Innovative Techniques for Characterization of Nonwoven Insulation Materials Embedded with Aerogel

Mohanapriya Venkataraman, Rajesh Mishra, Jakub Weiner, Adnan Mazari, Jiri Militky, Veera Kumar Arumugam

Abstract**—**The major objective of this study is to understand the potential of a newly fabricated equipment to study the thermal properties of nonwoven textile fabrics treated with aerogel at subzero temperatures. Thermal conductivity was calculated by using the empirical relation Fourier's law, The relationship between the thermal conductivity and thermal resistance of the samples were studied at various environmental temperatures (which was set in the clima temperature system between +25^{o}C to -25^{o}C). The newly fabricated equipment was found to be a suitable for measuring at subzero temperatures. This field of measurements is being developed and will be the subject of further research which will be more suitable for measurement of the various thermal characteristics.

Keywords**—**Thermal Measurements, Aerogel, Nonwoven, Hot plate Heading.

I. Introduction

TEXTILE materials have found a range of applications in the field of thermal insulation. 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 this regard, measurement of thermal properties of textile materials plays an important role. It is imperative that we study the standard measurement techniques to best understand their strengths and weaknesses and also endeavor to fabricate and try new equipments to compliment or replace existing measurement techniques and equipments. The thermal characteristics of textile fabrics are evaluated using devices that work according to the principles of thermodynamic systems, Heat transfer normally occurs through three modes namely, Conduction, Convection and Radiation. Conduction occurs through air and through material itself but heat transfer by conduction is too small to measure [1]. Conduction is due to fiber to fiber attachment [2]. Since textile fabric is a heterogeneous system of air and fabric, conduction through air and fibers contributes to total thermal conduction of the fabric [3]. In areas where skin comes into contact with fabric, large exchange of heat takes place [4].

A textile structure is essentially a mixture of fibers, air, and moisture, each having distinctly different thermal properties. Thus thermal behavior of the system is the collective and interactive results of these three constituents. Nonwoven materials, because of savings in both space and weight, are one of the most important products in textiles that are being used as thermal insulating materials. Nonwoven fabric is a thick layer of fiber designed to provide insulation and used in various items like, loft, quilts, pillow toppers, and heavy winter jackets. Thermal properties also impact performance in technical nonwoven usages, such as building insulation, automobiles, aircraft, and industrial process equipment. Silica aerogel is a translucent material consisting of a nanostructured SiO_2 network shown in Fig. 1 with a porosity of up to 99%. [5]. Silica aerogel is best suited for thermal insulation applications. Due to high volume of porosity (>95%) and pore sizes, aerogel have high thermal insulation properties. Silica aerogel primarily consists of air which leads to a low solid thermal conductivity [6].

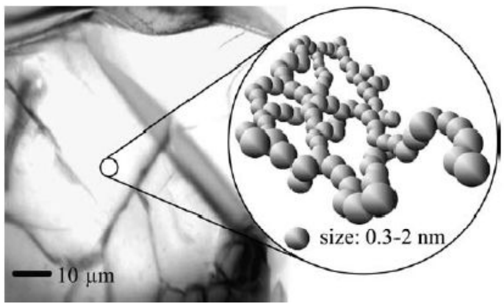

Fig. 1 Structure of the nanoporous SiO_2 network of silica aerogel

Several techniques are available to determine the thermal conductivity of aerogel. Zeng et al. [7] developed a thin- film heater apparatus using a 10 mm thick gold film for uniform spatial distribution of heat. Tests were conducted on opacified silica aerogel and thermal conductivity values of 10-15 mW/mK were reported. Harnath et al. [8] used the transient hot-wire probe method to determine thermal conductivity of silica aerogel prepared by varying molar ratios of TMOS, water, methanol, and catalyst. This method yielded a

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maximum thermal conductivity of 0.1 W/mK and a minimum of less than 0.02 W/mK for the various compositions considered. Other measurements of thermal conductivity have been made using heat-flux meters [9], hot disk thermal constant analyzers [10], and a laser flash apparatus [11]. The major objective of this study is to understand the potential of a custom-built equipment to study the thermal properties of textile fabrics in subzero temperatures. Aerogel treated nonwoven fabrics of different thickness were used as samples to study heat transfer by conduction. Thermal conductivity analyzer and newly fabricated equipments were used for the measurement of thermal properties. The newly fabricated measuring device works according to steady state method which is placed in Clima temperature system (chamber) which operates with the temperature range from -70^{o}C to +180^{o}C. TCi is based on Modified transient state and the data measured at sub-zero temperatures were correlated. A correlation of results from the new equipment and TCi would throw light on possibility of using the new equipment as replacement to TCi for selected thermal measurement experiments.

II. Methodology

A. Materials

In this study, 50:50 ratio composition of polyester/polyethylene nonwoven fabrics treated with aerogel were used. Polyester is the most versatile, most cost-effective and most widely used in various applications. Polyester is perfect for any application where a flexible non woven is required. It is also often supplied as the waterproof material and insulator for the winter clothing. It retains its physical properties when wet and stays extremely stable during humidity changes. This strong and light material resists moisture, staining and chemical attack. Polyethylene has properties like, 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 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 superinsulating properties of silica aerogel in a flexible form. It is excellent for ambient and sub-ambient insulating applications. The thermal wraps were chosen in three different thicknesses Sample 1 (3.5mm), Sample 2 (6.2 mm), Sample 3 (6.6 mm) shown in Table I.

TABLE I
Details of Aerogel Treated Nonwoven Fabric Samples

Sample No.	Fabric density (kg/m3)	Thickness (mm)
1	79.6	3.5
2	80.4	6.2
3	66.7	6.6

B. Methods

A new instrument was fabricated to measure the temperatures in different points for aerogel treated nonwoven fabric. C-Therm Thermal conductivity analyzer (TCi) results were used to correlate with the results from newly fabricated instrument. The thickness of the samples was measured using UNI-Thickness meter. The fabrics were cut for 10X10cm and the weight of the fabric was measured. The microscopic images were taken from scanning electron microscope (SEM) to compare the physical structures of the three fabrics on microscopic scale to determine if any difference were noticeable that could explain test results. The work was carried out in isothermal conditions. The results were found to be relevant for the classification of materials and eventually for quality assessment of multilayered fabrics. All the experiments were carried out in standard atmospheric conditions of about 20°±2°C and 65±2% relative humidity.

1) Scanning Electron Microscope (SEM)

The nonwoven fabric sample of three different thickness treated with aerogel was characterized using SEM (VEGA TESCAN Inc. USA) at 30kV. SEM provides detailed high resolution images of the sample by rastering a focused electron beam across the surface and detecting secondary or backscattered electron signal. It provides images with magnifications up to ~X50,000 allowing sub micron-scale features to be seen i.e. well beyond the range of optical microscopes. It is useful to characterization of particulates and defects in the material and examination of grain structure and segregation effects in the fabric structure [12].

2) Thermal Conductivity Measuring Methods

There are a number of techniques to measure thermal conductivity with each of them suitable for limited range of materials, depending on the thermal properties and the medium temperature. In general, various methods [13],[14] are used for measuring the thermal-insulating values of textile materials. Generally three different methods have been used in the determination of the thermal insulation of fabrics. The first is cooling method in which a hot body is surrounded by a fabric whose outer surface is exposed to the air, and the rate of cooling of the body is determined. Second is disc method, where the fabric is held between two metal plates at different temperatures, and the rate of flow of heat is measured and third is constant temperature method, where the fabric is wrapped around a hot body and the energy required to maintain the body at a constant temperature is found. The thermal properties of a fabric will determine not only its warmth in wear but also how warm or cool the fabric feels when first handled. In general, the heat transport properties can be divided into two groups [15]: steady-state thermal properties such as thermal conductivity and resistance which provide the information on the warmth of a fabric; and transient-state thermal properties such as thermal absorptivity which provides the information of warm-cool feeling when fabric handled first. In practice the measurement of the rate of heat flow in particular direction is difficult as a heater, even when supplied with a known amount of power, dissipates its heat in all directions. Most successful heat transport measuring instruments are: Togmeter [16], Guarded hot plate [17] Alambeta instrument [18], and Thermal conductivity analyzer (TCi). The principle of the apparatus is that for 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 drops across a material of known thermal resistance (standard resistance) and across a test specimen in series with it are measured, the thermal resistance of the test specimen can be evaluated.

3) Custom Built Instrument

The newly fabricated instrument works according to transmission of heat in the steady state condition as described in BS 4745:1971 [16]. Single plate method was used as reference to fabricate this instrument. In single plate method (Fig. 2), 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.

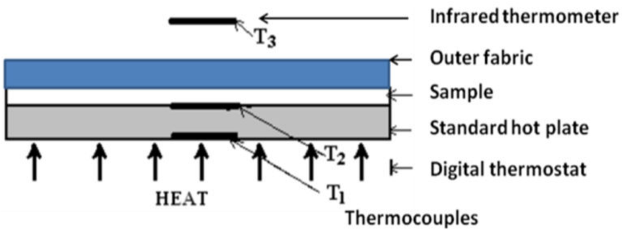


Fig. 2 Schematic diagram of the new fabricated instrument (Single plate method)

The instrument was used to determine the temperatures from various points from which the thermal conductivity and thermal resistance of the fabric is calculated. The sample is placed in Clima temperature system (chamber) which operates with the temperature range from -70°C to +180°C. The instrument measures the heat transport through textile material. The test specimen is placed on the cylindrical hot plate which is connected to the digital thermostat water bath where the skin temperature is maintained at ~ 33°C shown in Fig. 3. The test specimen is placed on the hot plate and up on the test specimen, the outer fabric (100% plain woven cotton fabric) with 10 gms weight on each side is placed. Two thermocouples and heat flow sensors are used to measure temperature variations. First one (T1) is fixed on the surface of the test specimen which touches the hot plate and the second one (T2) is fixed on the surface which is covered by the outer fabric. The hot plate is adjusted to the constant skin temperature and the clima temperature system is adjusted to a controlled constant differential temperature. The heat flow sensors act up at the contact faces of both the surfaces of the fabric. With the help of thermocouples, the temperature difference at the upper surface and the underside of the test specimen can be measured. The Infra red thermometer is used to measure the temperature variations on the surface of the outer fabric. The fundamental measuring principal implies the measuring and processing of the heat flows in dependence of time. The instrument measures parameters: (1) Temperature on the surface of the test specimen which is in contact with the skin (T1), (2) Temperature on the surface of the fabric which is in contact with the outer fabric (T2), (3) Temperature inside the clima temperature chamber which is set as the environmental temperature from + 25°C to -25°C (T3) (4) Temperature on the surface of the outer fabric which is sensed by infrared thermometer fixed on top of the surface fabric (T4).

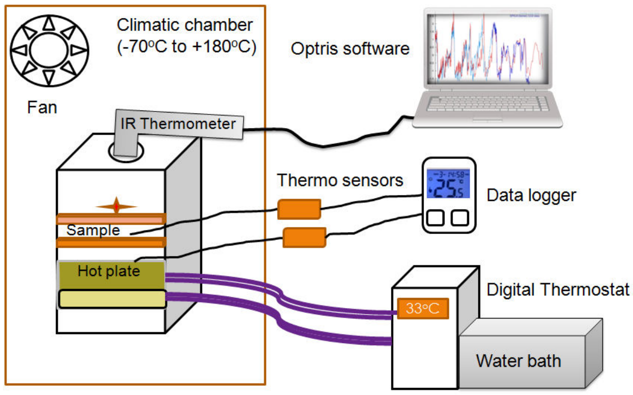


Fig. 3 Schematic diagram of custom built instrument for measuring thermal properties

III. Results and Discussion

A. SEM Micrographs

Scanning electron microscopy (SEM) uses electrons rather than light to form an image and provides useful tools for examining structural and surface characteristics of textile materials. A high resolution and depth of field of images for the aerogel treated nonwoven fabrics are shown in Fig. 4 which confirms that the aerogel is present in between the fiber structure.

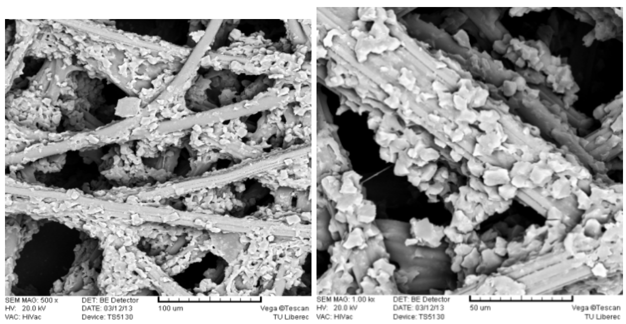


Fig. 4 Scanning electron microscope images of aerogel treated nonwoven fabrics

B. Effect of Temperature Variations

The environmental temperature versus the temperature near the surface of the fabric and outer fabric surface is shown in Figs. 5, 7, and 9. The temperature variations at each point varied for the test specimens with the change in clima-chamber temperature (environmental temperature). The temperature gradient was higher for the lower temperatures (sub-zero temperatures) as shown in Figs. 5-7. The temperature of materials is determined with thermal energy in the form of kinetic energy of disordered molecular movement [19]. Temperature gradient is an important factor for calculating the thermal conductivity of the test specimens. This higher difference in temperature gradient is due to the aerogel present in the nonwoven fabric Aerogel is the main component in the nonwoven fabric structure blocking the air into its highly porous structure which provides insulation and thereby considered to be beneficial for insulation.

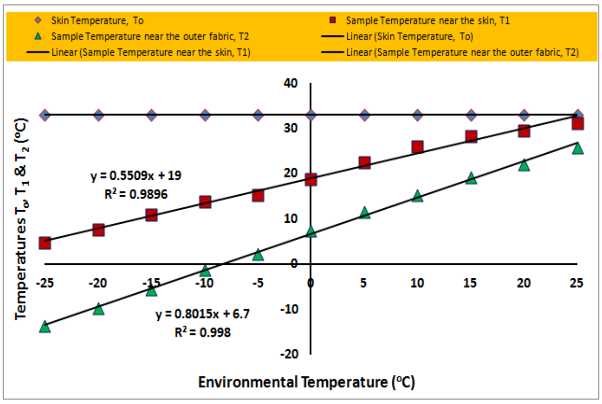


Fig. 5 Temperature variation graph for Sample 1

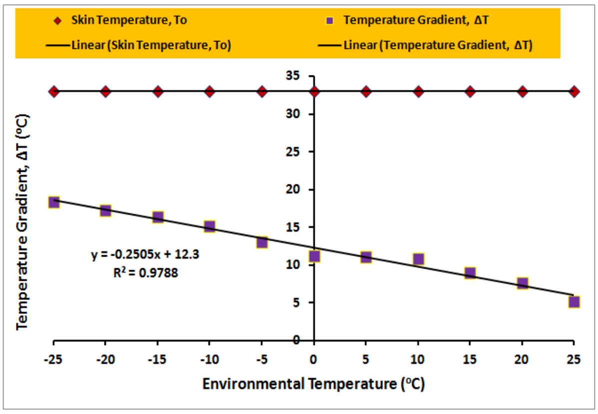


Fig. 6 Temperature gradient graph for Sample 1

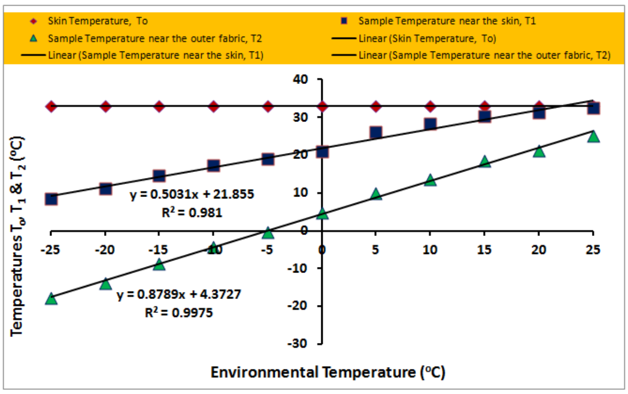


Fig. 7 Temperature gradient graph for Sample 2

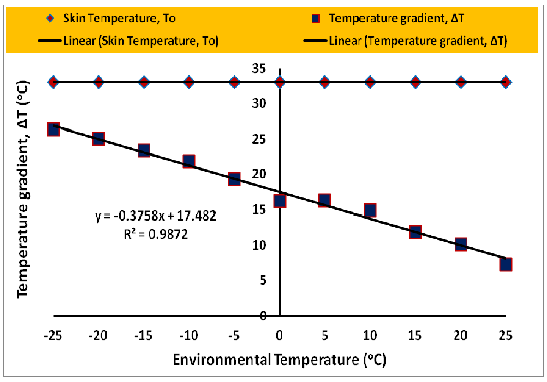


Fig. 8 Temperature gradient graph for Sample 2

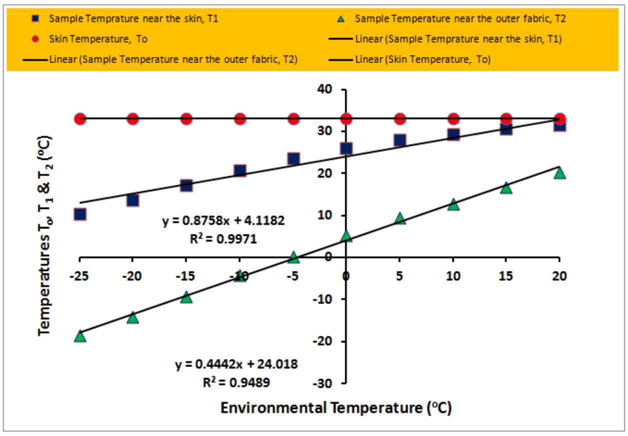


Fig. 9 Temperature variation graph for Sample 3

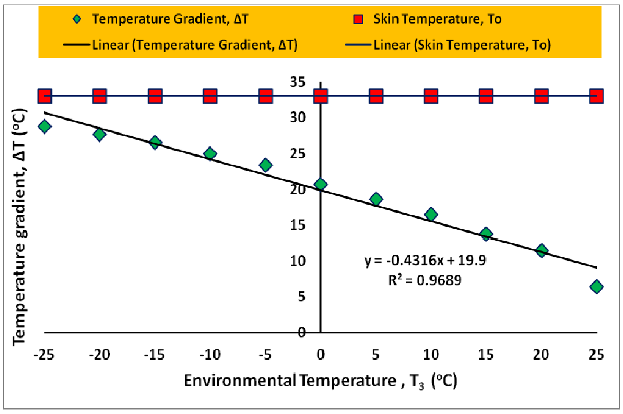


Fig. 10 Temperature gradient graph for Sample 3

Temperature gradient at different exposure temperatures (+25°C to -25°C)) through experiments are plotted in Figs. 6, 8, and 10. From the figures, it is found that the fabric temperature variations increase rapidly in the initial stage of the exposure temperature. This may be because of the temperature difference between the fabric sample and the exposed hot air is high in the early stage of the exposure process. As the temperature stabilizes, the variations are decreased.

C. Determination of Thermal Conductivity

Thermal conduction is the transfer of heat from one part of a body to another with which it is in contact. Thermal conductivity, λ is defined as ability of material to transmit heat and it is measured in watts per square meter of surface area for a temperature gradient of 1 K per unit thickness of 1 m. The thermal conductivity is not always constant. The main factors affecting the thermal conductivity are the density of material, moisture of material and ambient temperature. With increasing density, moisture and temperature the thermal conductivity increases too. Important is inner structure of materials. Materials with very small amount of solid matter and large proportion of voids have the lowest thermal conductivities.

D. Relationship between Heat Flow & Temperature Gradient: Fourier's Law

An empirical relationship between the conduction rate in a material and the temperature gradient in the direction of energy flow, first formulated by Fourier in 1822 [27] who concluded that "the heat flux resulting from thermal conduction is proportional to the magnitude of the temperature gradient and opposite to it in sign". For a unidirectional conduction process this observation may be expressed in (1):

$$q = -\lambda \frac{dT}{dx} \text{ [W/m}^2\text{]} \quad (1)$$

The rate of heat flow is proportional to the difference in heat between two bodies. A fabric sample of thickness x with temperature difference dT experiences heat flow q. where λ is a proportionality constant called the thermal conductivity (W/mK).

1) Determining Thermal Conductivity in Steady State

Thermal conductivity in steady state was calculated from (2):

$$\lambda = \frac{q \times d}{T_1 - T_2} \text{ [W/mK]} \quad (2)$$

where q is quantity of heat passing through a unit area of the sample in unit time [W/m^2]

d distance between two sides of the sample [m]

T1 temperature on warmer side of the sample [K]

T2 temperature on the colder side of the sample [K]

The quantity of transferred heat q is given in (3):

$$q = \frac{Q}{A} \text{ [W/m}^2\text{]} \quad (3)$$

where Q is quantity of heat passing through a base area of the sample [W]; A is base area of the sample [m2]

The quantity of heat transfer was calculated from the product of voltage (volts) and ampere (amps). The product of voltage and ampere was converted to watts. This product was taken as the heat flow 'Q' given in (4).

$$P \text{ (watts)} = V \text{ X } I \quad (4)$$

The calculated thermal conductivity and thermal resistance of the samples are shown in Tables II-IV. Based on the empirical relation expressed in (1), thermal conductivity, λ was calculated from (1) and thermal resistance was calculated from (5). For the calculated thermal conductivity, heat flux was calculated based on the electrical energy to heat energy conversion which from (4).

TABLE II
CALCULATED VALUE OF THERMAL CONDUCTIVITY (TC) AND THERMAL RESISTANCE (TR) OF SAMPLE 1 (3.5 MM)

Environmental temperature, T3 (°C)	TC, λ (W/mK)	TR, r (m2K/W)
-25	0.0248	0.1408
-20	0.0249	0.1403
-15	0.0250	0.1399
-10	0.0251	0.1393
-5	0.0253	0.1383
0	0.0255	0.1374
5	0.0255	0.1373
10	0.0255	0.1372
15	0.0257	0.1363
20	0.0258	0.1356
25	0.0260	0.1345

TABLE III
CALCULATED VALUE OF THERMAL CONDUCTIVITY (TC) AND THERMAL RESISTANCE (TR) OF SAMPLE 2 (6.2 MM)

Environmental temperature, T3 (°C)	TC, λ (W/mK)	TR, r (m2K/W)
-25	0.0429	0.1447
-20	0.0430	0.1440
-15	0.0433	0.1433
-10	0.0435	0.1425
-5	0.0439	0.1413
0	0.0444	0.1398
5	0.0443	0.1398
10	0.0446	0.1392
15	0.0450	0.1377
20	0.0453	0.1368
25	0.0458	0.1354

TABLE IV
CALCULATED VALUE OF THERMAL CONDUCTIVITY (TC) AND THERMAL RESISTANCE (TR) OF SAMPLE 3 (6.6 MM)

Environmental temperature, T3 (°C)	TC, λ (W/mK)	TR, r (m2K/W)
-25	0.0452	0.1459
-20	0.0454	0.1453
-15	0.0456	0.1448
-10	0.0458	0.1440
-5	0.0461	0.1433
0	0.0465	0.1420
5	0.0468	0.1409
10	0.0472	0.1399
15	0.0476	0.1386
20	0.0480	0.1375
25	0.0489	0.1350

Thermal conductivity increases with fabric density and also for constant thickness of fabric, below density of 60kg/m3, increase in fabric thickness causes increased thermal insulation and reduction in fabric temperature variations (up to a optimum level), as fabric density increases thermal conductivity also increases [20]. The increase in weight to thickness ratio causes increase in effective thermal conductivity due to increase in fiber to fiber contact and packing density causes increase in tortuosity i.e. mean free path for photons to be travelled increases so less heat flows through the channels in nonwoven [21]. Regardless the shape of the material, aerogel treated nonwoven fabric acts as an insulating layer with a conductivity that is constant. From the Fig. 11, the thermal conductivity of the samples didn't show much significant difference with respect to environmental temperature. Due to the open pore structure and irregular pore network of the fabric structure and aerogel present, solid thermal conductivity is reduced and gaseous thermal conductivity is also reduced. This reduction is due to the Knudsen effect, where the excited gas molecules that are entering the open pore structure of the silica aerogel collide with the surface of the aerogel and transfer their energy to the surface [22]. This reduces the gases movement, thus limiting the silica aerogel gaseous thermal conductivity. It is also found that gaseous thermal conductivity can be reduced by 33% by placing the aerogel under vacuum [23].

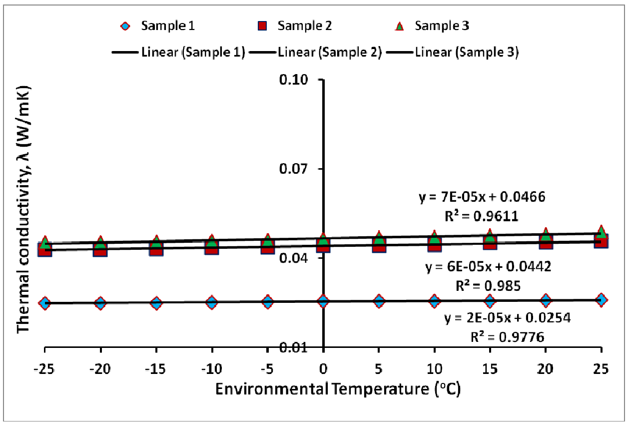


Fig. 11 Thermal conductivity Vs Environmental temperature

E. Determination of Thermal Resistance

Thermal resistance, (resistance to heat flow) is inversely proportional to thermal conductivity and is defined by the following equation:

$$\text{Thermal Resistance } R = \frac{h}{\lambda} \text{ [m}^2\text{W/K]} \quad (5)$$

where, h=thickness of the material; λ=thermal conductivity. Since λ is roughly constant for different fabrics, thermal resistance is approximately proportional to fabric thickness. It is therefore the thickness of the garment that determines its thermal resistance and gives the wearer protection against cold.

Heat loss is determined by insulation thickness and the skin coverage. Winter clothing tends to cover a larger proportion of the body than summer wear. Fig. 12 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 [26]. 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 [24]. The thermal insulation value of porous, low density nonwoven is affected by compression and hence the layered structure of aerogel treated nonwoven fabric gives better insulation because of good compression recoverability [25].

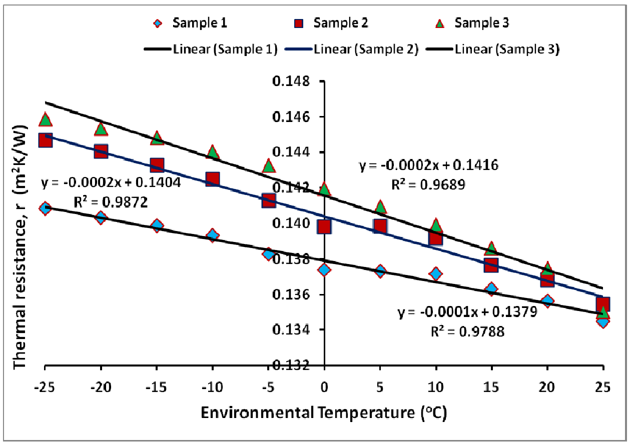
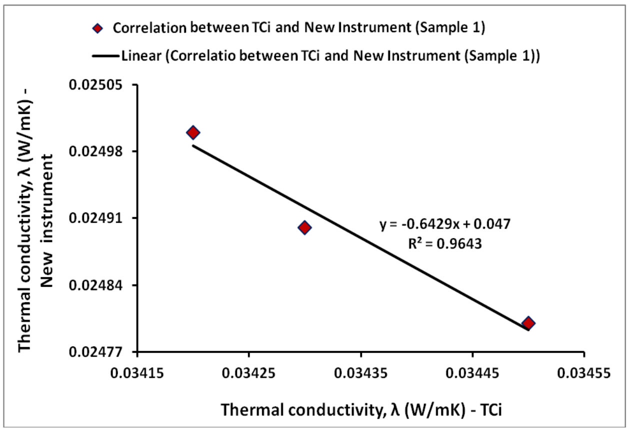


Fig. 12 Thermal resistance Vs Environmental temperature

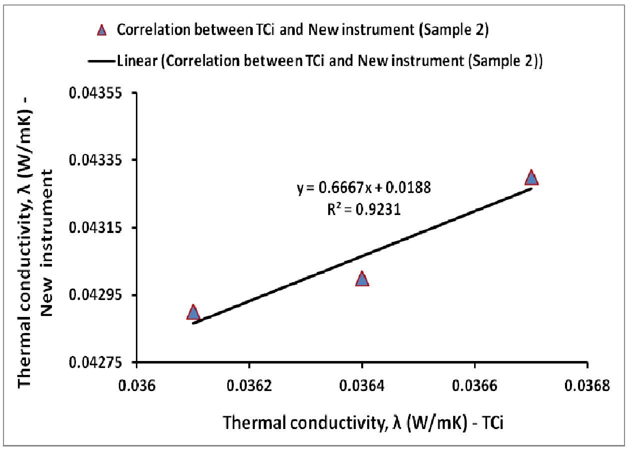
F. Correlation of TCi and New Fabricated Instrument

The two instruments, TCi and newly fabricated are correlated based on the results of thermal conductivity and thermal resistance which was measured under the environmental temperature (sub zero temperatures -15, -20 & -25 °C). Results of thermal conductivity of both the instruments are well correlated (R^2=0.9) which is shown in Figs. 13 (a)-(c). Due to the conductivities of enclosed air in the porous structure of the fabric, fabric conductivity is effectively a constant for fabrics of various thicknesses. Therefore, heat insulation is proportional to the thickness of the fabric.

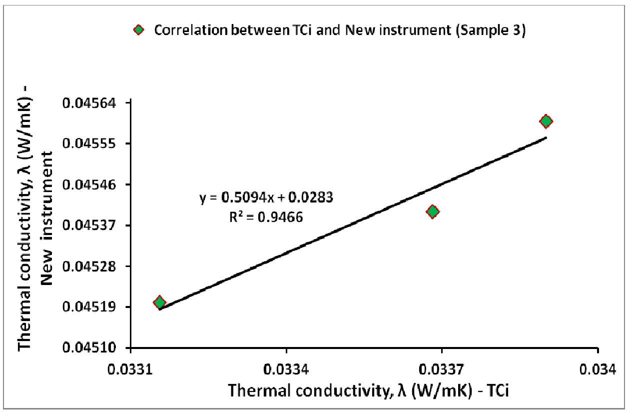
The total thermal resistance to transfer of heat from the body to the surrounding has three effective components namely, resistance to heat transfer from the material surface to surrounding, thermal resistance of clothing material itself and thermal resistance of the air trapped inside the fabric. The correlation of the two instruments for thermal resistance is shown in Figs. 14 (a)-(c). The thermal resistance of the both the instruments are correlated well with the value of around R^2 = 0.9 (R-squared is a statistical measure of how close the data are to the fitted regression line). The correlation of the values proves that the newly fabricated instrument is suitable for measuring the thermal properties.



(a)

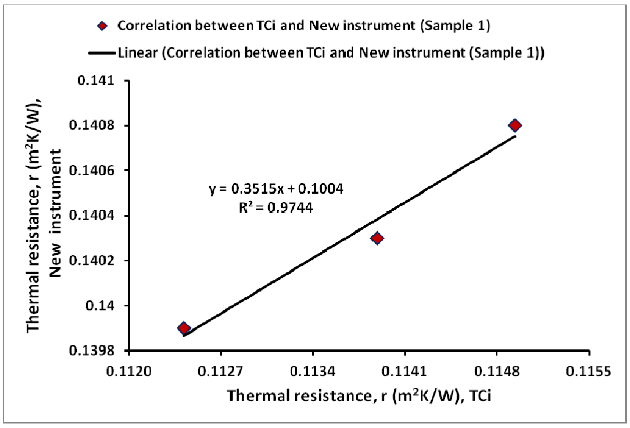


(b)

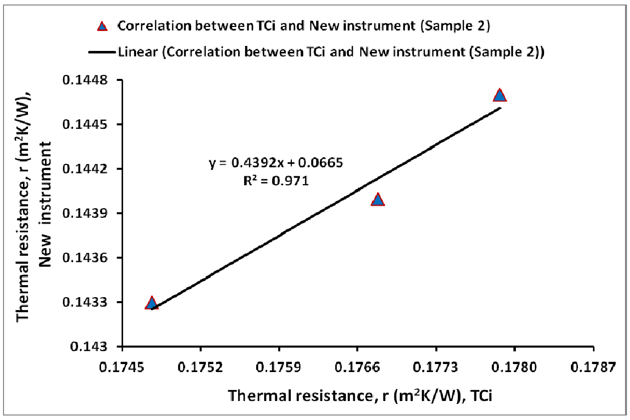


(c)

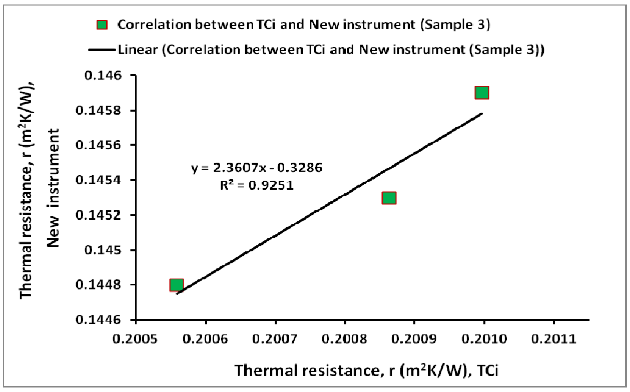
Fig. 13 Correlation of Thermal conductivity for Sample 1 (a), 2 (b) & 3 (c)



(a)



(b)



(c)

Fig. 14 Correlation of Thermal resistance for Sample 1 (a), 2 (b) & 3 (c)

IV. Conclusion

The aerogel based fabric samples were found to have low thermal conductivity and high thermal resistance even at very low temperatures. From the heat transfer mechanisms, we can conclude that high insulation is due to layered structure and higher thickness. In the case of cold weather clothing, higher thermal resistance is important. The objective measurement is required for accurate results in evaluation of heat transmission properties. From the study, the newly fabricated instrument was found to be effective for measuring the heat transport properties of fabrics as it measures the steady state thermo-physical properties (thermal insulation properties The study concludes that the selected fabrics have high thermal performance and thermal response as insulators. The correlation between thermal conductivity analyzer (TCi) and the newly fabricated instrument were seem to be good with the value of R2=0.9. The instrument is suitable to measure at sub-zero temperatures and convenient for the measurement and evaluation of various temperature variations at different points of the fabric. We are currently working towards improving our device to evaluate its influence on the experimental results. As future direction, this field of measurements is still open and will be the subject of further research of other methods.

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