THERMAL BEHAVIOR OF AEROGEL-EMBEDDED NONWOVENS IN CROSS AIRFLOW

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Abstract:

Thermal performance of aerogel-embedded polyester/polyethylene nonwoven fabrics in cross airflow was experimentally studied by using a laboratory-built dynamic heat transfer measuring device in which the fabric could be applied on a heating rod. Experiments were performed with different airflow velocities and heating conditions. The temperature–time histories of different materials were collected and compared. The temperature difference and convective heat transfer coefficient under continuous heating were analyzed and discussed. Results showed that under preheated conditions, the aerogel-embedded nonwoven fabrics had very small decrease in temperature and good ability to prevent against heat loss in cross flow. As for the continuous heating conditions, the heat transfer rate of each material showed an increasing trend with increase in the Reynolds number. The aerogel-treated nonwoven fabric with the least fabric thickness and aerogel content delivered a significantly increased heat transfer rate at higher Reynolds number. Thicker fabrics with higher aerogel content could provide better insulation ability in cross flow.

Keywords:

Nonwoven fabrics, silica aerogel, cross airflow, heat transfer coefficient

1. Introduction

High-loft fibrous materials are widely used in various fields for thermal insulating applications due to the large amount of void space in the fibrous structure. The thermal properties of a fibrous material are affected by the physical parameters of the fiber component and the structural parameters of the fibrous structure. Silica aerogel, as a coherent with a rigid three-dimensional network of contiguous particles of colloidal silica, prepared by the polymerization of silicic acid or by the aggregation of particles of colloidal silica, demonstrates superior thermal insulation performance with extremely low thermal conductivity and thus has been well acknowledged as one of the most attractive thermal insulating materials [1-2]. However, since silica aerogels generally have poor mechanical stability, they are usually incorporated with a lightweight fibrous material to deal with various heat transfer problems [3]. Various aerogel-embedded fibrous materials, developed by the sol–gel method or by incorporating aerogel beads into a nonwoven fibrous web by using low-melting fibers or additive binding materials, have been well studied [4-7]. These materials exhibit improved thermal insulation and thus have a potential to be used in buildings, industry facilities, and protective textile applications such as winter jacket, sleeping bed, and gloves in extremely cold weather.

Aerogel-embedded nonwoven fabric is basically a highly porous, fibrous material. It is well known that heat transfer in a fibrous material is a complex property because the three basic mechanisms of heat transfer, namely, conduction, convection, and radiation, play a part [8]. The insulating property, resulting from the fact that the gas contained in the pores is at rest, has been well understood and documented. Convective heat transfer through a fibrous material, resulting from a fluid moving across a surface that carries heat away, involves complex and diverse flow patterns around the solid particles or fibers [9]. Generally, the rate of convective heat transfer is a function of the fluid and surface temperatures, the surface area, and the speed of the flow across the surface. Due to the inherently air-permeable characteristic of a highly porous material, air intrusion through the void space usually occurs in the fibrous structure, which strongly affects the convective thermal behavior of a porous material. In practical use, the influence of air movement depends on the structural parameters of the fibrous material and the nature of the airflow as well [10]. Forced convection usually generates highly turbulent, multidirectional flows as a function of venting characteristics, material geometries, and wind speed [11]. Due to the complexity of the geometry and flow pattern, it is difficult to obtain a clear relationship between the individual fabric parameters and the thermal behavior, as most of them are interrelated to each other and therefore impossible to separate. In order to observe the convective heat transfer through textiles, approximate solutions based on computational fluid dynamics and well-established dimensionless numbers are usually used [12]. The effect of fibrous structures on fluid flow has been numerically studied...
[13]. A study on the modeling and simulation of convective heat transfer in aerogel-embedded nonwoven fabric has also been carried out [14]. Experimental investigations of convective thermal behavior of aerogel-embedded fibrous materials in a controlled climate chamber have been reported [15-16]. However, all these works deal with a simple airflow moving over an absolutely flat fabric placed on a heating plate. In some actual cases, the airflow and the state of the fabric are more complicated, especially in applications involving buildings and industrial facilities, for example, fibrous insulators applied on domestic hot water plumbing lines to improve energy efficiency, on process equipment, piping, steam distribution systems, and boilers for process control, energy efficiency and safety. Such applications involve a cross airflow around a hot cylinder that is insulated with a fibrous material.

The aim of the present work is to perform an experimental study on the thermal behavior of aerogel-embedded polyester/polyethylene nonwovens when subjected to wind-induced cross airflow. Aerogel-embedded polyester/polyethylene nonwovens with different structural parameters and aerogel content were selected to carry out the measurements. A laboratory-built dynamic heat transfer device was used to figure out the convective thermal behavior of the selected materials under different airflow velocities and heating conditions. Real-time temperatures of the fabrics were collected and compared. The temperature difference and heat transfer coefficient under continuous heating condition were calculated and investigated.

### 2. Experimental

#### 2.1. Materials

Three types of polyester/polyethylene nonwoven fabrics with at 50:50 composition ratios and embedded with aerogel were selected to assess their thermal performances under convective heat transfer with air. The aerogel used was hydrophobic amorphous silica aerogel, which is mesoporous and has nearly 98% of air and 2% solid. Its specifications are presented in Table 1. Due to the interconnected nanoporous characteristic, the aerogel can hold air within its structure and does not allow free flow of air, which enables it to be a superior thermal insulation material. The aerogel particles were added during thermal bonding of the nonwoven web. A high-resolution image of the aerogel/polymer nonwoven fabric B is shown in Figure 1. It is clear that aerogel particles are dispersed both on the surface of a single fiber and in the void spaces between fibers. The physical properties of the aerogel-embedded nonwovens are given in Table 2. All these fabrics have high porosity of >90%.

#### 2.2. Measurement of thermal behavior in cross flow

##### 2.2.1. Experimental setup

The tests were carried out in a laboratory-built device; the experimental section is presented in Figure 2. The main part of the measured section consists of a subsonic wind tunnel with a square cross section of 20 cm x 20 cm, an electric heating rod with a diameter of 2 cm placed perpendicular to the airflow direction in the wind tunnel, and a fan ventilator connected in the right corner of the lower duct. The heating rod, composed of a Ni-Cr 80-20 heating wire with a stainless steel shell, having a rated power of 500 W and voltage of 230 V, was connected to a control unit and powered by a Sefram DC power supply. The input power was adjusted by the control unit. The fan ventilator, acting as a suction fan, supplies airflow at room temperature. Different airflow velocities can be achieved by adjusting the fan speed.

The experiments involve measurements of real-time temperatures of the heating rod, the fabric insulators, and the upstream airflow, as well as determination of the velocity of the upstream airflow. Temperatures of the heating rod and the fabric were measured with T-type copper–constantan thermocouples. Two thermocouples were respectively attached on the heating rod and the fabric surface with the help of high-temperature RTV silicone. A thermoanemometer sensor FVAD35TH5 was mounted in the upstream region to monitor the velocity and temperature of the free stream. All these thermocouples and sensor were connected through an ALMEMO 2590-2A - 2 data logger to a personal computer device.

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**Table 1. Amorphous silica aerogel specifications**

| Properties          | Value range         |
|---------------------|---------------------|
| Particle size range  | 0.1–0.7 mm          |
| Pore diameter       | ~20 nm              |
| Density             | 135±15 kg/m³        |
| Surface chemistry    | Fully hydrophobic    |

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**Figure 1.** Scanning electron microscope (SEM) image of aerogel/polymer nonwoven.
2.2.2. Experimental procedures

The selected aerogel-embedded nonwoven fabric was cut into 20 cm x 8 cm pieces and wrapped on the heating rod; the lateral gap was sealed with insulating rubber tape. Any gaps between the measured fabric and the heating rod were eliminated. The tests were carried out with two types of heating conditions, i.e., preheated and continuous heating conditions, to investigate how the materials prevent against heat loss from the heating rod. The preheated condition refers to the preheating of the heating rod to a specific temperature and subsequently switching off the heating power to let the system cool down at a selected air flow velocity. The continuous heating condition involves nonstop heating during the whole measurement process. The voltage and current supplied from the direct current (DC) power for heating were 37 V and 0.33 A, respectively, for each measurement. Five air flow velocity levels, i.e., 0, 1, 5, 10, and 15 m/s were used to study the effect of air flow velocity on the heat loss rate of different fabrics during cross flow.

In this study, the preheated temperature was chosen to be around 60°C, and the ambient temperature was maintained at 23°C±2°C. At the beginning of a measurement at the preheated condition, the heating rod was heated to 60°C, the power supply was cut off, and the fan ventilator was switched on to let in airflow with a selected velocity. The sensed data on temperatures and air flow velocities were collected at intervals of 3.2 seconds. During the continuous heating measurement, the heating rod was maintained being powered, and the airflow was allowed to be delivered when the temperature of the heating rod reached 60°C. Data were taken as soon as the inlet airflow reached a selected velocity. The experimental work includes two parts: the first dealt with the flow around a heating rod without fabric, and the second with the flow around the porous fabric wrapped on the heating rod. For each part, measurements were performed under both preheated and continuous heating conditions at different air velocity levels. Each measurement was conducted three times, and the results were averaged.

3. Results and discussion

3.1. Fluid flow around the heating rod without fabric

For the circular heating rod in cross airflow, as the airflow approaches the front side of the rod, the fluid pressure rises and the free stream fluid is brought to rest at the forward stagnation point [17]. The high pressure forces the fluid to move along the surface, and boundary layers develop on both sides. The free stream velocity depends on the angle from the stagnation point. The pressure force is counteracted by viscous forces, and the fluid separates from both sides of the rod and forms two shear layers. The innermost part of the shear layers is in contact with the rod surface and moves slower than the outermost part. As a result, a highly irregular wake is formed in the downstream region. The flow pattern is dependent on the Reynolds number Re, which is given by the following expression:

\[ Re = \frac{VD}{v} \]  

where \( V \) is the velocity of air (in meter/second [m/s]), \( D \) is the diameter (in meters), \( v \) is the kinematic viscosity of air at the film temperature (in square meter per second [m²/s]), which is 15.89 × 10⁻⁶ m²/s at 25°C.

The Reynolds number range for the heating rod was 1259–18880. The temperature–time histories of the heating rod are presented in Figure 3. Apparently, under the preheated condition, there is a rapid decrease in temperature and a high heat loss rate; this rate subsequently slows down until the heating rod cools to ambient temperature. The overall heat loss rate is determined by the airflow velocity. At air velocity 0 m/s, the rod temperature slowly decreases. As the airflow velocity increases, the temperature values dramatically decrease, and the overall heat loss rate significantly increases. As for the continuous heating condition, the same trend is observed. Remarkably, at airflow velocity 1 m/s, the heating rod quickly reaches a stable temperature value. The probable reason is that at this airflow velocity, heat gain due to the heat flow inlet into the heating rod is exactly equal to the heat loss, leading to a stable temperature value.
to a steady state without any change in temperature of the heating rod. As expected, an increase in airflow velocity gives rise to a dramatic rise in the rate of heat transfer and thus a rapid decrease in heating rod temperature.

3.2. Thermal behavior of the heating rod and fabrics under preheated condition

In the preheated condition, the heating rod has an initial temperature around 60°C. It loses heat by conduction due to the temperature difference between the heating rod and the fibrous insulator, and the fabric gains heat. Some of this heat energy is turned into heat capacity if the fabric temperature increases, and the remainder is transferred to the fabric surface and lost as the air flows over it. The net heat loss from the system results in the changes of the rod temperature and the fabric temperature.

The temperature–time histories of different fabrics are compared in Figure 4. Apparently, a low airflow velocity gives a gentle downslope of the heating rod and fabric temperatures, whereas a high velocity causes rapid temperature decline and higher heat loss rates of the system. Comparing with the temperature of the naked rod, the heating rod wrapped with an aerogel-embedded nonwoven fabric has much lower heat loss rate, indicating an effective insulating function of the fabrics during cross flow. Meanwhile, very small temperature decreases are observed for all the three fabrics, further improving their good thermal performance during cross flow. With the increase in airflow velocity, the heating rod temperature lowers down; the decrease in each temperature–time curve is more obvious. Generally, the heating rod with aerogel-treated nonwoven samples B and C demonstrates higher temperature in comparison with sample A, and the temperature gradient is more significant at higher airflow velocities. This could be explained by the difference of fabric structural parameters and aerogel content. Nonwoven fabrics have very close porosity values > 90%, with pore size ranging from 2 µ to 4.5 µ, which allows the bulk of air molecules to flow through [18]. However, the aerogel particles, with an average pore size around 20 nm, will retard – or even prevent – airflow stream. As a result, greater aerogel content gives less permeability to airflow and thus lowers the heat transfer rate. Meanwhile, thinner fabrics are easier to be penetrated by the air stream, causing more heat loss from the heating rod. As a result, aerogel-treated nonwovens with higher aerogel content and fabric thickness demonstrate better ability to prevent against heat loss under airflow-induced convection. Moreover, at higher airflow velocity, fabrics with more mesopores (diameter: 2 –50 nm) tend to be less affected by the airflow. This is further proved by the higher temperature values observed for fabrics with more aerogel content when the airflow velocity is >5 m/s.

3.3. Thermal behavior under continuous heating

In the continuous heating condition, a specific electric power is supplied to the heating rod. For the system composed of the heating rod and the fabric, the heat flow generated by the heating rod was partly converted into its heat capacity, and the remainder was conducted to the fabric and finally turned into heat capacity of the fabric or dissipated by air-induced convection. The whole dynamic process is influenced by power supply, airflow nature, physical parameters of the heating rod, as well as the physical and structural parameters of the fabric.

The real-time temperature curves of the heating rod and different fabrics under continuous heating are presented in Figure 5. Generally, the fabrics maintain quite stable temperature values under continuous heating, while the heating rod temperature curves have slight fluctuations at low airflow speed (1 m/s and 5 m/s), which gently increase at a higher airflow speed (10 m/s). These fluctuations are well consistent with the current switch. It is notable that the heating rod with Fabric A has rapid temperature decrease from 58°C to 48.8°C when the airflow velocity is 15 m/s. This implies that the aerogel content and fabric thickness are very important factors in protecting against heat loss at high airflow velocity. Similar to the results from the preheated condition, samples B and C, with higher fabric thickness and aerogel content, demonstrate better ability to prevent against heat loss from the heating rod. Especially at higher airflow speed (10 m/s and 15 m/s), the heating rod is able to achieve quite high temperature values, indicating better thermal protection given by these fabrics. For
Figure 4. Temperature-time histories of the heating rod and fabric under preheated condition.
the reason given with reference to the preheated condition, the real-time temperature curves of different fabrics vary with airflow velocity.

3.4. Heat transfer coefficient under continuous heating

The continuous heating of the system under airflow-induced convection is a dynamic process involving complex flow patterns around solid particles or fibers. Due to the random orientations of the solid phase, exact solutions to the detailed local flow field are impossible. In order to compare the thermal performance of different fibrous materials, the system can be considered to reach steady state if the temperature of the heating rod and the fabric are fluctuating within a narrow range or showing a very gentle upslope. In this case, the heat gain by the system is roughly equal to the heat loss from the fibrous material by convection, as shown in Figure 6.

Heat flow was measured by noting the current and voltage input to the heating rod. The average heat transfer coefficient is determined by the following expression:

$$h = \frac{Q_{\text{inlet}}}{S(T_f - T_{\text{air}})}$$

where $Q_{\text{inlet}}$ is the heat flow into the heating rod (in Watts); $T_f$ is the temperature of the fabric surface (in Kelvin); $T_{\text{air}}$ is the temperature of ambient air (in Kelvin); and $S$ is the surface area of the fabric exposed to the airflow (in square meters $[m^2]$).

Since the Reynolds number is important in predicting flow patterns in different fluid flow situations for convective heat transfer problems, the heat transfer coefficient is plotted for different Reynolds number in Figure 7. The heat transfer coefficient increases with the increase in Reynolds number. The data fall in distinct groups depending on the fabric density and permeability of the material. For lower-density materials, dispersion dominates any molecular conduction, resulting in heat transfer independent of solid conductivity but more affected by the airflow. The heat transfer coefficient of each material shows an increasing trend with the increasing of Reynolds number. A flat upstream trend is observed for aerogel-treated nonwoven fabrics B and C. Aerogel-treated nonwoven fabric A, having the least fabric thickness and aerogel content, delivers slightly lower heat transfer rate at small Reynolds number. However, the coefficients significantly increase with the increase in airflow velocity and Reynolds number. For Reynolds number <10000 (airflow velocity <10 m/s), the heat transfer rates of different fabrics are quite close because of free
Figure 5. Temperature–time histories under continuous heating.
fibrous materials for thermal insulation. Additional fundamental and numerical works are necessary for better understanding of convective heat transfer through aerogel-embedded fibrous materials.

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3.5. Difference in temperature between heating rod and air under continuous heating

Figure 8 shows the difference in temperature between heating rod and airflow under continuous heating. The temperature difference is fairly invariant over a range of Reynolds numbers. For the heating rod without fabric, temperature difference lies in the range of 32°C to 8°C, showing considerable decrease with increasing Reynolds number, as expected. The present fabric maintains the heating rod at a higher temperature because of its ability to prevent against heat loss. Comparing the temperature differences of different fabrics, it is seen that the heat losses from fabrics B and C are very close because of the close proximity of their thickness and greater aerogel content. Meanwhile, Fabric A gives much greater heat loss. It can be concluded that fabrics with higher thickness and aerogel content provide better insulation ability during cross flow, especially for high Reynolds numbers.

4. Conclusions

In this work, three aerogel-embedded nonwoven fabrics were selected to investigate thermal behavior in cross airflow by using a laboratory-made device. It was found that under preheated conditions, all the three fabrics showed very small temperature decrease, indicating that these fabrics are effective in preventing against heat loss during cross flow. The fabric with higher thickness and aerogel content had better ability to retain heat during cross flow. The results from continuous heating showed that the thinner fabric with lower aerogel content had limited ability to protect against heat loss at high airflow velocity, while the thicker fabrics with higher aerogel content demonstrated lower heat transfer rate, especially at high Reynolds numbers or airflow velocity >10 m/s. The findings can be used for further study in the areas of aerogel-embedded high-performance fibrous materials for thermal insulation. Additional fundamental and numerical works are necessary for better understanding of convective heat transfer through aerogel-embedded fibrous materials.

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Figure 8. Comparison of differences in temperature between heating rod and air.

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