the thermal measurement techniques used for insulation materials. To analyze and compare the thermal properties of the insulation materials produced in our laboratories and selected from the market. This comparison will enable us to choose the best insulation material and study its application for extreme temperature conditions.

2.2 New Method and Fabrication of Instruments for Thermal Measurements

To explore new experimental methods and to fabricate new instruments to study the thermal properties of textile fabrics under extreme temperatures (subzero). The major objective was to develop new methods and new equipments to test the samples by conductive and convective heat transfer at extreme temperatures.

2.3 Correlation of Theoretical Model and Experimental Measurements

To correlate conventional and unconventional thermal measurement techniques which are different in conception. Correlation of theoretically calculated data and measured data will provide further insights into efficacy of various techniques for thermal measurements.

2.4 Study and Analyze Convective Heat Transfer through Insulation Material

To understand the convective heat transfer phenomena through insulation materials. In this regard, different techniques like particle image velocimetry (PIV) and laboratory set-up equipments are to be used.

2.5 Electrospinning of PUR and PVDF Nanofibrous Layer with Silica Aerogel

To understand the heat transfer behavior of low-density nanofibrous layers. Understanding heat transfer through nanofibrous layers embedded with silica aerogel structures will allow us to exploit the unique properties of polymer nanofibers for high performance textile applications. To study the mechanisms of heat transfer through fibrous insulation where the fiber diameter is less than 1 micrometer (μm).

2.6 Modeling and Simulation of Heat Transfer

To develop suitable computational models to simulate and predict the insulation behavior of nonwoven fabrics without and with aerogel. The results of simulation to be correlated to experimental measurements for validation.

3 Overview of the current state of the problem

Measurement of thermal properties of textile materials plays an important role. A number of instruments have been developed for this purpose. These instruments can broadly be categorized as steady state measurement and transient measurement devices. Thermal resistance is commonly measured using steady state method and thermal diffusivity in the transient state method. Study of recent developments show that further studies have been conducted to understand the transient properties of fabrics than the steady state aspects. Hence, sweating plates and copper manikins are being increasingly used instead of simple hot plate or cylindrical devices. However, a measurement based on the standardized steady-state dry heat transfer method has its own advantages in experimental simplicity and low equipment cost. Research is ongoing to achieve understanding of heat transfer principles through fabrics and a number of theories have been put forth to understand and predict the steady state thermal properties of textile materials [11]. As part of review of existing literature [13-16] many papers devoted to thermal insulation, comfort properties of clothing and to the related experimental techniques and measurement methods were reviewed. In addition, several existing standard procedures and testing methods have been developed in order to specify fabric IR properties [12, 13] . Some of the proposed approaches are based on the establishment of a steady-state thermal conductivity regime where an electric heater provides a temperature field in a given sample [14] . In addition, other experimental devices like the “hot disk” [15] and the FRMT [16] have also been proposed in recent years to test the thermal comfort of textile fabrics . These have been successfully applied [4, 17] to the characterization of several kinds of textile fabrics, including the effect of different fabric covering factors and finishing agents. Two such commercially available devices are (1) Thermolabo KES-FB7 system developed by Kawabata [18] and (2) Alambeta apparatus built by Hes and Dolezal [19, 20]. The former allows the measurement of the textile thermal contact properties which enter into the definition of the so-called “warm/cool feeling”. The measurement protocol of thermal and transpiration properties is coded in the European Standard UNI EN 31092 [21]. This code is based on the use of a steady-state device – the so-called “Skin Model” – simulating the amounts of heat and humidity exchanged between the human body and the external environment through the clothes worn. However, the methods employed have the disadvantage of measuring the fabric surface temperature in a single point, and then assuming a uniform temperature distribution over the textile surface. This is not the case for fabrics characterized by low covering factors showing highly variable temperature values over their structure [22]. It is important that the standard measurement techniques are studied to understand their strengths and weaknesses and also fabricate new equipments to compliment or replace existing measurement techniques and equipments. Literature searches on the subject of submicron fibers in thermal insulation reveal no fundamental or applied work using polymer nanofibers for thermal insulation applications.

4 Methods used, Studied Materials

In this study, 50:50 ratio compositions of six polyester/polyethylene non-woven fabrics treated with aerogel were used. Polyester is the most versatile, most cost effective and most widely used fiber in various applications. It is perfect for any application where a flexible non-woven fabric is required. It is also often supplied as the waterproof material and insulator for the winter clothing. It retains the physical properties when wet and stays extremely stable during humidity changes. This strong and light material resists moisture, staining and chemical attack. Polyethylene has excellent chemical resistant, impact strength and electrical properties, as well as low water absorption, this tough and flexible material is ideal for non-toxic skin contact, and is perfect for clothing. The type of aerogel used was hydrophobic amorphous silica aerogel which is most suitable for application in textile material which provides the super insulating properties of silica aerogel in a flexible form. It is excellent for ambient and sub-ambient insulating applications. The aerogel particles were added during thermal bonding of the non-woven web. The samples were chosen in six different thicknesses as are widely used in most textile insulating applications. These thicknesses are commonly used for insulation of clothing, tents and buildings. Sample H1 is Needle punched struto nonwoven structure having One layer of PP web (Top layer) + One layer of spunbond PP web having melt blown polyamide nanofibers on both sides (Middle layer)+One layer of PP web (Bottom layer). Sample H2 is Needle punched struto nonwoven structure having one layer of PP web (Top layer) + Two layers of spunbond PP web having meltblown polyamide nanofibers on both sides (Middle layer)+One layer of PP web (Bottom layer). Sample M1 was purchased from Elastic Gros Braun patent no. M123A2046 and Sample M2 were purchased from POLARTEC with 100% polyester and 100 gsm alpha insulation. Silica aerogel powder and granules were purchased from Cabot aerogel Corp. Polyurethane (PUR) and Polyvinylidene Flouride (PVDF) was used from the CxI lab (nanocenter, TUL, Czech Republic). To obtain an indication of the effect of areal density on thermal properties, fabrics with comparable densities in different thicknesses and their corresponding weights were measured. The density difference in samples may be attributed to the fabric structure and also in aerogel treated nonwoven fabrics the percentage of aerogel particles present in the fiber.

4.1 Scanning Electron Microscope (SEM) and Confocal Microscope

The non-woven fabric samples were characterized using SEM (VEGA TESCAN Inc. USA) at 30 kV and confocal microscope (OLYMPUS Confocal Scanning IR Laser Microscope, LEXT LS3000-IR). SEM provides detailed high resolution images of the samples by a focused electron beam across the surface and detecting secondary or backscattered electron signal. It provides images with magnifications up to ~ x 50, 000 allowing sub micron-scale features to be seen i.e. well beyond the range of optical microscopes. It is useful for characterization of particulates and defects in the material and examination of grain structure and segregation effects in the fabric structure.

4.2 Gas/Vapor Adsorption

This is the most widely available and utilized method for determining aerogel porosity. In this technique a gas, usually nitrogen, at its boiling point, is adsorbed on the solid sample. The amount of gas adsorbed depends of the size of the pores within the sample and on the partial pressure of the gas relative to its saturation pressure. By measuring the volume of gas adsorbed at a particular partial pressure, the Brunauer, Emmit and Teller (BET) equation gives the specific surface area of the material.

4.3 Air Permeability Measuring Instrument

The principle of FX 3300 air permeability instrument depends on the measurement of air flow passing through the fabric at a certain pressure gradient *Δp*. In this instrument any part of the fabric can be placed between the sensing circular clamps (discs) without the garment destruction. As the fabric is fixed firmly on its circumference (to prevent the air from escaping), the fabric dimensions do not play any role. There is also enough space between the clamps and the instrument frame, which allows the measurement on large samples.

4.4 Modified Particle Image Velocimetry - PIV Setup

Particle Image Velocimetry (PIV) is a whole-flow-field technique providing instantaneous velocity vector measurements in a cross-section of a flow. Two velocity components are measured, but use of a stereoscopic approach permits all three velocity components to be recorded, resulting in instantaneous 3D velocity vectors for the whole area. The use of modern digital cameras and dedicated computing hardware, results in real-time velocity maps. In normal PIV systems, the chamber set-up was very big and the hot plate was not used to determine the thermal properties. In our research, the chamber was made with the dimensions of 10 x 10 cm wide and 70 cm height. Three different set-ups were custom built to measure the velocity profile above the fabric sample shown in figure 1. The first set-up was placing the fabric sample directly on the hot plate. The second and third set-up was to place the fabric sample 2 and 5 cm above the hot plate respectively.

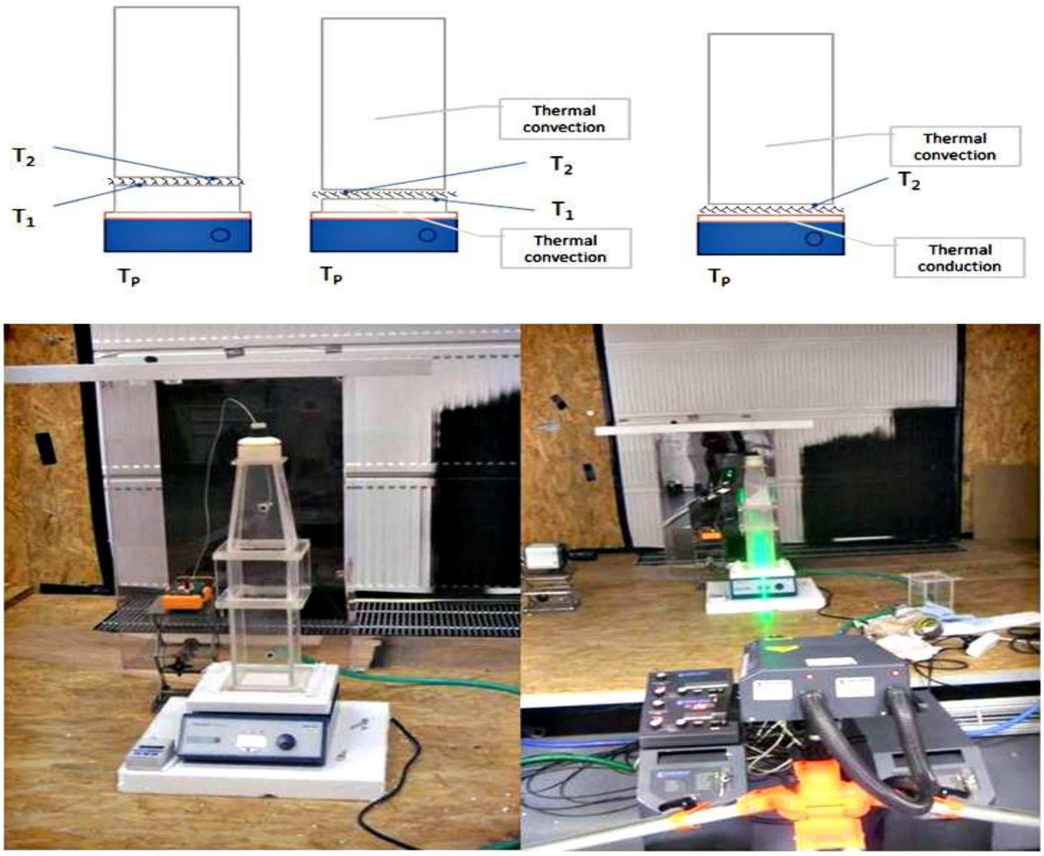


Figure 1. Experimental set-up for PIV measurements.

After the test is performed with the tracer particles for the heat flow, the image captured by the CCD camera is saved in the system. First, the images are divided into small windows called interrogation regions. Using a statistical method called cross-correlation, the displacement of each window from frame 1 to frame 2 is determined from the peak point in the cross correlation function. The most probable displacement over the time interval is the average velocity vector in one interrogation window, i.e. $\Delta x / \Delta t \approx v$, shown in figure 2. By repeating these calculations, the velocity field of the entire image area is obtained.

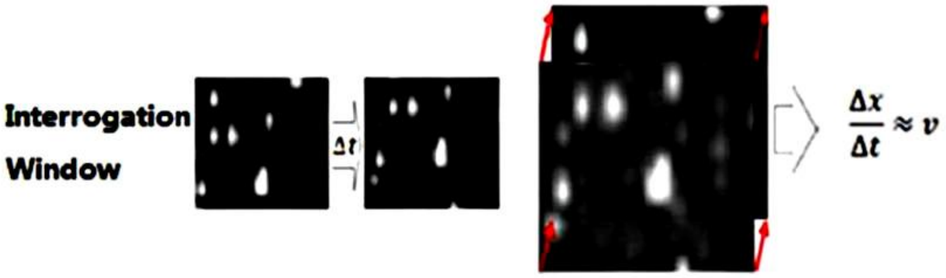


Figure 2. Average velocity vector of one interrogation window obtained by cross correlation [23].

Details of the PIV technique, including the tracer particle size, light source, light sheet optics, digital image recording, post-process data analysis and mathematical background of the statistical PIV evaluation can be found in the state of the art section [24].

4.5 Custom Built Steady State Thermal Measurement Instrument

The newly fabricated instrument works according to transmission of heat in the steady-state condition as described in BS 4745:1971. Single-plate heating method was used as reference to fabricate this instrument. In single-plate method (figure 3), the specimen under test is placed on the heated lower plate covered with 100% cotton as an outer fabric, since the issue of thermal contact is also very important. Fixed pressure (10 g/cm^2) was applied on the test specimen during the measurement which ensures good contact without deformation of textile structure. The surface temperature of the outer fabric is measured using the infrared thermometer.

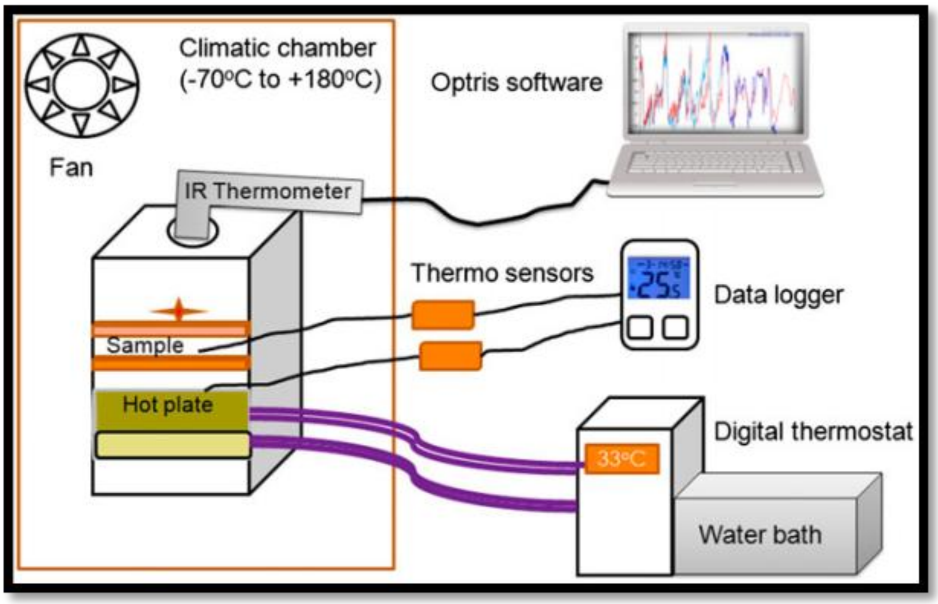


Figure 3. Schematic diagram of custom-built instrument for measuring thermal properties.

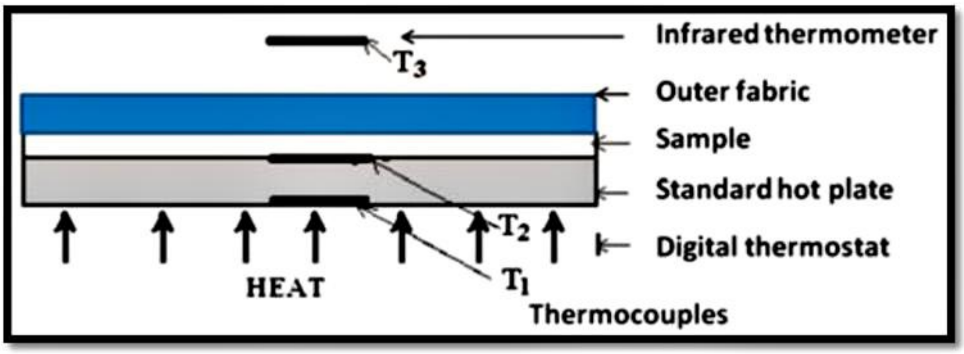


Figure 4. Schematic diagram of the newly fabricated instrument (single-plate method).

The instrument was used to determine the temperatures at various positions on the aerogel-treated fabric. From these measurements, the thermal conductivity and thermal resistance were calculated. The sample was placed in a climatized temperature system (chamber) which operates with the temperature range from (−70 to +180 °C). The instrument measures the heat transport through textile material. The test specimen was placed on the cylindrical hot plate which is connected to the digital thermostat water bath where the skin temperature is maintained at ~33 °C as shown in figure 4. The test specimen was placed on the hot plate and the outer fabric (100% plain woven cotton fabric) was placed over the test specimen applying 10 g weight on each side. Two thermocouples and heat flow sensors were used to measure temperature variations. First one (T_1) is fixed on the surface of the test specimen which touches the hot plate and the second one (T_2) is fixed on the surface which is covered by the outer fabric. The hot plate was adjusted to constant skin temperature and the climatic temperature system was adjusted to a controlled constant differential temperature. The heat flow sensors act on both the surfaces of the fabric. with the help of thermocouples, the temperature difference between the upper surface and the inner side of the test specimen can be measured. The Infrared thermometer was used to measure the temperature variations on the surface of the outer fabric. The fundamental measuring principle implies the measuring and processing of the heat flows with dependence to time. The instrument measures parameters: (1) Temperature on the surface of the test specimen which is in contact with the skin (T_1), (2) Temperature on the surface of the fabric which is in contact with the outer fabric (T_2), (3) Temperature inside the climatic temperature chamber which is set as the environmental temperature from (+25 to −25 °C) (T_3) and (4) Temperature on the surface of the outer fabric which is sensed by infrared thermometer (T_4).

4.6 Development of Heat Convection Instrument (Laboratory Set-Up)

The thermal property of fabrics under heat convection was evaluated by a laboratory model device developed in department of material engineering, Technical University of Liberec, shown in figure 5. This device consists of one air tunnel, sample holder, heater, several sensors, data acquisition module and laptop. The thermocouples are attached to one to heater and the other to the fabric, and the anemometers are on both sides of fabric, data acquisition module connects sensors with PC. The air flow goes through the testing sample, the temperatures of both sides of the fabric can be real-time monitored and saved in laptop. The output of heater was around 60 ^{o}C at 2.5 m/s.

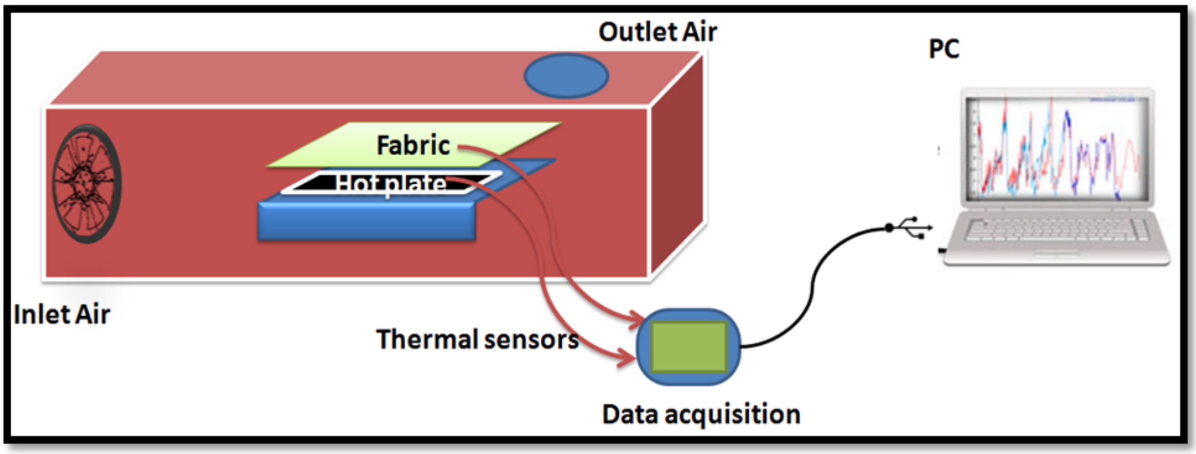


Figure 5. Schematic of laboratory model thermal convection instrument.

4.7 Alambeta Instrument

Alambeta is an objective evaluation of warm-cool feeling of fabric developed at Technical University of Liberec. This computer controlled semi-automatic instrument calculates all the statistic parameters of the measurement. It also shows the instrument auto-diagnostics to avoid faulty instrument operation. The whole measurement procedure, including the measurement of thermal conductivity λ, thermal resistance R, maximum heat transfer rate q_{max}, sample thickness and the results evaluation, lasts less than 3 to 5 mins. As the objective measure of warm-cool feeling of fabrics, so called thermal absorptivity b [$Ws^{1/2}/(m^2K)$] is introduced [25].

4.8 C-Therm Thermal Conductivity Analyzer (TCi)

The principle of the apparatus (TCi) is based on conductors in series with respect to the direction of heat flow. The ratio of the temperature drop across the conductors is equal to the ratio of their thermal resistance. Thus, if the temperature drop across a material of known thermal resistance (standard resistance) and across a test specimen in series is measured, the thermal resistance of the test specimen can be evaluated. The TCi developed by C-Therm Company, measures the thermal conductivity of a small sample using the modified transient plane source (MTPS) method. The TCi consists of a sensor, power control device and computer software [26, 27].

4.9 Compression Test and Thickness Measurement Using The KES-FB3

The KES-FB3 measures properties of compression and thickness. These properties are not dependent on direction and hence measurements in the warp and fill directions are not needed. The instrument applies a force up to 50 gf/cm^2 to a 2 cm^2 circular area at a constant velocity and measures the thickness with respect to the force per area applied. The device takes measurements during the compression process and the recovery process. Important properties of this instrument include compressibility, compression resilience, and thickness. EMC, denoting compressibility, is a comparison of the initial thickness measurement to the thickness at the maximum applied force.

4.10 Kawabata (Thermolabo) - Small Hot Plate

KES-FB7 instrument and NT-H1 (where, N stands for NISHIMATSU and TOYONORI) works in accordance with the standard procedure ASTM 1518 and similar principle (surface: 10 cm^2, temperature difference between the two sides: 10 ^oC). Thermolabo II evaluates warm or cool feeling through evaluation of q_{max} (Time: 1 min); measurement of thermal conductivity and heat diffusion (Time: 2 to 3 mins) and measurement of heat retention properties (Time: 2 to 5 mins). Kawabata Thermolabo unit is also known as the 'Sweating Guarded Hot Plate' or 'Small Hot Plate', is used for quantitative measurement of the cooling ability and the breathability of the fabric. It is designed to quantitatively measure the thermal comfort properties of the fabric. This test is performed on the Kawabata KES F7 under controlled environment at 21 ºC and 65% R.H [28, 29].

4.11 P.T. Teknik Thermal Manikin

Thermal manikin manufactured by P.T.Teknik system is used to evaluate whole garments systems (or components of garment systems) for heat and moisture management related to garment insulation and breathability. By measuring these values on a human form, garments are evaluated as they would be worn in the field, accounting for effects of fit, garment construction and design (including trapped air layers). Insulation and breathability of garment systems are measured by the following ASTM F 1291 "Standard Method for Measuring the Thermal Insulation of Clothing Using a Heated Manikin" and ASTM F 2370 "Standard Test Method for Measuring the Evaporative Resistance of Clothing Using a Sweating Manikin, respectively". The P.T.Teknik thermal manikin, University of Lodz was used for the study. The fabric was fixed only to left and right upper arm of the manikin.

4.12 Electrospun Nanofibrous Layers and Thermal Insulation

Recently many researchers have claimed advanced thermal insulation with nanofibrous layers. Electrospinning is carried out using nano spider technology as a modified electrospinning technique, Nanospider laboratory machine NS LAB 500S from Elmarco s.r.o. Electrospinning is widely accepted as a technique to fabricate submicron polymer fibers. It is a fiber-forming process, where high voltage is used to create an electrically charged jet of polymer solution or melt from the needle. The polymer solidifies as it travels towards the collecting plate, often producing nanometer scale fibers [2-4, 30, 31].

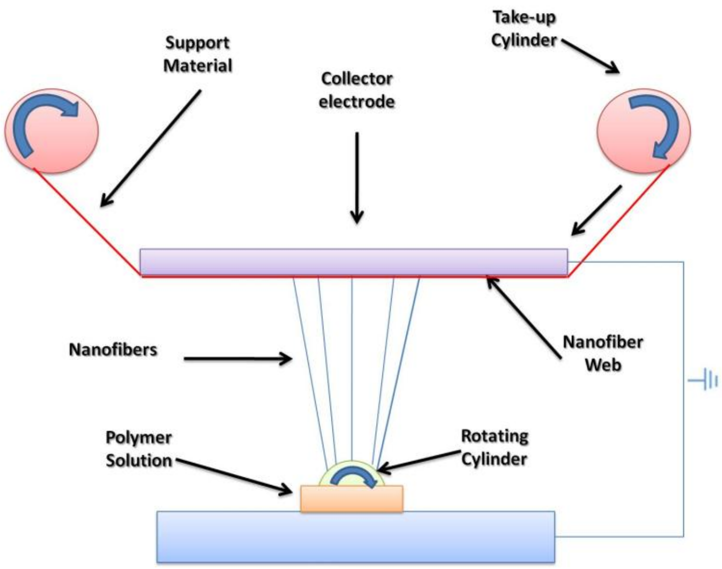
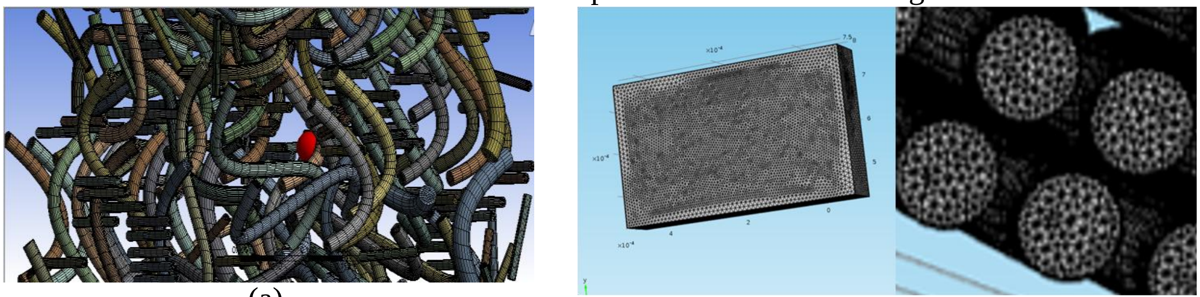


Figure 6. Schematic of electrospinning setup "Nanospider" [32].

This commercial method for production of polymeric nanofiber is used in industrial range. This is a simple and versatile method for production of ultrathin fibers from a variety of materials that include polymers. In addition, Nanospider has the ability to process a wide range of polymers in diameters of 50 to 300 nm into nonwoven webs [8].

4.13 Computational Simulation of Convective Heat Transfer through Aerogel Treated Nonwoven

In ANSYS workbench, two types of thermal analysis can be carried out, namely Steady-State and transient thermal analysis. Owing to the highly random structure of non-wovens/sheet/batt, a unit cell was considered. Individual fibers were modeled, each having a circular cross-section and a random shape. For this, a spline (a curve) was made, and the profile of a circle was swept over the spline to create the fiber. The modeled fibers were assembled together to create a nonwoven structure, such that the fibers occupy 26.27% space inside the unit cell, so as to give 73.73% porosity to the fabric. This assembly of fibers was saved as a PART file so that it could be used as a component in the further complex assembly. A chain of unit cells, about 3.5 mm long, was assembled using the 'mate' function to give a more realistic view of the fabric – this was simulated in Ansys Workbench 14. A model view of the structure of the non-woven fabric developed has been shown in figure 7.



(a) (b)

Figure 7. Meshing of elements in the unit cell (a) ANSYS (b) COMSOL.

A unit cell to represent the fabric sample was modeled in solidworks. The fiber percentage in the unit cell was approximately 26.5%. The simulation of heat transfer through the fabric unit cell was done in COMSOL. The input given was heat capacity, density, thermal conductivity for both fiber and surrounding fluid and the viscosity and the ratio of heat capacity at constant pressure and constant volume (gamma). Since the fluid responsible for the convection taking place was the same for both aerogel and free air, the viscosity, density and gamma values were the same for both simulations. The thermal conductivity and the heat capacity for both fluids were different. In the model used, most of the heat transfer was because of the convection by the fluid and conduction between air and fiber, very less due to the conduction in fibers itself since none of the fibers in the model touch each other. The conjugate heat transfer module, which combines the heat transfer through solids module and heat transfer through fluids module, was used. The heat transfer in solids module considers the fact that conduction is more prominent and the heat transfer in fluids module considers convection to be more prominent. This module couples the heat transfer module with the fluid flow module. The simulation was done assuming laminar and compressible flow and results obtained were for the steady state. One of the faces of the fabric was given a constant temperature of 329.19 K and the outside temperature was taken to be 263.15 K. This was done for 4 cases: (1) Aerogel as the fluid in the fabric with forced convection (2.5 m/s wind at the outer surface); (2) Aerogel as the fluid in the fabric without forced convection. (3) Air as the fluid in the fabric with forced convection (2.5 m/s wind at the outer surface) and (4) Air as the fluid in the fabric without forced convection**.** The model was meshed and various boundary conditions were given as shown in figure 7. For both with and without forced convection cases, one face was given a temperature of 329.19 K and initial temperature of the whole fabric was given as 263.15 K. For the forced convection case, the opposite face was given a convective flux with convection factor 23.76 [W/(m^2K)] (2.5 m/s wind) and 263.15 K outside temperature.For the case without forced convection, the opposite face was given an open boundary condition with outside temperature of 263.15 K.

5 Summary of the results achieved

5.1 Microscopic Analysis of Samples

Results for the characterization of aerogel treated nonwoven fabrics and needle punched struto nonwoven structure samples by SEM, Confocal/optical microscopy, DSC, FTIR and BET analysis as confirmation techniques are discussed. The aerogel deposition in the fabric between the fibers was observed. These images provide a more clear understanding of the deposition of silica aerogel particles on the fiber surface.

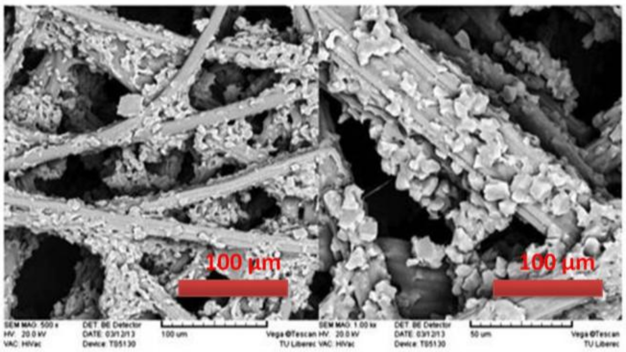


Figure 8. Scanning electron microscope images of aerogel-treated non-woven fabrics.

The struto fabric shown in the figure 9 is in the form of corrugated structure where top and bottom layer is of polypropylene web and the middle layer consists of melt blown polyamide nanofibers on both sides of spunbond PP web with two different compositions.

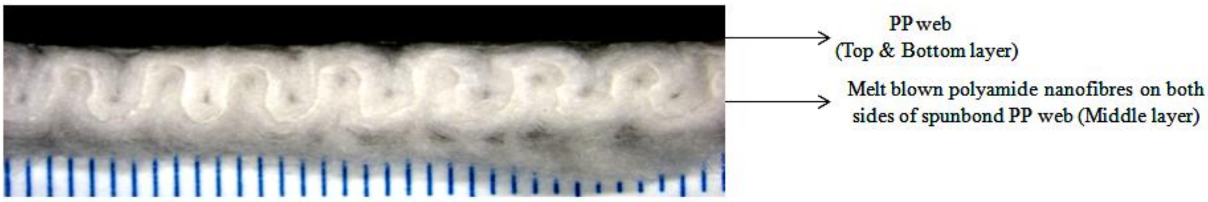


Figure 9. Needle punched struto nonwoven structure.

Figure 10 shows the morphologies and microstructures of electrospun PUR & PVDF nanofibrous layers. The electrospun nanofibrous layers have better integrity and flexibility. The different microstructures could be observed with and without aerogel particles present which were electrospun from the solutions with the concentration of 18wt.%.

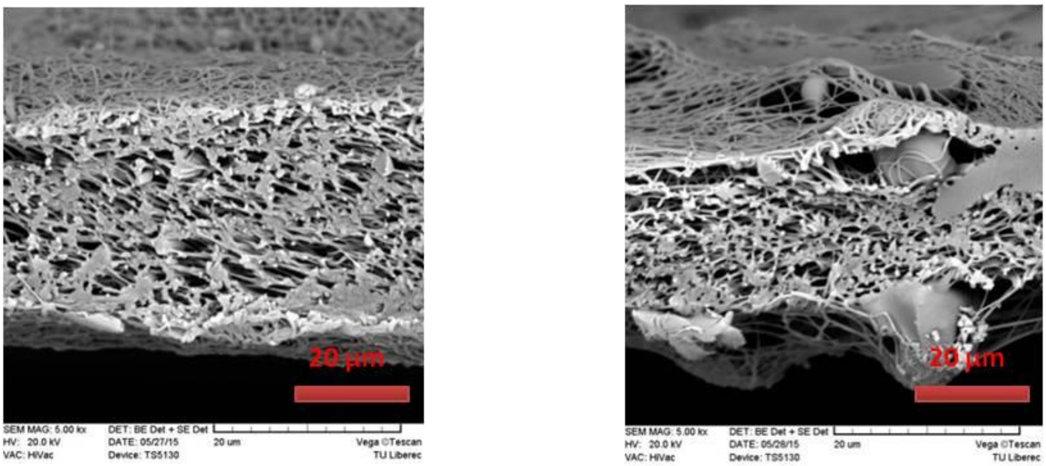


Figure 10. Morphology and microstructure of electrospun PUR nanofibrous layers embedded with SiO_2 aerogel from 18 wt.%.

5.2 Flow Rate Dependence on Pressure of Insulation Materials

Air permeability is the measure of airflow passed through a given area of a fabric. This parameter influences the thermal comfort properties of fabrics to a large extent. It is generally accepted that the air permeability of a fabric depends on its air porosity, which in turn influences its openness. With more porosity, more permeable fabric is obtained.

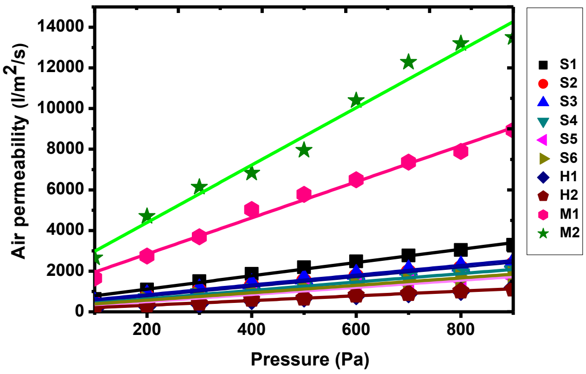


Figure 11. Flow rate dependence on pressure.

Statistical analysis results show that the there is a significance on the air permeability values of the aerogel treated nonwoven fabrics ($p = 0.003$). Figure 11 shows the air permeability with respect to different pressure levels of the fabrics. The result indicates that air permeability is directly proportional to the pressure level. On comparison of ten fabrics, the air permeability is higher in the case of sample M2. It may be due to the fact that air permeability is related to porous structure of the fabric and is directly proportional to percentage of porosity of the fabric. It was also noticed that when the pressure level increased, the flow rate also increased. Irrespective of different pressure levels, the air permeability was low for samples S1 to H2. It may be attributed to the layered structure and high porosity.

5.3 Effect of Temperature Variations

The environmental temperature versus the thermal conductivity of the fabric is shown in figure 12. The temperature variations at each point varied for the test specimens with the change in climatic chamber temperature (environmental temperature).

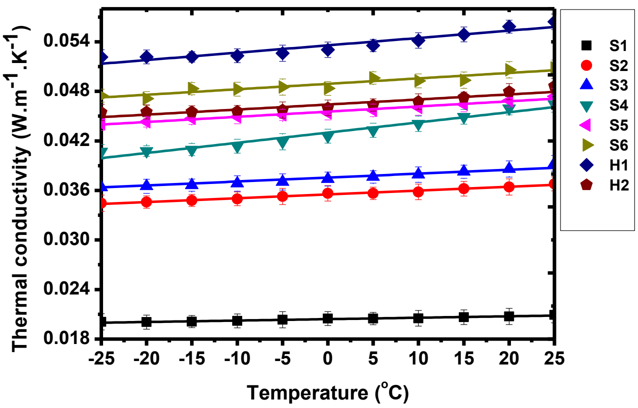


Figure 12. Thermal conductivity (custom built Instrument).

The temperature gradient was higher for the lower temperatures (sub-zero temperatures). The temperature of materials is determined with thermal energy in the form of kinetic energy of disordered molecular movement [33]. The difference in temperature gradient may be attributed to the aerogel present in the non-woven fabric. Aerogel is the main component in the non-woven fabric structure blocking air pockets inside its highly porous structure which provides thermal insulation and thereby considered to be beneficial for such applications. From the figure 12, it is found that the fabric temperature variations increase rapidly during initial stage of the exposure. This may be because of the temperature difference between the fabric sample and the exposed air is high in the early stage of the exposure process.
Thermal conductivity increases with fabric density and also for constant thickness of fabric; and below density of 60 kg/m^3, increase in fabric thickness causes increased thermal insulation and reduction in fabric temperature variations (up to an optimum level). The increase in weight-to-thickness ratio causes increase in effective thermal conductivity due to increase in fiber-to-fiber contact and packing density. It causes increase in tortuosity i.e. mean free path for photons to be travelled and so less heat flows through the channels in nonwoven fabric [34, 35].

5.4 Determination of Thermal Resistance at Various Temperatures

Figure 13 demonstrates how the environmental temperature affects the result in an almost linear relation between fabric thickness (expressed as volume of insulation material per unit of fabric area) and insulation [36]. Uniform distribution of heat provides the best insulation in the extreme cold conditions. Thermal insulation increases with thickness due to increased quantity of enclosed air, whereas if thickness is maintained constant, then thermal insulation decreases with increase in weight as quantity of enclosed air is reduced [37]. The thermal insulation value of porous, low-density non-woven fabric is affected by compression and hence the layered structure of aerogel treated non-woven fabric gives better insulation because of good compression recoverability. It can be observed that samples S2, S3, S4, S5 and S6 have higher resistance when compared to sample S1, H1 and H2. Thus, it can be stated that thickness and aerogel present had more profound effect on insulation compared to the material composition.

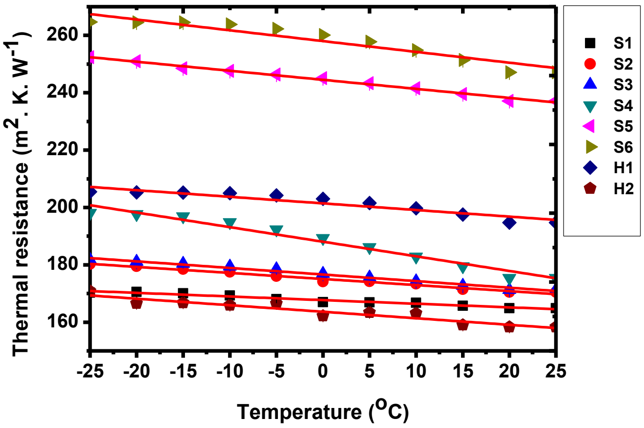


Figure 13. Thermal resistance (custom built instrument).

A large F is evidence against H_0 (null hypothesis), since it indicates that there is more difference between groups than within groups. ANOVA was done to analyze the results with 95% confidence level. A significant difference ($p < 0.05$) has been observed in the thermal resistance and conductivity properties of the nonwoven fabrics with different thicknesses.

5.5 Effect of Aerogel on Thermal Insulation of Fabrics

The influence of wind speed on the thermal insulation properties of the fabrics has been studied. It is expressed as a percentage which represents the reduction in the rate of heat loss due to the insulation, relative to the heat loss from the surface. If we consider figure 15, it can be observed that heat retention properties is always more important for fabrics in colder environments; besides there is a linear relationship with the air flow velocity. The fabrics with high porosity will prevent air passage and then reduce convection heat loss.

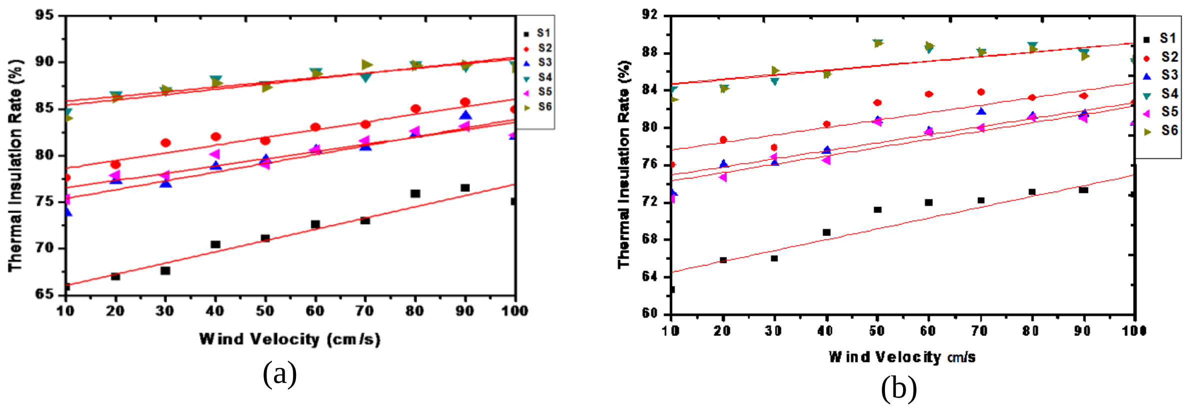


Figure 14. Thermal Insulation of fabrics (a) KES Thermolabo II (b)NT-H1.

It is observed from figure 14 that with the increase in aerogel content, the thermal insulation rate increases with increase in wind velocity. This may be attributed to higher thickness of the fabric having higher aerogel content. All data were analyzed and found to fit the linear regression model. The residuals approximates (independent random errors) and goodness of fit (coefficient of determination, R^2), were calculated to see how closely values obtained from fitting a model match the dependent variable the model is intended to predict. The calculated results showed closer fit to data (goodness of fit was closer to 1 ($R^2 = 1$).

5.6 Validation of Theoretical Model with Experimental Data

The correlations between experimental and theoretical model data were done. Theoretical model data was correlated with the measured data of three instruments namely, alambeta, TCi and custom built instrument. The theoretical model data were calculated as per the formulae given below. The thermal conductivity of parallel arrangement λ_{hP} (higher limit) is equal to,

$$\lambda_{hP} = P \ \lambda_a + (1-P) \ \lambda_f \tag{5.1}$$

For serial arrangements is thermal conductivity λ_{hS} (lower limit) defined as

$$\lambda_{hs} = \frac{\lambda_a \ \lambda_f}{P \ \lambda_f + (1-P) \ \lambda_a} \tag{5.2}$$

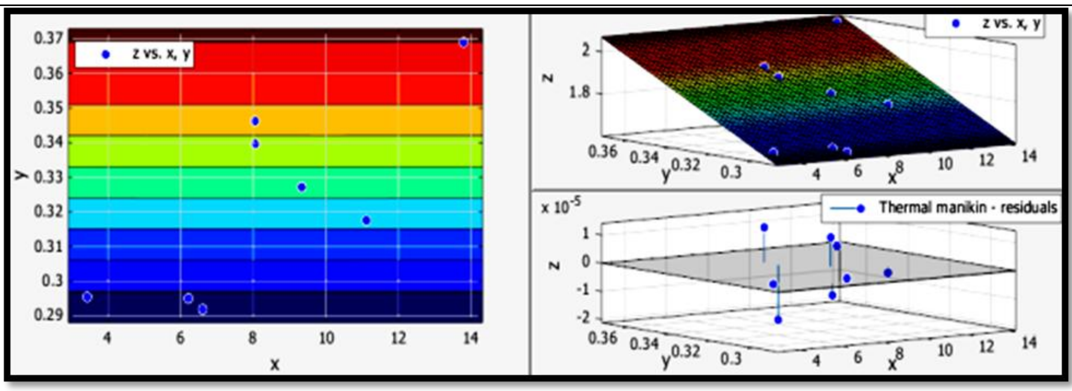
Actual composition of a fibers and air phases can be presented by linear combination of parallel and series structures [38]. The compromise is to compute the mean thermal conductivity of hollow fiber λ_h as arithmetic mean between upper and lower limit.

$$\lambda_h = \frac{\lambda_{hP} + \lambda_{hS}}{2} \tag{5.3}$$

The parallel/series structure gives a firsthand prediction and would give reasonable prediction accuracy for practical application due to its simplicity. The theoretical model and experimental data. From the results, it can be seen that the correlation between the theoretical and experimental values of thermal resistance were around R^2 = 0.8 for alambeta and custom built instrument. Around R^2 = 0.9 was for TCi instrument. Since the correlation between the theoretical calculation and the experimental values are good, it can be concluded that the data generated from the experiments are theoretically compatible.

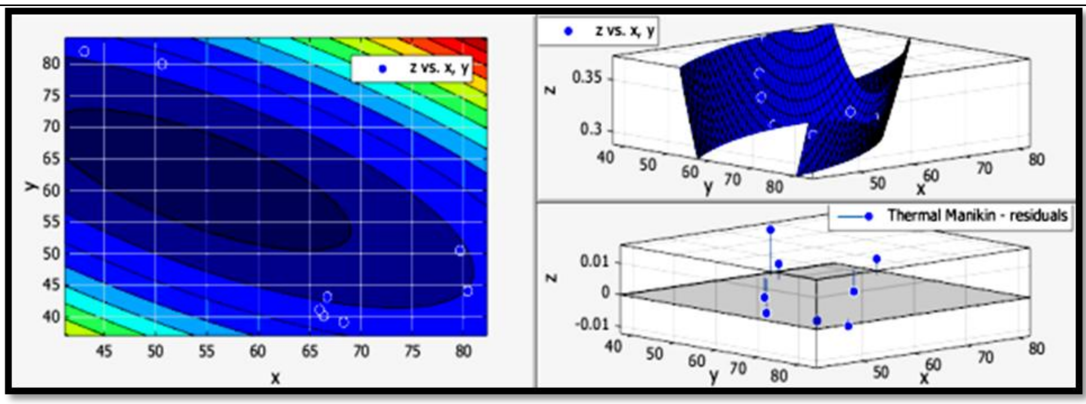
5.7 Assessment of Thermal Properties Using a Thermal Manikin

Methods for the calculation of clothing insulation depend on the operating mode of the manikins. Heat Loss Potential [W/m^2] is calculated for a standard environment by combining both the dry and sweating components of heat loss measured in their respective states. Since different fabric layers and reinforcements are used in clothing systems, resultant data from sweating manikin tests provide a powerful basis for understanding how to optimize the materials and clothing design to minimize heat loss from the full ensemble.



Linear model Poly 22: f(x,y) = p00 + p10 x + p01 y + p20 x^2 + p11 x y + p02 y^2	
Goodness of fit:	Coefficients (with 95% confidence bounds):
SSE: $6.798e^{-010}$ R-square: 1 Adjusted R-square: 1 RMSE: $1.844e^{-005}$	p00 = -0.002523 (-0.0151, 0.01005) p10 = $-7.515e^{-005}$ (-0.0005783, 0.000428) p01 = 5.573 (5.483, 5.663) p20 = $-1.653e^{-006}$ ($-1.086e^{-005}$, $7.556e^{-006}$) p11 = 0.000316 (-0.00167, 0.002302) p02 = -0.03054 (-0.1919, 0.1308)

Figure 15. 3D fit model (Thermal manikin) where x = Thickness [mm], y = R-Value [(m^2 K)/W] & z = Clo value.



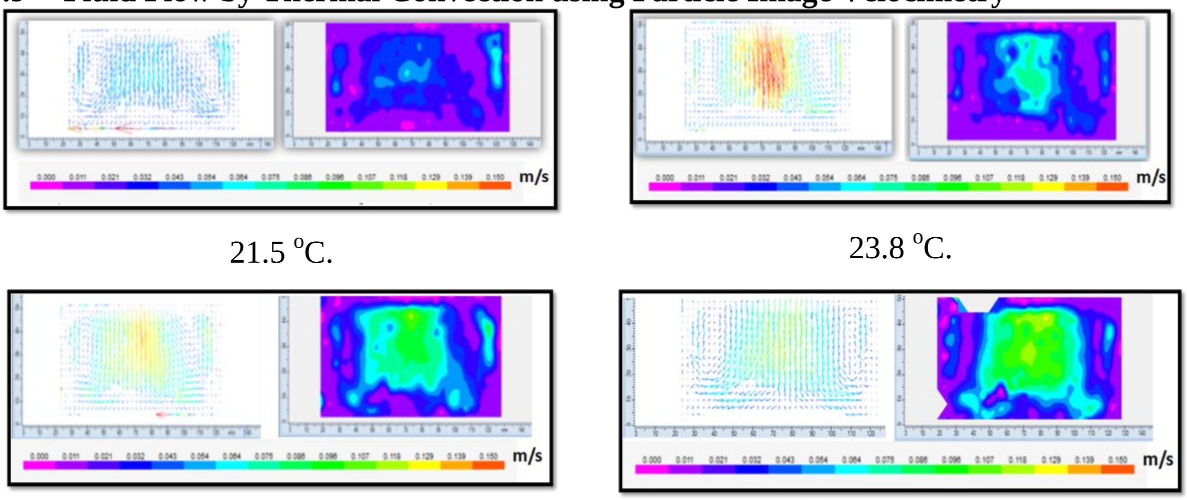
Linear model Poly22: f(x,y) = p00 + p10 x + p01 y + p20 x^2 + p11 x y + p02 y^2	
Goodness of fit:	Coefficients (with 95% confidence bounds):
SSE: 0.000474 R-square: 0.9137 Adjusted R-square: 0.6979 RMSE: 0.01539	p00 = 6.683 (-6.816, 20.18) p10 = -0.09256 (-0.3402, 0.155) p01 = -0.1301 (-0.3412, 0.08104) p20 = 0.000412 (-0.00079, 0.001614) p11 = 0.0007745 (-0.0009191, 0.002468) p02 = 0.000713 (-0.0002566, 0.001683)

Figure 16. 3D fit model (Thermal manikin) where x = Fabric density [kg/m^3], y = Heat flux [W/m^2] & z = R-value [(m^2 K)/W].

5.8 Convective Heat Transfer by Forced Convection - Laboratory setup Instrument

It was observed from the results that the aerogel treated nonwoven fabrics has highest thermal resistance. The needle punched struto nonwoven fabrics show least thermal resistance value. The higher thermal resistance in aerogel treated nonwoven fabric is mainly due to presence of higher amount of air within the structure. The thermal resistance differs with respective to thickness of the fabrics used in the study. From the statistical analysis, it is observed that the type of fabric significantly affects the thermal resistance of multilayered fabrics. The effect of type of fabric on thermal resistance is statistically significant at 95% confidence interval. The thermal transmission at this situation is solely governed by the thermal resistance of the component fabric layer. The only difference between the fabrics H1 and H2 is the middle layer, i.e. meltblown polyamide nanofiber NF1 and NF2, respectively. It is also evident from that in general the thermal resistance of fabric H1 and H2 are lower than the S1 to S6. The reason for this is that the middle layer of the S1 to S6 fabric consist of aerogel with relatively higher thermal resistance than needle punched struto nonwoven fabric (H1 and H2). Convective heat transfer coefficient depends on air velocity, which defines the type of the convection [39].Since fabrics were measured in forced convection mode, the heat transfer coefficient is calculated with air velocity 2.5 m/s. By substituting the air velocity in the equation 4.5, the heat transfer coefficient for forced convection is 21.75 W/(m^2K).

5.9 Fluid Flow by Thermal Convection using Particle Image Velocimetry



21.5 ^{o}C. 23.8 ^{o}C.

37.5 ^{o}C. 51.0 ^{o}C.

Figure 17. Vector and scalar maps for different temperature gradient

Vector and scalar maps of the fluid flow developed by thermal convection above the textile sample were plotted for different temperature gradients. The vector maps are colored to highlight the acceleration zones. The scalar maps were put in one scaling and could be compared. Scalar maps are used to display the on-screen multiple data derived from the velocity fields. The x and y axis scales in vector and scalar maps illustrate the magnitude and direction of the out-of-plane velocity component. Vorticity contours for the instantaneous flow structure is a vector field that gives a microscopic measure of the rotation at any point in the fluid. Vector and scalar maps for temperature gradients corresponding to difference between human body and chilling atmosphere are shown in figure 17. Evaluation recorded is based on the relationship between speed, distance, and time, where distance represents the displacement of particles entrained in the surrounding fluid (air) flowing in a defined time interval between two laser pulses. The distance and air velocity diagram is shown in figure 18. These charts describe the behavior at different temperature gradients (between the textile sample and temperature of neighborhood). As it is expected, the fluid flow motion accelerates according to the increasing temperature gradient. This velocity profile is taken 25 mm above the free surface of the textile sample. The maximum velocity is reached with temperature gradient of 51.0 ^{o}C. The construction of the testing chamber did not allow observing the situation just above the surface of textile sample due the reflections.

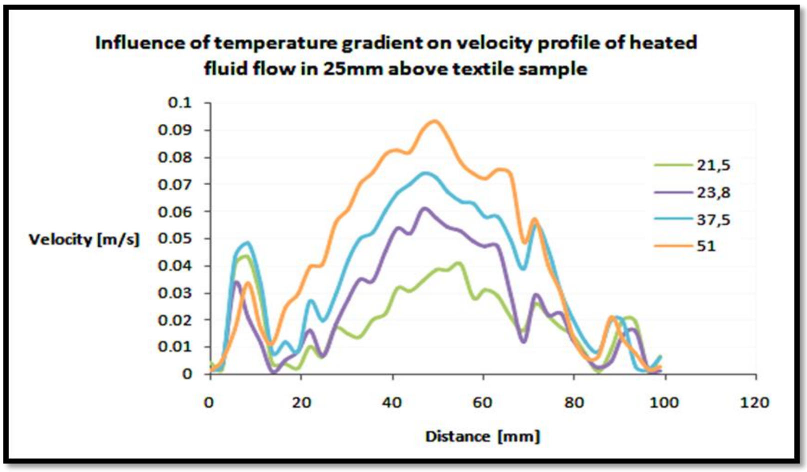


Figure 18. Distance and air velocity diagram.

These results are very important for setting the boundary condition of numerical simulation, describing the behavior of textile samples in the subzero temperature condition as well as for simulation of heat transfer through the porous media.

5.10 Thermal Properties of Electrospun Nanofibrous PUR and PVDF Layer embedded with SiO2 Aerogel

Thermal conductivity as a function of areal density for PUR and PVDF electrospun nanofibrous layer embedded with silica aerogel is shown in figures 20. As shown in figure 19, thermal conductivity of the electrospun nanofibrous layer decreased with increase in density. This can be explained by the fact that as the density increases; it makes the fibrous structure more packed. This causes the mean free path (distance travelled by a photon before it collides with another fiber surface [38] for a photon movement to decrease thus causing a decrease in the heat transfer because of radiative conduction. When the density comes to a critical point, the increase in conduction through solid phase (fibers) and decrease in radiation conductivity results in an increase in total thermal conductivity [40, 41]. In fact, in fibrous structures the small size of the pores and the tortuous nature of the air channels present prevents any heat transfer by convection [42]. According to thermal conductivity curves which is apparent in figures 20, decrease in the average nanofiber diameter leads to lower limit of conductivity.

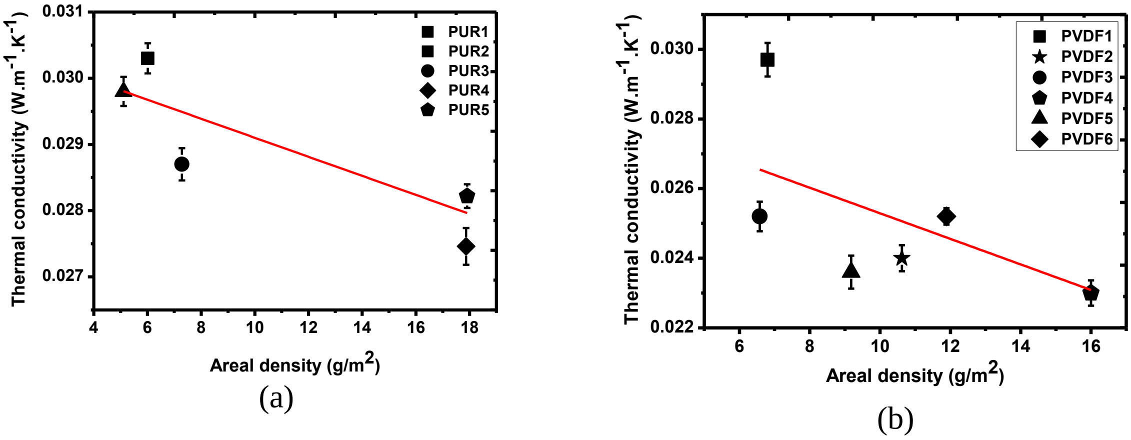


Figure 19. Thermal conductivity Vs GSM (a) Electrospun PUR nanofibrous layers embedded with silica aerogel (b) Electrospun PVDF nanofibrous layers embedded with silica aerogel.

The results for the two nanofiber insulation materials (electrospun PUR and PVDF nanofibrous layer) showed excellent reduction in overall heat transfer compared to standard low-density fibrous insulating materials (at areal densities above 40 g/m^2). The PVDF nanofibrous layer, in particular, showed superior insulation at higher areal density values. Thermal conductivity testing confirmed that decreasing fiber diameter tends to increase the thermal resistance of fibrous insulation materials. However, the nanofiber/aerogel becomes an effective insulator since the aerogel structure suppresses conduction and convection, and the fibers reduce radiation heat transfer while increasing the strength of the brittle and weak aerogel structure. Although the aerogel/nanofiber combination has good thermal properties, the volume fraction of fiber must be fairly high to support and protect the aerogel matrix. Thus the aerogel materials can’t achieve the same thermal conductivity at densities as fibrous insulation, but they do achieve better thermal resistance for an equivalent thickness of material.

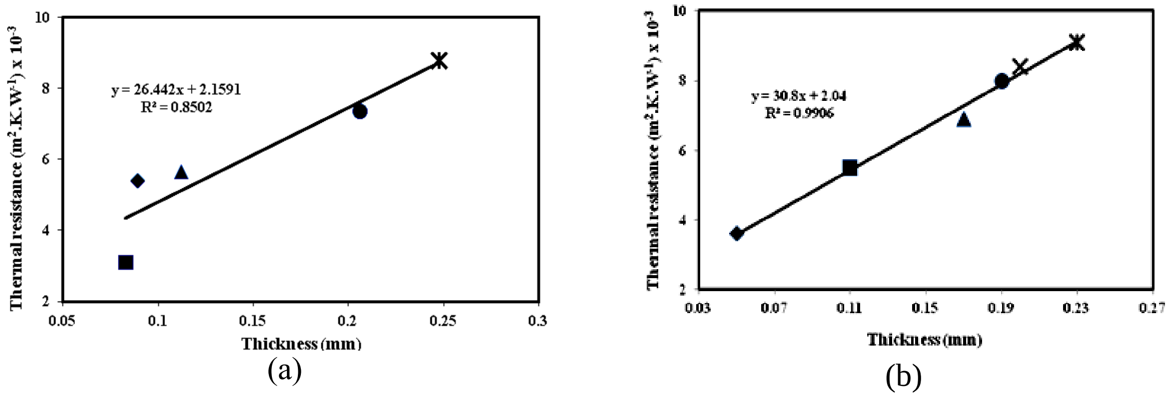


Figure 20. Thermal resistance Vs Thickness (a) Electrospun PUR nanofibrous layers embedded with silica aerogel) linear function (b) Electrospun PVDF nanofibrous layers embedded with silica aerogel.

High porosity of electrospun fibrous mesh is able to trap air which potentially gives it a good thermal insulation property. This is confirmed using thermal conductivity tests which show that decreasing fiber diameter leads to an increase in thermal resistance [4]. As mentioned previously, nanofiber/aerogel have shown superior insulation properties for applications where thickness is of concern. Air permeability is a very important parameter for thermal insulation of electrospun nanofibrous layer. Lower air permeability causes lower air flow;

consequently, more thermal insulation. The air permeability of electrospun nanofibrous layers are shown in figure 21. According to the figures; samples containing PUR nanofiber with double layer showed less air permeability. This behavior can be attributed to the finer diameter of PUR nanofiber compared to PVDF nanofiber diameter.

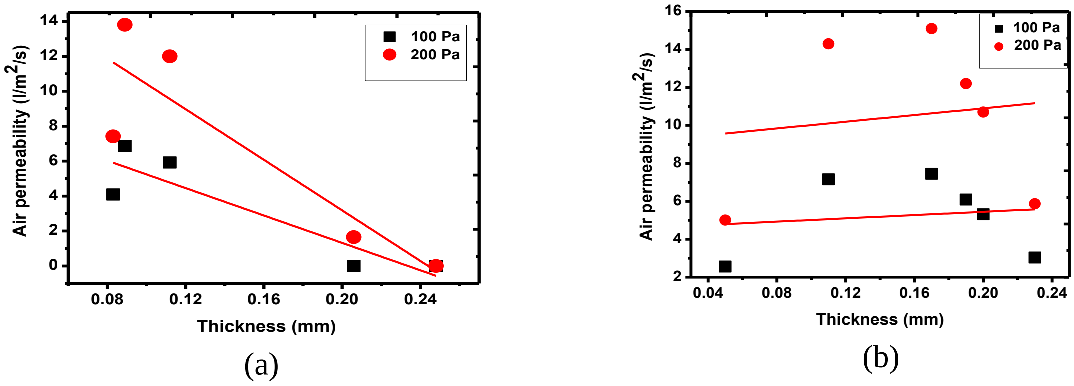


Figure 21. Air permeability (a) Electrospun PUR nanofibrous layer embedded with silica aerogel) 100 Pa (b) Electrospun PVDF nanofibrous layer embedded with silica aerogel)

As can be seen from the figures, by increasing the number of nanofibrous layers, lower air permeability was achieved, confirming the relation of this important parameter with thermal insulation ability. Figure 21 shows that sample PUR4, PUR5 and PVDF5 were impermeable at 100 and 200 Pa.

5.11 Modeling and Simulation of Heat Transfer by Convection through Aerogel Treated Nonwoven Fabrics

During simulation a constant ambient temperature of -10 ◦C was considered. Simulation was done so as to allow heat to flow along the thickness of the fabric (perpendicular to both the machine and the cross direction).

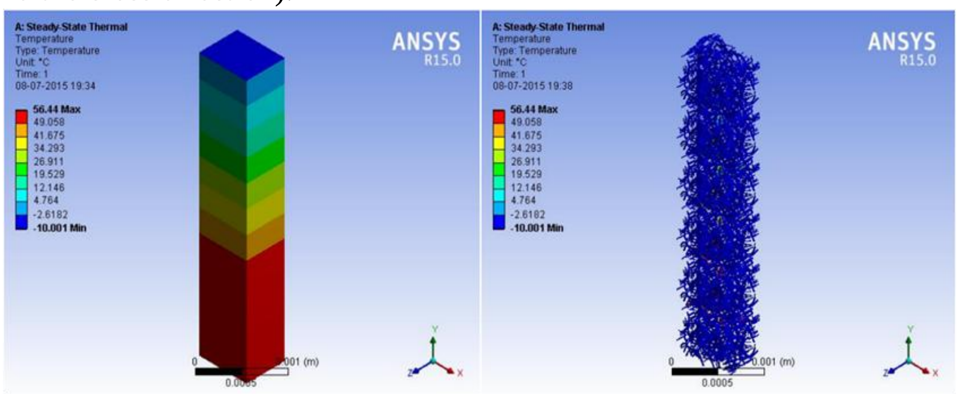


Figure 22. Temperature gradient for aerogel treated nonwoven (ANSYS).

As the heat flows under the temperature gradient provided, various levels of the fabric thickness settle down to different equilibrium temperatures which is depicted in the 'Temperature' diagram shown in figure 22. Apart from this, variations in the 'Total Heat Flux' and the 'Directional Heat Flux' (along the Y axis – because that is the major direction for heat transfer) have been shown. Clearly, the heat retention in the nonwoven structure with aerogel is 67% higher than in the nonwoven structure without aerogel implying that aerogel hinders heat transfer, thus keeping the body warmer.

In the case of standard nonwoven without forced convection shown in figure 23, the temperature at the surface exposed to outside air was 329.18955 K and the heat rate through the fabric was 2.185 e^{-8} W.

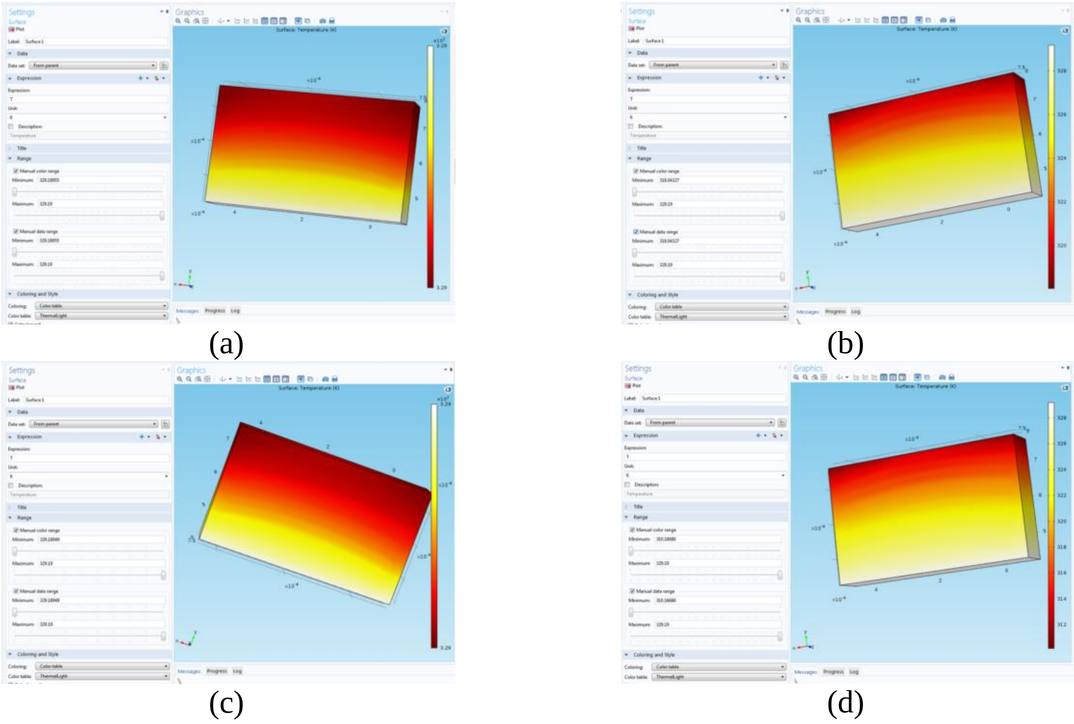


Figure 23. Heat transfer through standard nonwoven (a) without forced convection. **(b)** with forced convection. Aerogel treated nonwoven (c) without forced convection. **(b)** with forced convection (COMSOL).

In the case of standard nonwoven with forced convection showed in figure 23, the temperature at the surface exposed to outside air was 318.04327 K and the heat rate through the fabric was 1.024 e^{-8} W. In the case of nonwoven with aerogel and without forced convection shown in figure 23, the temperature at the surface exposed to outside air was 329.18949 K and the heat rate through the fabric was 1.267 e^{-8} W. In the case of nonwoven with aerogel and with forced convection, the temperature at the surface exposed to outside air was 310.16686 K and the heat rate through the fabric was 9.801 e^{-9} W.

In the case of forced convection, the difference between the surface temperatures in case of air and aerogel for is almost 8 K even for such a small unit cell. When forced convection was not taken into account, the temperature difference was very less (6 e^{-5} K). But in both cases, the heat flow through air is higher than in case of aerogel. In the case with forced convection, the heat rate was around 5% higher and in the case without forced convection, the heat rate was more than 72% higher. That is, the heat loss through the air is 1.7 times the heat loss through aerogel, in the case without any forced convection. The total net heat rate is defined as the net incoming and outgoing heat fluxes through all the surfaces of the body. This value for forced convection case is seen to be less in both aerogel and air because the outgoing flux is much more when there is a forced convection. The temperature versus length plot was also made. This was a smooth curve for the cases of forced convections but in the cases with no forced convections, the graph obtained had steps maybe because of very less variation of temperature in those regions.

6 Evaluation of results and new finding

This research has produced new ideas, large amount of data and conclusions that can have a significant impact on the research of thermal behavior of high performance textiles. A detailed analysis of various measurement techniques have helped in identifying the optimal one for different scenarios. A comparative analysis of thermal properties of insulating materials showed that aerogel has a significant potential to be used as insulation material for textile applications. New instruments were fabricated according to proven theoretical principles and were found to correlate with the results from other standard equipments. This provides an alternative mode to measure thermal properties. New insights into using unconventional techniques like PIV were gained. A detailed exercise to correlate results from conventional and unconventional techniques has generated a large amount of baseline data that could be useful for future research. By exploring electrospinning of PUR and PVDF nanofibrous layers embedded with silica aerogel, a new avenue to understand the potential of nanofibers and aerogel combined; in the area of high performance clothing has arisen. The detailed study of the convective heat transfer through insulation material provided data and models to simulate the heat transfer mechanisms. This reduces the amount of effort required for lab and field experiments and empowers researchers to simulate test environments and generate relevant data. These results and findings have been published in various books, peer-reviewed journals and international conferences.

The ideas, experiments and data generated as part of this research, have added to the knowledgebase that could be useful to define the future direction and provide insightful references to researchers. The potential of this research can be realized by pursuing further studies into areas given below:

- Synthesis & Characterization of various types of aerogel suitable for textiles.
- Explore various conventional and unconventional thermal measurement techniques.
- Develop new methods to treat fabrics with aerogel particles.
- Fabrication of new devices for measurement of thermal properties in fibrous structures.
- Development of electrospun nanofibrous layers embedded with aerogel for low density and effective thermal insulation.
- Comparison of efficacy of different Insulation materials.
- Modeling of convective heat transfer phenomena in fabrics treated with aerogel.
- Develop or update standards for thermal measurement in insulation materials used for textile applications.

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8 List of papers published by author

8.1 Publications in journals

[1] Mohanapriya Venkataraman, Rajesh Mishra, T. M. Kotresh, Tomonori Sakoi, Jiri Militky, *Effect of compressibility on heat transport phenomena in aerogel treated nonwoven fabrics*, Journal of Textile Institute - accepted, 2015 (***Impact factor: 0.722***).

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[8] Mohanapriya Venkataraman, Rajesh Mishra, Jaromir Marek, Jiri Militky, *Electrospun nanofibers from PUR and PVDF embedded with SiO_2 Aerogel for Advanced Thermal Properties*, Nanoletters (under review).

[9] Mohanapriya Venkataraman, Rajesh Mishra, Guocheng Zhu, Jiri Militky, *Dynamic heat flux measurement for advanced insulation materials*, Journal of Industrial Textiles (under review).

[10] Mohanapriya Venkataraman, Rajesh Mishra, Jakub Wiener, Jiri Militky, *Comparative Analysis of High Performance Thermal Insulation Materials*, Autex Research Journal (under review).

[11] M. Venkataraman, R. Mishra, T. M. Kotresh, J. Militky and H. Jamshaid, *Aerogels for thermal insulation in high-performance textiles*, Textile Progress, Taylor& Francis (under review).

8.2 Book Chapters

[1] Mohanapriya Venkataraman, Rajesh Mishra, Jiri Militky, "*Advanced fibrous materials for thermal insulation-I*". in: Progress in fibrous material science. 2014. ISBN:978-80-87269-40-4

[2] Mohanapriya Venkataraman, Rajesh Mishra, Jiri Militky, "*Advanced fibrous materials for thermal insulation-II*". in: Progress in fibrous material science. 2014. ISBN:978-80-87269-40-4

[3] Mohanapriya Venkataraman, Rajesh Mishra, Jiri Militky, "*Performance of aerogel treated blankets under extreme temperatures*". in: Progress in fibrous material science. 2014. ISBN:978-80-87269-40-4

[4] Mohanapriya Venkataraman, Rajesh Mishra, Hafsa Jamshaid and Jiri Militky, "*Aerogels: Novel Materials for Insulative Textiles*". in: Selected Properties of Functional Materials. OPS, 2013. ISBN: 978-80-87269-29-9

[5] Mohanapriya Venkataraman, Rajesh Mishra, Hafsa Jamshaid and Jiri Militky, "*Aerogel Based Insulation Materials: Characterization of Thermal, Electrical and Electromagnetic Behavior*." in: Selected Properties of Functional Materials. OPS, 2013. ISBN: 978-80-87269-29-9

8.3 Contribution in conference proceedings

[1] Mohanapriya Venkataraman, Rajesh Mishra and Jiri Militky, *Heat Transport Phenomena in Aerogel Treated Nonwoven Fabrics,* 11th Joint International Conference CLOTECH'2015, June 17th-19th, 2015 Lodz, Poland.

[2] Mohanapriya Venkataraman, Rajesh Mishra and Jiri Militky, *Heat Transport Phenomena in Advanced Insulation Materials,* 6th International Technical Textiles Congress, 14-16 October, 2015 İzmir-TÜRKİYE.

[3] Mohanapriya Venkataraman, Rajesh Mishra, Jakub Weiner, Marie Stepankova, Veerakumar Arumugam, Jiri Miltky, *Effect of Laser Irradiation on Kevlar Fabric Treated with Nanoporous Aerogel,* 7th International Conference on Nanomaterials - Research & Application (NANOCON 2015), October 14th - 16th 2015 / Hotel Voronez I, Brno, Czech Republic, EU, ***Thomson Reuter, Indexed in ISI Web of Knowledge***.

[4] Mohanapriya Venkataraman, *Dynamic Thermal Measurement for Advanced Insulation Materials and Their Biological Implications*, 8th Textile Bioengineering and Informatics Symposium (TBIS), Zadar, Croatia , 2015, ***CPCI/ISTP, ISI web of knowledge, Scopus & Ei compendex***.

[5] Mohanapriya Venkataraman, Rajesh Mishra, Jakub Weiner, Adnan Mazari, Jiri Militky, Veera Kumar Arumugam, *Innovative Techniques for Characterization of Nonwoven Insulation Materials Embedded with Aerogel*, ICTCME 2014, Switzerland

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[7] Mohanapriya Venkataraman, Rajesh Mishra, Veerakumar Arumugam and Jiri Militky, *Thermal analysis of aerogel treated non woven fabrics*, Fibre society spring conference, May 21-23, 2014, ***Scopus***.

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[11] Mohanapriya Venkataraman, Rajesh Mishra, Veerakumar Arumugam and Jiri Militky *Thermodynamical Characterization of Aerogel Treated Nonwoven Fabrics*, 7th International Textile, Clothing & Design Conference (ITC&DC), Dubrovnik, Croatia, 05-08, October, 2014, ISBN 978-953-7105-549, ***CPCI/ISTP ISI web of knowledge***.
[12] Mohanapriya Venkataraman, Rajesh Mishra, Veerakumar Arumugam and Jiri Militky, *Thermodynamics of aerogel treated non woven fabrics*, ICIC 2014, Coimbatore , 29-30 April 2014, ISBN: 9788192375243.
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[14] Mohanapriya Venkataraman, Rajesh Mishra and Jiri Militky, *Analysis of thermal properties of aerogel treated non-woven fabrics*. 42nd Textile Research Symposium. Mount Fuji, Japan, 28th to 30th August 2013.
[15] Mohanapriya Venkataraman, Rajesh Mishra and Jiri Militky, *Analysis of thermal properties of aerogel treated non-woven fabrics*. 8th International Conference-Textile Science. Liberec, Czech Republic. 23rd to 25th September 2013. ISBN:978-80-7372-989-9
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[20] Mohanapriya Venkataraman, Rajesh Mishra and Jiri Militky, *Unconventional Methods to Study Thermodynamics of Aerogel Treated Fabrics*. 3rd International Science Congress. Karunya University, Coimbatore, India. December 2013
[21] Mohanapriya Venkataraman, Rajesh Mishra and Jiri Militky, *Aerogels: A Novel Material for Thermal Insulation*. 19th International Conference STRUTEX. Liberec, Czech Republic. December 2012. ISBN: 978-80-73729-13-4
[22] Mohanapriya Venkataraman, Rajesh Mishra and Jiri Militky, *Comparative Analysis of Thermal Insulation Measurement Techniques in Textiles*. 19th International Conference STRUTEX. Liberec, Czech Republic. December 2012. ISBN: 978-80-73729-13-4

9 Curriculum Vitae

PERSONAL INFORMATION

Name	Mohanapriya Venkataraman **M. Tech., M. F. Tech., (Ph.D.)**
Department	Technical University of Liberec Faculty of Textile Engineering Department of Material Engineering
Address	**Studentska 2, 46117 Liberec, Czech Republic**
Mobile	**00420604605433**
E-mail	**Mohanapriya.venkataraman@tul.cz**
Nationality	INDIAN
Date of birth	23/01/1981

EDUCATION AND TRAINING

• Dates	Jan 2016 (Expected)
• Name of organisation providing education	**Ph.D (Doctoral studies) - Faculty of Textile Engineering, Technical University of Liberec, Czech Republic**
• Principal subjects	Thermodynamic Analysis of Aerogel Treated Textiles at extreme temperatures
• Dates	May 2010
• Name of organisation providing education	**Post Graduation – Department of Textile Technology, Anna University, Chennai, Tamil Nadu, India.**
• Principal subjects	Specialization: Textile Technology
• Dates	May 2010
• Name of organisation providing education	**Post Graduation – National Institute of Fashion Technology (NIFT), Chennai, Tamil Nadu, India.**
• Principal subjects	Specialization: Fashion Technology
• Dates	May 2004
• Name of organisation providing education	**Post Graduate Diploma – National Institute of Fashion Technology (NIFT), Chennai, Tamil Nadu, India.**
• Principal subjects	Specialization: Garment Manufacturing Technology
• Dates	May 2002
• Name of organisation providing education	**Graduation (Bachelors) - – Department of Textile Technology, Anna University, Chennai, Tamil Nadu, India.**
• Principal subjects	Specialization: Textile Technology
• Dates	2006/2007
• Name of organisation providing training	**Silverplus Laboratory Certification – Limited Brands.**

• Principal subjects	Specialization: Laboratory Certification
• Dates	2007
• Name of organisation providing training	**Six Sigma Green Belt (Certification) – Intimate Fashions India Private Limited, Chennai, Tamil Nadu, India.**
• Principal subjects	Specialization: Six Sigma
• Dates	May 2002
• Name of organisation providing training	**Bullet Proof Manager (Certification) – Crestcom International Private Limited, Chennai, Tamil Nadu, India.**
• Principal subjects	Specialization: Management
• Dates	May 2008
• Name of organisation providing training	**Executive Development Program (Certification) – Loyola Institute of Business Administration (LIBA), Chennai, Tamil Nadu, India.**
• Principal subjects	Specialization: Management

PRESENT POSITION AND RESEARCH

- since 1.1.2012 – research scholar at Faculty of Textile Engineering, Technical University of Liberec
- research activities in the area of thermodynamic analysis of aerogel treated textiles.

• Organizational experiences

- Organization of various academic, cultural and sports programmes during Ph.D., Post graduate and Bachelors.
- 2004-2008, Organization of Induction programs for new Employees
- 2004-2008, Organization of ISO 9001:2000 / ISO 14001:2004 training for Employees
- 2004-2008, Organization of Six Sigma training for Employees
- 2004-2008, Organization of behavioural and management programs for team

• Professional experience

- June, 2004 – June, 2008, worked as Executive, Material Quality Assurance at Intimate Fashions India (P) Ltd., India.
- since 2012 research in field of thermodynamic analysis of aerogel treated textiles at extreme temperatures.
- 2014 – internship, Central Leather Research Institute, India
- 6/2014 – internship, Shinshu University, Japan
- 12/2013 – internship, Central Leather Research Institute, India
- 10/2013 – internship at Indian Institute of Technology (IIT-M), India

• Pedagogic experience

- Part-time lecturer: Comfort of textiles, Quality control, Garment Manufacturing etc.
- 2004-2008, Internal trainer for ISO, Six Sigma, Orientation, Behavioural and Management programs at Intimate Fashions

India Private Limited.

10 Brief description of current expertise, research and scientific activities

[1] Preparation of aerogel based insulation materials

[2] Study of thermal behavior of aerogel based materials

[3] Heat transfer phenomena in fibrous structures

[4] Comfort of protective fabrics at extreme temperature conditions.

[5] Explore unconventional methods to measure thermal properties

[6] Prediction and Modeling of heat transfer through convection

11 Record of the state doctoral exam

TECHNICKÁ UNIVERZITA V LIBERCI
Fakulta textilní

ZÁPIS O VYKONÁNÍ STÁTNÍ DOKTORSKÉ ZKOUŠKY (SDZ)

Jméno a příjmení doktorandky: **Mohanapriya Venkataraman**

Datum narození: **23. 1. 1981**

Doktorský studijní program: **Textilní inženýrství**

Studijní obor: **Textile Technics and Material Engineering**

Termín konání SDZ: **15. 4. 2015**

prospěla **~~neprospěla~~**

Komise pro SDZ:

		Podpis
Předseda:	prof. Ing. Jiří Militký, CSc.	
Místopředseda:	prof. Ing. Jaroslav Šesták, DrSc., dr.h.c.	
Členové:	doc. RNDr. Jiří Vaníček, CSc.	
	doc. Mgr. Irena Lovětinská-Šlamborová, Ph.D.	OMLUVENA
	Ing. Blanka Tomková, Ph.D.	Tomková

V Liberci dne 15. 4. 2015

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12 Recommendation of the supervisor

TECHNICKÁ UNIVERZITA V LIBERCI
Fakulta textilní

Supervisor's opinion on PhD thesis of Ing. Mohanapriya Venkataraman

The PhD candidate has followed objective measurements for evaluation of heat transmission properties. The selection of hydrophobic amorphous silica aerogel is quite appropriate for application in textile material which provides the super insulating properties of silica aerogel in a flexible form. The coverage of structural variable is quite wide to investigate the effect. The custom built instrument and the laboratory set-up equipment were found to be effective in measuring the heat transport properties of fabrics as they measure the steady-state thermophysical properties (thermal insulation properties) even at sub-zero temperatures.

From the heat transfer mechanisms, it is concluded that high insulation is due to layered structure and higher thickness. The thermal resistance of the fabric is directly proportional to its thickness. The findings show that the aerogel based fabric samples show considerably low thermal conductivity and high thermal resistance even at extreme low temperatures. In my analysis, various measurement techniques carried out to study thermal properties are quite exhaustive exercise and shows the high quality research for award of PhD. A comparative analysis of thermal properties of insulating materials has been carried out and finally it is concluded that aerogel has a significant potential to be used as insulation material for textile applications. Some instruments are fabricated and the results obtained from them are authenticated to correlate with the results from other standard equipments. This is how the work is completed by developing a process, product and characterization technique.
The thesis is quite systematic and it is presented according to a format I believe. All experimental procedures are written clearly with specific objective. Language level is quite high and meets the PhD standard. It appears the candidate is clear about her objective.

The chapter about nanofibrous layer with embedded aerogel is quite innovative and provides some nes findings on application of such advanced materials in small dimensions. Though the conductivities are extremely low, the thickness of the material will be important determinant of the overall insulation property.

Her publication activities are in very good level. She has 10 papers in impact factor journals and about 20 papers presented individually or jointly at international conferences.

I therefore recommend the thesis for defence.

D. 17. 12. 2015

doc. Rajesh Mishra, PhD
Supervisor

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13 Opponent's reviews

Indian Institute of Technology, Delhi

Hauz Khas, New Delhi-110 016

14th December 2015

From
Prof. Bijoya Kumar Behera, Ph.D.
Department of Textile Technology
Indian Institute of Technology Delhi

To
Ing. Jana Drašarová, Ph.D.
Dean, Faculty of Textile Engineering
Technical University of Liberec

Review report of the Doctoral thesis of Mohanapriya Venkataraman,

On the topic

"Thermal Insulation of High Performance Fibrous Materials".

(a) Importance of the PhD Thesis for the field of science

The study of thermal properties for fibrous material is important and complex because of the fact that many variables and interactions among the variables significantly influence the properties. This is more relevant in the present context due to advent of new fibres, innovative textile structures, post manufacturing treatments, new chemicals and applications and a wide range of measurement techniques depending on end uses. Understanding the role of each parameter on thermal property and interactions among them generated obvious interest and significance in the field of textile science. This research focus on several aspects of investigation of measurement techniques of thermal properties , which can be considered as important component in the field of science. The study of thermal properties of aerogel treated fibrous material is of vital importance both in apparel and technical applications.

(b) The methodology adopted for fulfilment of the set aim

The researcher has realised the need of objective measurement methods in accurate evaluation of heat transmission properties. Therefore, they have used various thermal measurement techniques and also different types of insulation materials were characterized with regard to thermodynamical properties at different temperature gradients. The selection of hydrophobic amorphous silica aerogel is quite appropriate for application in textile material which provides the super insulating properties of silica aerogel in a flexible form. The coverage of structural variable is quite wide to investigate the effect. I think it makes sense to justify the overall fulfilment of methodology to achieve targeted aim. Study of the electrospun PUR and PVDF nanofibrous layer embedded with silica aerogel regarding their thermal behaviour seems to be a new addition to the field.

(c) The importance of the author's contribution

In this research, it is concluded that the thickness, density and mainly the aerogel present in the fabrics are three important factors which determines the insulation property. The thickness of fabric strongly affects amount of heat insulation , which is also an established fact. In general, the greater the fabric thickness, greater the thermal insulation. The custom built instrument and the laboratory set-up equipment were found to be effective in measuring the heat transport properties of fabrics as they measure the steady-state thermophysical properties (thermal insulation properties) even at sub-zero temperatures. From the heat transfer mechanisms, it is concluded that high insulation is due to layered structure and higher thickness. The thermal resistance of the fabric is directly proportional to its thickness. The findings show that the aerogel based fabric samples show considerably low thermal conductivity and high thermal resistance even at extreme low temperatures. In my analysis, various measurement techniques carried out to study thermal properties are quite exhaustive exercise and shows the depth of research for award of PhD. A comparative analysis of thermal properties of insulating materials has been carried out and finally it is concluded that aerogel has a significant potential to be used as insulation material for textile applications. Some instruments are fabricated and the results obtained from them are authenticated to correlate with the results from other standard equipments. This is how the work is completed by developing a process, product and characterization technique.

(d) Methodicalness, clarity of structure, layout and the language level of the PhD Thesis

The thesis is quite methodical and it is presented according to a format I believe. All experimental procedures are written clearly with specific objective. Language level is quite high and meets the PhD standard. It appears the scholar is clear about her objective.

(e) The student's publications

The scholar has already published her work in five peer reviewed journals and another six papers are under review. The research work is also presented in many conferences. The requirement for PhD in this aspect is university specific.

(f) I recommend the PhD thesis for the defence.

Prof. Bijoya Kumar Behera

Dr. B. K. BEHERA
Professor

Opponent's review

This opponent's review was elaborated based on Ing. Jana Drašarová, PhD. (dean of Faculty of Textile, Technical University in Liberec) assignment for review Ph.D. dissertation thesis (ref. no. TUL-15/4814/042704, dated 9. 11. 2015) of **Mohanapriya Ventakaraman, M.Tech.** entitled **"Thermal Insulation of High Performance Fibrous Materials".** Tutor of the PhD. student was Doc. Rajesh Mishra, PhD. Above mentioned Ph.D. dissertation thesis forms broad scientific study on the latter topic of thermal insulation of high performance fibrous materials of the total 149 A4 pages split into 5 chapters. Thesis presented fulfills all requirements stated in "Study and execution order" of Technical University in Liberec published on 11. 6. 2012, paragraphs 21 and 22 with respect to the composition and structure of the dissertation thesis requirements. Dissertation thesis of Ms. Mohanapriya Venkataraman represents relatively novel and wide set of data of thermal properties of fibrous nonwoven materials. These materials are interesting from commercial point of view. All scientific methods used and the overall scientific approach applied for this type of study are adequate to the up to date scientific knowledge. From the formal point of view, dissertation theses were written in proper English language style however missing in some parts more scientific specificity and in detail focus (e.g. in some experimental techniques there is not sufficient described apparatus and measurement conditions details – sections 3.2.1., 3.3.3 and , 4.2 etc.). Some of the graphs are not sufficiently descriptive and not well designed for the reader to give the ability to fully understand and follow the author´s message and information delivered (e.g. missing proper scale description in fig. 22, fig. 44 too many valid digits present, fig. 84 missing legend for data points etc.). However, the aims of the thesis were fulfilled and completed. There were designed new measurement techniques of thermal properties such as particle image velocimetry, steady state thermal measurement instrument and heat convection instrument and they were tested and evaluated with respect to the statistical robustness and precision. Author has published some of the data obtained during the PhD. studies in relatively high number of scientific papers in well-established journals (7 items) and 4 others are under review at the present moment. Ms. Venkatamaran is the author of 5 book chapters.

Based on the thesis, I would like to hear answers from the applicant on the following questions: Which experimental technique did you used for FTIR measurements? How do you describe the effect of air flow resistivity on thermal insulation properties?

Based on the latter mentioned facts and by the course of law (Higher Education Law No. 111/1998. Sb.) §47 I recommend to accept the PhD. dissertation thesis of Mohanapriya Ventakaraman, M.Tech. for defense.

In Zlín, November 18, 2015

prof. Ing. Lubomír Lapčík, Ph.D.

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