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Evaluation of Heat Resistance Characteristics of Fibrous Material for Cold Weather Application

M. D. Bangera [a], Y. S. Chavan [a], S. V. Patel [b]*, V. N. Patil [b]

[a] *Research scholar, Bharati Vidyapeeth College of Engineering, Navi Mumbai, 400614, India*
[b] *Mechanical Engineering, Bharati Vidyapeeth College of Engineering, Navi Mumbai, 400614, India*

KEYWORDS

Nonwovens;
Polyester fibers;
Cold weather apparel;
Thermal insulation.

ABSTRACT

The denier, cross-section, mass density, porosity, and depth of the nonwovens are the nonwovens' physical characteristics that depend on the thermally resistant layer. In this study, we use solid and hollow polyester fibers of various deniers to attempt to optimize these factors for extreme bulk nonwovens. An analysis of contributions has been done to determine the importance of thickness, spatial density, fiber fineness, and form. Better thermal insulation is provided by finer fibers. Nonwovens have a relatively high porosity, and their thermal resistance is particularly low for the lighter and thinner varieties. Thinner and lighter extreme cold-weather apparel is best made from hollow, finer fibers because of their higher thermal insulation. For any studied solid fiber nonwoven with constant thickness, the intrinsic thermal insulation of the nonwoven decreases with an increase in areal density. For 15 mm thick nonwoven, the maximum thermal insulation of 0.4522 m^2K/W is obtained for nonwoven with an areal density of 100 g/m^2 with 4 denier polyester solid fiber, and the minimum thermal insulation of 0.305 m^2K/W is obtained for nonwoven with an areal density of 300 g/m^2 with 10 denier polyester solid fiber. The same trends are obtained for nonwovens with thicknesses of 10 mm and 5 mm.

1. Introduction

The utilization of numerous layers of fabric assembly rather than a single bulky layer is the foundation of extreme cold-weather clothing. When wearing only one layer of clothes, it is challenging to adapt to shifting climatic conditions and metabolic activity. Overall, thermal insulation suffers, as does moisture transfer. The multilayer clothing system normally consists of a three-piece outfit, with each layer serving a particular purpose. First is the basal layer, which oversees the transfer of moisture and maintains the skin's dryness. The second layer is the insulating layer, which traps air to keep the wearer warm. The third function of the protective layer is to serve as a barrier against wind, rain, snow, and other weathering elements.

Obendorf and Smith [1] examined fiber web thermal resistance. It was found that the heat conductivity of the nonwoven web is not directly proportional to the fiber surface outer diameter, regardless of the manufacturing process. Accordingly, fine-diameter fibers have higher updraft resistance. Jirsak et al. [2] examined fiber web thermal insulation. Perpendicular-laid nonwoven webs were more thermally resistant than cross-laid ones due to their mass. Thus, nonwovens must trap more air. Punch density decreases needle-punched nonwoven fabric thickness, increasing thermal conductivity [3]. Many researchers have examined how pressure and temperature affect nonwoven structures' thermal resistance. Pressure decreases heat resistance in nonwovens, but it stabilizes them [3–4]. Fibers' thermal conductivity increases with temperature [5]. Epps [6] examined fabric air permeability and heat transfer correlations. Layers reduce air permeability and thermal transmission.

Depth, spatial density, and air volume determine the fabric's heat-insulating ability [7]. Many scholars have studied these factors, but the interaction between them is the missing piece. A fabric with tiny fibers will have a different ideal

* Corresponding author. Tel.: +91- 9619721741
E-mail address: shital.patel@bvcoenm.edu.in

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porosity than one with coarser fibers. Debnath & Madhusoothanan investigated PET nonwovens' updraft opposition [8]. This study created polyester fiber cross-sections with round, hollow, and trilobal shapes using comparable manufacturing processes. Trilobal polyester fiber nonwoven fabric had the best thermal resistance because it was the thickest. Most research [9] did not control thickness, which affects nonwoven structures' thermal resistance.

Fiber denier, cross-section, areal density, and thickness affect nonwoven fabric thermal resistance. Many researchers have found this [10]. Few have studied the thermal resistance of multi-layered or composite nonwovens. Mohammadi et al. [11] assumed parallel fibers to calculate multi-layer nonwoven thermal conductivity. Epps [12-13] found that layering woven, knitted, and nonwoven textiles decreased thermal transmittance. Roger and Barker examined how nonwoven thickness, bulk density, and porosity affected hydroentangled nonwovens with one, two, or three layers [7]. Porosity, thickness, and GSM improve thermal resistance. Layers increase heat resistance. Lin [8] and Lou [14] sandwiched loose nonwoven layers between needle-punched nonwovens to make composite nonwovens. They adjusted the loose nonwoven layers but kept the top and bottom needled fabrics.

Wu & Fan's [15] study of the dry heat loss characteristics of wool and polyester nonwoven layers sandwiched between Gore-Tex fabrics found that keeping the polyester fabric closer to the hot plate caused more dry heat loss than keeping wool on the inner layer. Mao et al. layered warp knit spacer textiles with thin spun laced wool [16]. Wool-spun lace over spacers reduces thermal conductivity. Shabaridharan et al. [17] examined three-layer fabric assemblies' areal density, thickness, porosity, and pore size using the Taguchi approach. knitted, thru-air-bonded nonwoven, and coated woven fabrics. Each layer's three variations are examined. The outer layer's area density and fiber fineness affected the two-layer fabric assembly's thermal resistance. Hu, Mao, and Shabaridharan [14-17] found that the topmost layer's porosity and pore size significantly affect multi-layer fabric assemblies' heat resistance. The thermal resistance of a nonwoven with the same area density and thickness depends on the fiber denier and cross-section. Layered, needle-punched nonwoven compressibility was examined. They used compression and recovery parameters. Dimensionless metrics are useful for assessing nonwoven compression and recovery behavior. Jirsak [2] examined cross- and perpendicular-laid nonwoven heat resistance at 0–2500 Pa pressure. Finer fiber performed worse under pressure than coarser fiber. Both nonwovens behaved similarly.

Still, the air in clothing layers absorbs most of its thermal insulation. Air's main drawback is its radiative heat vulnerability. Radiant heat is unimpeded by air. Textile fibers reflect little. Thus, a suitable material is needed to reflect skin infrared heat radiation. One solution is using metal-coated fabrics as reflecting barriers. Morrisey et al. [18] found that metal coatings increase thermal insulation by 30–75%.

Hsu et al. [19] examined how silver nanowires (Ag NW) in textiles reduced human body heat loss. They found that nanowire-covered textiles reflect a lot of radiative heat radiation to the skin. Silver nanowires reflect 97% of source radiation at 0.03. Normalized reflectance remains unchanged until 600 nm, but as angles approach 90°, it decreases. Human bodies reflect over 40% of Ag N W (silver nanowires), compared to 1.3% for clothing. IR cameras measure the temperature of Ag N W and regular gloves. AgNW gloves are 2–40 °C cooler.

Goosedown is ideal for cold-weather clothing. Goosedown is known for its softness and resilience. Wool and cotton absorb moisture more slowly than polyester and down. Polyester, wool, and cotton are less resilient than goose down. Goosedown has lower thermal conductivity than wool, polyester, and cotton [20]. Chen and Cluver [21] investigated poplar seed hair fiber as a cold-weather insulator. Poplar tree seed pods provide these fibers. These fibers are short, usually 0.95–1.59 cm. Poplar seed fibers are 80–90% hollow. These fibers have thermal resistance comparable to hollow polyester fibers but less than down feathers.

Synthetic microfibers may replace goose down. These one-denier fibers are under 10 microns. Schacher et al. compared micro-denier polyester's thermal resistance to standard polyester [22]. Under different pressures, microfibers had lower qmax values, higher thermal resistance, and lower thermal conductivity than ordinary fiber. Sol-gel and high-pressure drying create aerogels. They have air-like thermal conductivity and a low density (0.09 g/cm3). [23-24] Super-insulating materials. Many researchers have tried to embed materials into aerogels to overcome their brittleness. Mohanapriya et al. studied aerogel nonwoven composites' thermal insulation [25]. These composites had low thermal conductivity from -25 to +25°C. Aerogel nonwoven composites become more thermally resistant as temperatures drop. Wei et al. [26] examined aerogel thermal conductivity from 300 to 700 K. Temperature increases aerogel thermal conductivity. The authors [27–32] studied the effect of various factors on the thermal insulation of high-bulk nonwovens at different operating conditions.

This paper aims to investigate the impact of areal density and fiber denier on thermal insulation in lightweight fabric assemblies for extreme cold weather apparel. The primary objective is to develop lighter, thinner fabric constructions that provide effective thermal insulation while offering flexibility for wearers to endure temperatures as low as -60 °C in wind chill conditions. By optimizing the fiber fineness, the researchers aim to enhance the thermal performance of the nonwoven fabric. The effect of fiber structure on thermal insulation for the same denier, area density, and porosity has been studied in the present work. The research also examines the effect of fiber structure on thermal insulation. Fiber structure refers to the arrangement, shape, and composition of the individual fibers within the nonwoven fabric. The study investigates how different fiber structures influence thermal insulation when other factors such as fiber densities, areal density, and porosity are kept constant. Through a series of planned studies, variations in areal density and fiber denier will be examined to assess their influence on thermal resistance.

2. Materials and Methods

The samples used in our experiment had a controlled thickness as a result. This work has examined the effects of fiber cross-over, diameter, and other essential cloth features, as well as their relationships.

2.1. Sample Preparation

To create the thermally bonded nonwovens for this study, polyester fibers with solid and hollow cross sections were used. In the hollow and solid fibers, linear densities of 4 deniers, 6 deniers, and 10 deniers were chosen. A denier can be defined as the weight of fiber in grams for a 9000-meter length of the fiber. The hollowness of the selected fiber is the same, i.e., 25%. The hollowness can be calculated as

$$hollowness\ (\%) = \left(\frac{inner\ diameter}{outer\ diameter}\right)^2 \quad (1)$$

With this selection of fibers, it is possible to evaluate how fiber properties like linear density and cross-sectional shape affect the thermal insulation of thermally bonded nonwovens. Using a scanning electron microscope, fiber structural properties like diameter, length, and hollowness are measured (Table 1).

Table 1. Solid and hollow polyester fiber characteristics

Sr. No	Linear density (denier)	Inner dia. (μm)	Outer dia. (μm)	Hollowness (%)	Fiber length (mm)
1	4	0	20.5	0	62
2	6	0	25	0	62
3	10	0	32	0	62
4	4	12	23.55	25.96	62
5	6	14.25	28.5	25	62
6	10	18.5	37	25	62

There are two methods for producing thermal bonding on nonwoven webs: calendar bonding and through-air bonding. Since they trap more air with fewer fibers, heat-bonded fiber webs are typically the optimum form for heat protection purposes. They are three-dimensional constructions with substantial bulk and resistance to compression. Any textile structure's heat resistance is primarily influenced by its thickness. Therefore, the thickness of the nonwovens should be kept constant in order to evaluate the impact of different qualities on the material's thermal resistance. Although it can be challenging to create a heat-bonded web with a precise thickness, Here, it is also possible to precisely maintain the nonwoven's thickness. In this method, the fiber web is first created by opening the fiber on a fiber opener, then it is carded. To speed up the bonding process, 15% low-melting PET fibers are added to the standard fibers (Fig. 1). To obtain a web with the specified GSM (g/m^2), the carded web is cross-lapped (Fig. 2).

Fig. 1. Photographs of selected Polyester fibers

Fig. 2. Photographs of Carded web

In this method, fiber webs made of a mix of regular and low-melt polyester fibers are passed between two hot rollers. This method works for thermoplastic fibers (calendar rollers). The web of natural fibers is joined by the melting or partial melting of the thermoplastic fiber. The roller temperature is maintained at a higher temperature than the melting point of low-melt fibers but lower than the melting point of regular polyester fibers, It is also possible to combine low-melt bi-component polyester or polyolefin fibers with synthetic fibers. Lightweight coverstock textiles are made for diaper top sheets using this technique. To achieve effective heat transfer and effective bonding, the calendar pressure must be raised as fabric mass increases. The temperature of the calendar is maintained fairly close to the binder's or low-melt fiber's melting point. When sheath-core bicomponent fibers are employed as a binder, the temperature is set above the sheath's melting point but significantly below the core polymer's melting point. The microscopic images of thermally bonded nonwoven are shown in Fig. 3 (a-d). Figure 3 (a) shows the actual image of the fabric and Figure 3 (b-d) shows the microscopic SEM images of thermal bonded nonwoven. The SEM images 3 b, c, and d were taken at 100x, 300x, and 1000x magnification, respectively, for understanding the bonded nonwoven. Figure 3 (b-d) shows the bonding using colour dotted lines.

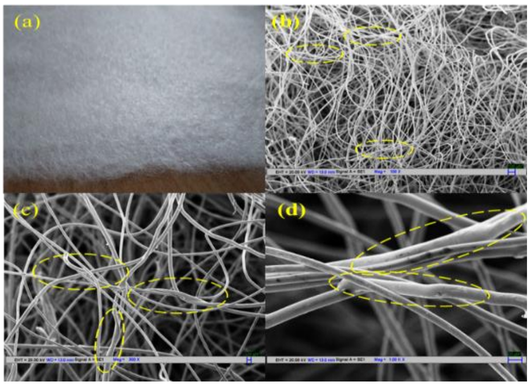

Fig. 3. Micro images of thermal bonded nonwoven

With an increase in binder fiber content, the nonwoven fabric's strength rises. Because there is enough binder to melt and flow to create strong bond points when there are more binders present. To make stronger thermobonded polyester nonwovens, 10 to 25 percent of binder fibers are often combined with regular fibers. Although the bulk of thermoplastic fiber nonwovens typically has a bond area of about 15%, acceptable mechanical qualities require an embossed calendar roll with about 30% contact area. An alternative is hot air-through bonding, which involves passing a web that contains a thermoplastic binder through a hot air oven.

The nonwoven web's bonding process is completed after the created web spends 20 minutes being compressed between heated rollers. All of the fibers used in this investigation were made in three distinct thicknesses and three different areal densities (i.e., 100, 200, and 300 g/m^2) (5 mm, 10 mm, and 15 mm). There were so many such combinations made, one for each type of fiber. A 100 GSM web is used in layers to create thermally bonded nonwovens with higher areal densities [27–32]. This allows for the evaluation of the impact of nonwoven structural parameters on its thermal resistance properties, including areal density, thickness, bulk density, and porosity. The density of manufactured nonwovens can be calculated as follows:

$$porosity = 1 - \frac{density\ of\ fabric}{density\ of\ fibre} \quad (2)$$

2.2. Experimentation

On a heated plate with sweat guards, the nonwovens' thermal resistance is assessed. In this, a hot plate that is held at 35 °C is kept in a 25 °C chamber (ISO 11092). The airflow inside the chamber is stopped to prevent forced convective heat loss (shown in Fig. 4). The impermeable membrane is used to prevent the free escape of air from the nonwoven. The temperature difference will result in heat loss from the plate. The amount of energy (W) needed to maintain the hot plate's fixed temperature is noted. Heat loss can be reduced by keeping a fabric over an area that is heated. The fabric's thermal resistance affects how well it prevents heat from escaping. The thermal resistance of the fabric can be calculated as follows:

$$R_{ct}\left(\frac{m^2K}{W}\right) = \frac{Area(m^2)\ \times Temperaturedifference\ (K)}{Heatloss\ (W)} \quad (3)$$

Intrinsic fabric thermal resistance can be calculated as

$$R_{cf} = R_{ct} - R_{c0} \quad (4)$$

where R_{c0} is the bare plate thermal resistance.

Fig. 4. Sweating guarded hot plate.

3. Results and Discussion

3.1. Effect of Areal Density and Fiber Denier

The effect of areal density and fiber densities on the intrinsic thermal insulation of 15-mm nonwovens made up of solid fibers is shown in Fig. 5. The thermal resistance values obtained from the sweat-guarded hot plate of solid fiber nonwovens with a constant thickness of 15 mm For any studied solid fiber nonwoven with constant thickness, the intrinsic thermal insulation of the nonwoven decreases with an increase in areal density. As the areal density increases, the porosity of the nonwoven decreases. The porosity is directly proportional to the volumetric contribution of air. The thermal conductivity of polyester is higher than that of air. Therefore, for a constant thickness nonwoven, with an increase in areal density, the conductivity of the fabric increases, which results in a decrease in the thermal insulation.

For constant areal density and thickness of the nonwoven, as fiber fineness increases, the thermal insulation also increases. As fiber fineness increases, the pore size of the nonwoven decreases, which results in an increase in the number of pores. For 15 mm thick nonwoven, the maximum thermal insulation of 0.4522 m^{2}K/W is obtained for nonwoven with an areal density of 100 g/m^2 with 4 denier polyester solid (4 D S) fiber and the minimum thermal insulation of 0.305 m^{2}K/W is obtained for nonwoven with an areal density of 300 g/m^2 with 10 denier polyester solid fiber (10 D S). The study also highlights that, for nonwovens with a constant areal density and thickness, an increase in fiber fineness contributes to improved thermal insulation. This is due to a decrease in pore size and an increase in the number of pores as fiber fineness increases.

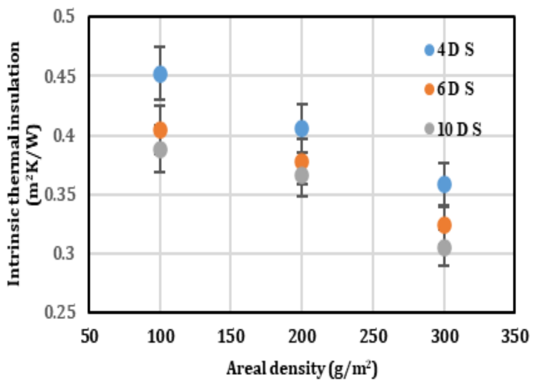

Fig. 5. Effect of areal density and fiber denier on intrinsic thermal insulation of 15 mm thick nonwoven.

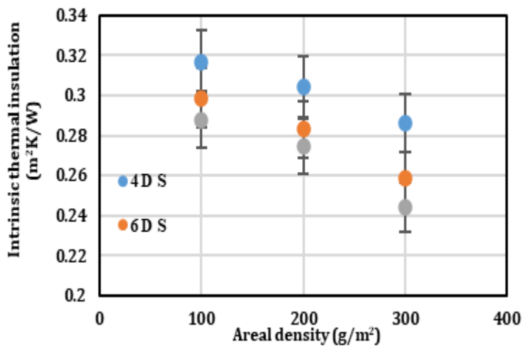

Fig. 6. Effect of areal density and fiber denier on intrinsic thermal insulation of 10 mm thick nonwoven

Figure 6 shows how areal density and fiber denier affect 10 mm nonwoven fabric thermal insulation. A 100 g/m^2 nonwoven made of 4 denier polyester solid fibers has the highest thermal insulation value of 0.3165 m^{2}K/W. A 300 g/m^2 nonwoven with 10 denier polyester solid fibers [10 D S] has the lowest thermal insulation value of 0.244 m^{2}K/W.

Porosity, thermal conductivity, and fiber characteristics explain these results. Increased areal density decreases thermal insulation at 10 mm thickness. Porosity decreases with areal density. Porosity decreases the air volumetric contribution within the nonwoven, decreasing its insulating effect. The findings suggest that balancing areal density and fiber densities in a 10-mm nonwoven fabric optimizes thermal insulation. 100 g/m^2 and 4 denier polyester solid fibers provide the highest thermal insulation, while 300 g/m^2 and 10 denier polyester solid fibers [10 D S] provide the lowest. Fiber denier also affects thermal insulation. Thermal insulation improves as fiber densities decrease. Fiber fineness affects pore size. Finer fibers reduce nonwoven pore size, increasing pore count. Thus, the nonwoven fabric improves thermal insulation.

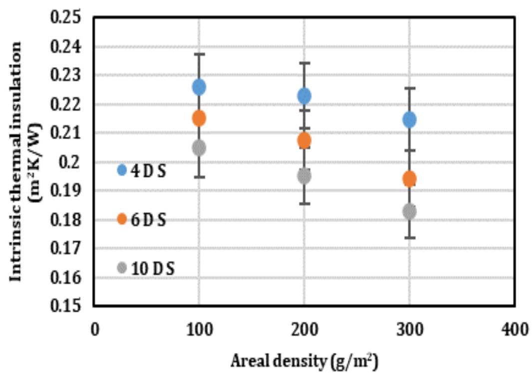

Fig. 7. Effect of areal density and fiber denier on intrinsic thermal insulation of 5 mm thick nonwoven

3.2. Effect of Fiber Structure and Areal Density

Figure 7 shows how areal density and fiber denier affect 5 mm nonwoven fabric thermal insulation. A 100 g/m^2 nonwoven made of 4 denier polyester solid fibers (4 D S) has the highest thermal insulation value of 0.2261 m^{2}K/W. A 300 g/m^2 nonwoven with 10 denier polyester solid fibers has the lowest thermal insulation value of 0.183 m^{2}K/W. Increased areal density decreases thermal insulation at 5 mm thickness. Porosity decreases with areal density. Lower porosity reduces air volume in the nonwoven, reducing insulation. Polyester fibers conduct heat better than air. Thus, the fabric's thermal conductivity increases as areal density decreases porosity, decreasing thermal insulation. For a 5 mm nonwoven fabric, optimal thermal insulation requires careful consideration of areal density and fiber denier. The highest thermal insulation value is achieved with 100 g/m^2 areal density and 4 denier polyester solid fibers, while the lowest is achieved with 300 g/m^2 and 10 denier. Fiber denier affects thermal insulation. Lower fiber densities improve thermal insulation. Nonwoven pore size changes explain this relationship. Finer fibers reduce pore size, increasing pore count. This improves fabric insulation.

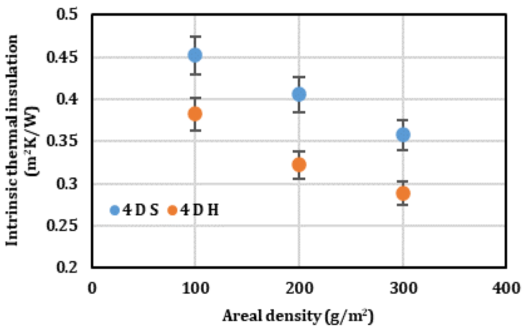

Fig. 8. Effect of fiber structure and areal density on intrinsic thermal insulation of 15 mm thick nonwoven made up of 4 denier solid and hollow fiber

The effect of fiber structure and areal density of a constant 15 mm thick nonwoven made up of 4 denier solid (4 D S) and 4 deniers hollow fiber (4 D H) nonwovens on intrinsic thermal insulation is shown in Fig. 8. The thermal resistance values obtained from the sweat-guarded hot plate of solid and hollow fiber nonwovens of 4 denier fibers with a constant thickness of 15 mm For any studied solid and hollow fiber nonwoven with constant thickness, the intrinsic thermal insulation of the nonwoven decreases with an increase in fiber outer diameter. As the fiber's outer diameter increases, the pore size of the nonwoven increases. Which results in the free escape of thermal radiation and increases the thermal conductivity. Therefore, for a constant thickness nonwoven, with an increase in fiber outer diameter, the conductivity of the fabric increases, which results in a decrease in the thermal insulation. For constant areal density and thickness of the nonwoven, solid fiber nonwoven provides more thermal insulation than that of hollow fiber nonwoven. For 15 mm thick nonwoven, the maximum thermal insulation of 0.4522 m^{2}K/W is obtained for nonwoven with an areal density of 100 g/m^2 with 4 denier polyester solid fiber, and the minimum thermal insulation of 0.2885 m^{2}K/W is obtained for nonwoven with an areal density of 300 g/m^2 with 4 denier polyester hollow fiber (4 D H).

The effect of fiber structure and areal density of a constant 15 mm thick nonwoven made up of 6 denier solid and hollow fiber nonwovens on intrinsic thermal insulation is shown in Fig. 9. For 15 mm thick nonwoven, the maximum thermal insulation of 0.405 m^{2}K/W is obtained for nonwoven with an areal density of 100 g/m^2 with 6 denier polyester solid fiber (6 D S), and the minimum thermal insulation of 0.2775 m^{2}K/W is obtained for nonwoven with an areal density of 300 g/m^2 with 6 denier polyester hollow fiber (6 D H).

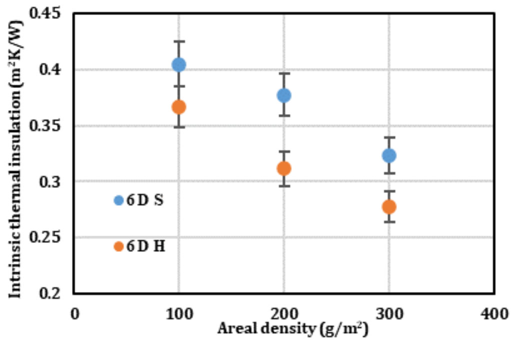

Fig. 9. Effect of fiber structure and areal density on intrinsic thermal insulation of 15 mm thick nonwoven made up of 6 deniers solid and hollow fiber

Figure 10 shows how the structure of the fibers and the area density affect the thermal insulation of a nonwoven fabric with a constant thickness of 15 mm and 10 denier solid and hollow fibers (10 D S and 10 D H, respectively). The results show that a nonwoven made with 10 denier polyester solid fibers and an area density of 100 g/m^2 has the best thermal insulation value of 0.3885 m^{2}K/W. On the other hand, a nonwoven made with 10 denier polyester hollow fibers and a density of 300 g/m^2 has the lowest thermal insulation value at 0.2558 m^{2}K/W. If the thickness stays at 15 mm and the area density goes up, the thermal insulation goes down. The fact that the porosity decreases as the area density increases can help to explain this. The amount of air in a nonwoven fabric decreases as its area density goes up. This makes the fabric better at transferring heat, or thermal conductivity. Because of this, thermal insulation goes down. Solid fibers have a continuous structure that makes it hard for heat to move through, while hollow fibers have a space inside that makes it easier for heat to move through. The results show that for a 15-mm nonwoven fabric, the best thermal insulation comes from a combination of an area density of 100 g/m^2 and 10-denier polyester solid fibers (10 D S). The worst thermal insulation comes from a combination of an area density of 300 g/m^2 and 10 denier polyester hollow fibers.

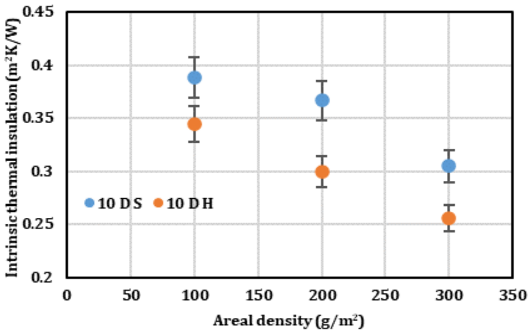

Fig. 10. Effect of fiber structure and areal density on intrinsic thermal insulation of 15 mm thick nonwoven made up of 10 denier solid and hollow fiber

4. Conclusions

In this work, the effect of fiber denier, areal density, thickness, and fiber hollowness on the thermal resistance of nonwovens is studied in detail. Solid and hollow polyester fibers with linear densities of 4 deniers, 6 deniers, and 10 deniers were used. The thermal resistance of the nonwoven structure is inversely related to the denier of the fiber, regardless of the cross-sectional form of the fiber.

For any studied solid fiber nonwoven with constant thickness, the intrinsic thermal insulation of the nonwoven decreases with an increase in areal density. For 15 mm thick nonwoven, the maximum thermal insulation of 0.4522 m^{2}K/W is obtained for nonwoven with an areal density of 100 g/m^2 with 4 denier polyester solid fiber, and the minimum thermal insulation of 0.305 m^{2}K/W is obtained for nonwoven with an areal density of 300 g/m^2 with 10 denier polyester solid fiber. For 10 mm thick nonwoven, the maximum thermal insulation of 0.3165 m^{2}K/W is obtained for nonwoven with an areal density of 100 g/m^2 with 4 denier polyester solid fiber, and the minimum thermal insulation of 0.244 m^{2}K/W is obtained for nonwoven with an areal density of 300 g/m^2 with 10 denier polyester solid fiber. For 5 mm thick nonwoven, the maximum thermal insulation of 0.2261 m^{2}K/W is obtained for nonwoven with an areal density of 100 g/m^2 with 4 denier polyester solid fiber, and the minimum thermal insulation of 0.183 m^{2}K/W is obtained for nonwoven with an areal density of 300 g/m^2 with 10 denier polyester solid fiber.

Conflicts of Interest

The author declares that there is no conflict of interest regarding the publication of this manuscript. In addition, the authors have entirely observed the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancy.

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