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High-Temperature Thermal Conductivity of Ceramic Fibers

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The ceramic fibers VK-60, ABK, and VK-80 produced by steam blowing and nozzle dissemination methods have been investigated for the effect of nonfibrous material content, pressure, and temperature on the thermal conductivity at ambient and higher temperatures. It was noticed that with an increase in the aluminum content of the ceramic fibers the thermal conductivity of the material decreased while the insulation properties improved. The VK-80 fibers have the lowest and the VK-60 fibers the highest value of thermal conductivity at ambient temperature. At ambient temperature, the value of thermal conductivity increased with an increase in pressure for all analyzed fibers. ABK fibers showed the least increase and VK-80 registered an increase of about 10% in the values of thermal conductivity for pressures ranging from 0.6 to 6.6 kN/^{2}. However, beyond a pressure of 6.6 kN/m^2, the thermal conductivity of all samples increased. To assess the insulation properties of investigated fibers, the thermal conductivity was measured at different temperatures up to 800 °C. From the obtained results, it was concluded that all three types of fibers have a good potential for future applications, showing good performance in the investigated temperature range.

Keywords aluminum oxide, ceramic, fibers, thermal conductivity

Introduction

The advanced ceramic fiber materials are potential candidates for high-temperature applications due to their low weight and excellent thermal insulation properties. The fact that these fibrous materials have been primarily designed for the internal isolation of space vehicles and missiles, and as a reinforcement for the metal matrix and ceramic matrix composites, which are used under extreme environmental conditions, the exact information on their thermal transport properties is the most essential for their proper use. Recently, these fibers have also been used in industrial boilers, furnaces, chemical reactors, *etc.*

The current work emphasized the thermal properties of different types of ceramic fibers (inorganic based alumna-silica fibers) over a wide range of temperatures. The difference in the thermal properties of various fibers may be correlated to the variation in their structure and chemical composition. It is common knowledge that various factors, such as manufacturing technique, structural behavior, density, applied pressure, impurities of the material, *etc.*, influence the thermal conductivity. The main aim of this investigation was to study the influence of these factors and the effect of high-temperature treatment on the thermal conduction of the investigated alumna-silica fibers. As a result, it has become possible to identify the material having an optimum performance, *i.e.*, lower thermal expansion and conductivity at high temperature, so that insulation with a high margin of safety and lower cost may be obtained. Consequently, a suitable ceramic fiber may be recommended in accordance to its specific applications.

Among others, the most commonly used materials are basalt, boron, and silicon carbide fibers. These are relatively inexpensive and easy to manufacture. However, ceramic fibers have an advantage over these fibers, since they possess a higher thermal stability and have better insulation properties. Such fibers can be produced either by the melt extraction technique or from colloidal solution by the nozzle dissemination method. Depending upon the content of aluminum oxide, the product may be amorphous or crystalline. Fibers with oriented grains have lower values of thermal conductivity and are better for high-temperature applications.

Materials and Method

Three types of fibers with different contents of aluminum oxide (Table 1) produced at "NPO Stekloplastic" have been

Table 1 Chemical composition of fibers

	Chemical composition (wt.%)					
Fiber trademark	Al_2O_3	SiO_2	B_2O_3	Application temperature	Density g/cm^3	Production method
VK-60	60	40	. . .	1350	2.94	Stema blowing
ABK-70	70	28	2	1400	3.05	Nozzle dissemination
VK-80	80	20	. . .	1450	3.20	Nozzle dissemination

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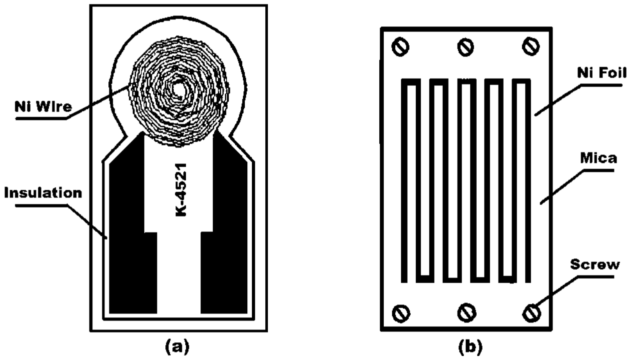

Fig. 1 Design of TPS hot disk and TPS strip

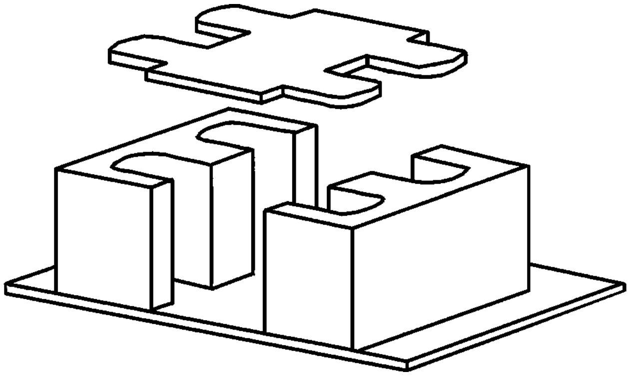

Fig. 2 Sketch of sample holder

investigated.[1,2] The fiber diameter for analyzed materials varied from 3 to 5 m. The steam blowing method (melt extraction technique) allows production of only discontinuous fibers, whereas the nozzle dissemination method is suitable for manufacturing both discontinuous and continuous fibers. The diameter of continuous fibers is usually higher and varies from 10 to 12 m. In this work, we analyzed the properties of discontinuous fibers only. The length of analyzed fibers was not greater than 25 mm.

The Measuring Techniques

The existing thermal conductivity measurement techniques may be classified as steady-state and non-steady-state methods.[3–7] In this work, the transient plane source (TPS) technique was chosen. This method provides a greater accuracy in thermal conductivity measurements for materials with low thermal conductivity.

The key measuring device in such a method is the TPS sensor,[8–10] which can be either in the shape of bifilar Ni spiral, known as hot disk (Fig. 1a), or strip (hot strip) shown in Fig. 1(b). The hot disk can be insulated by mica or caption. For room and cryogenic temperatures, caption insulation is preferred, and, for elevated temperature, mica is the choice. The hot strip is isolated by two mica sheets.

For better measurement accuracy, a good contact between the sample and the TPS element is essential. For this reason, fibrous materials were placed in the sample holder (Fig. 2) mounted in a high-temperature furnace. The temperature was thermostat controlled with a deviation of ±3 °C. The thermal conductivity at a uniform pressure of 1.658 kN/m^2 was obtained over a wide range of temperatures. In order to avoid random errors, the value of each fiber was determined three times. A detailed description of the technique used is given elsewhere.[9–11]

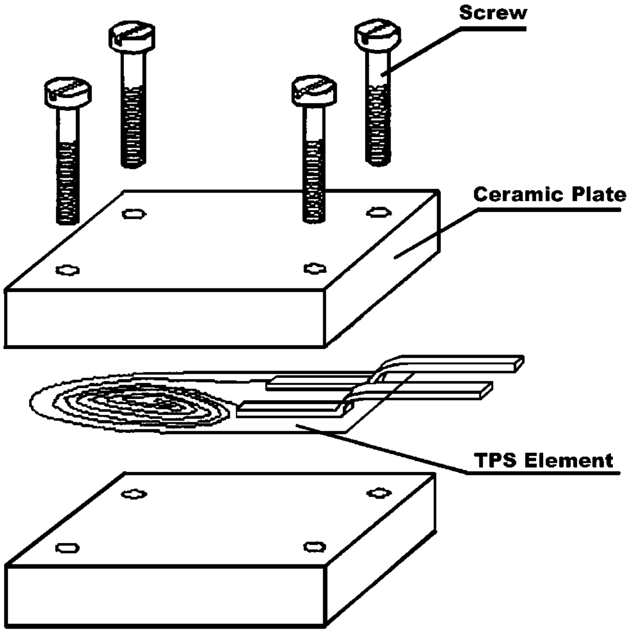

Fig. 3 Sketch of measuring device analyzed

Results and Discussions

The fibers under investigation (Table 1) have different compositions and application temperatures. The VK-60 fiber contains 60% of aluminum oxide, which is the maximum possible content attainable by the melt extraction technique. This method ensures high productivity and a good quality level. In the melt extraction technique, an electrical arc oven is used to melt raw alumna-silica. The melt from the oven is forced through a fiber formation nozzle, which is supplied by overheated steam. In the fiber formation nozzle, the drops of melt are entrapped by overheated steam (supplied at a supersonic speed) and laminated into fibers.[1] The obtained material contains about 0.15% of organic binder and has approximately 50% of nonfibrous particles. The main advantage of these fibers is their low cost and suitability for use at high temperature.[12]

It is known that an increase in the aluminum oxide content results in an improvement in thermal stability, so there was a demand for fibers with higher content of aluminum oxide. Both ABK and VK-80 fibers were produced from colloidal solution by the nozzle dissemination process. In this process, a complex solution is forced through dies into a working chamber, where it is laminated into fibers by two air jets. The formed fibers land on a transporter net and are treated then at a high temperature.[2] In ABK fibers, besides the main oxides, boron oxide is also added in order to stabilize the Al_2O_3 and improve the mechanical properties of the fiber.

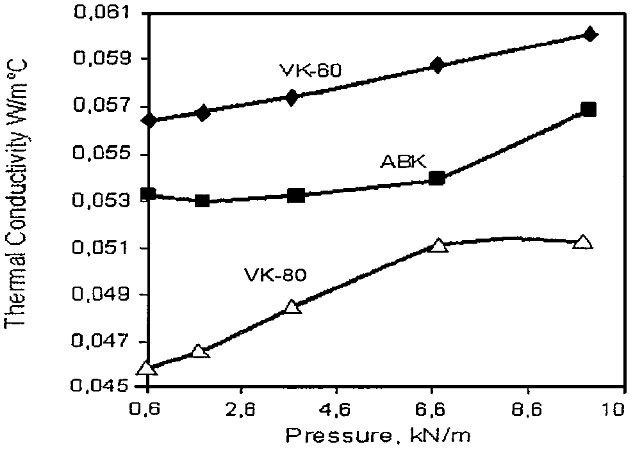

Fig. 4 The impact of pressure on thermal conductivity

The XRD analysis showed that VK-80 and ABK fibers have crystalline structure, whereas VK-60 fibers showed a typical low-angle broad peak, indicating the presence of amorphous phase.

Evaluating the applications of the fibers, it is important to consider the effect of material bulk density on thermal conductivity. Since the bulk density is a function of applied pressure, the analyzed specimens were put in a sample holder and the thermal conductivity was measured as a function of applied pressure, which was varied in the range of 0.46 to 9.66 kN/m^2.

Based on the results obtained, a correlation between the thermal conductivity and the applied pressure (press load) was obtained (Fig. 4). It can be seen that the ABK fibers do not show any significant increase in thermal conductivity at a pressure range of 0.6 to 6.6 kN/m^2. This implies that these fibers have higher compressive strength due to the presence of the boron oxide additive.

In VK-60 fibers, it was found that the thermal conductivity is linearly dependent on pressure. The VK-80 has a higher sensitivity to low pressure with the saturation effect present at a pressure of 6.6 kN/m^2. Above this value, the applied pressure showed no effect on thermal conductivity, which has a constant value of 0.051 Wm/C. It may be worth mentioning that the average increase of thermal conductivity between the minimum and maximum points under the investigated range was approximately the same for all fibers.

Since VK-60 fibers showed linear dependence of thermal conductivity against applied pressure (press load), the estimate of thermal conductivity as a function of bulk density can be made by the following model:[13]

$$\lambda\,(\rho,T) = a_0 + a_1\rho + a_2T + a_3T^2 + a_4T^3$$

where ρ is density; T is temperature; and a is the multiple regression coefficient, which is statistically calculated and is necessary to avoid errors for minor deviations from a linear dependency of density and temperature. However, this formulation is only valid in a narrow range of temperatures.

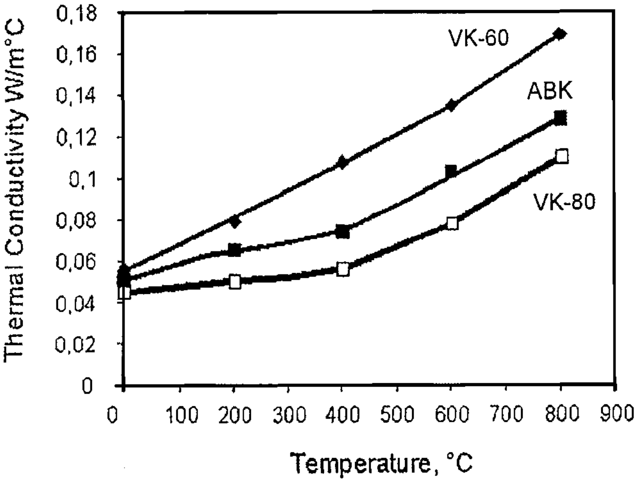

Fig. 5 High-temperature thermal conductivity of ceramic fibers

Table 2 Content of nonfibrous particles in different types of ceramic fibers

Production method	Fiber trademark	Content of nonfibrous particles, %	Thermal conductivity (Wm/ C) at 25 C
Steam blowing	VK-60	51.6	0.055
Nozzle dissemination	ABK	0	0.053
Nozzle dissemination	VK-80	0	0.046

Similarly to other fibrous materials, the thermal conductivity of analyzed ceramic fibers increased at higher pressure. This can be attributed to the release of the static air, which has a thermal conductivity of 0.26 Wm/C.[14]

High-temperature measurements showed that thermal conductivity of all three fibers increased gradually with temperature.

Figure 5 shows the changes in thermal conductivity as a function of temperature. Although the main trend is the same, each type of fiber has a different value of thermal conductivity, which may be attributed to a difference in the manufacturing techniques and chemical compositions of the fibers.

The difference in the thermal behavior of ceramic fibers can also be explained by variation in the content of nonfibrous particles. The purity of the fibers is one of the aspects that influences the thermal conductivity. The content of nonfibrous particles in analyzed materials was measured at "NPO Stekloplastic" and is given in Table 2.

The effect of the percentage of nonfibrous particles on thermal conductivity for VK-60 fibers is shown in Table 2. These fibers were produced by the steam blowing method and have 51.6% of nonfibrous particles. For fibers produced by the nozzle dissemination method, the absence of nonfibrous particles along with a higher density in VK-80 fibers and the presence of boron oxide in the ABK material may lower the value of thermal conductivity.

For fibers produced by the steam blowing method, the content of nonfibrous materials can be reduced by applying different purification techniques or by using stabilizing admixtures. This will decrease the content of nonfibrous particles from 50 to

60% to less than 15%; as a result, material with lower thermal conductivity can be obtained. Besides, in a steam blowing method,[12] such technological parameters as melt theology, air pressure, debit of the flow, *etc.* can significantly influence the content of nonfibrous particles in the final product. These technological parameters should be thoroughly controlled by the manufacturers.

A set of additional stabilizing additives Cr_2O_3, CaO may be used to achieve better oriented structure[14] and improve chemical resistance of the fibers.

Analysis of the thermal transport properties showed that the VK-60 fibers have an acceptable level of thermal conductivity and can be classified as good isolation materials. These fibers have a lower content of aluminum oxide and can also be used as a high-temperature electrical insulator.

Suggestion

The future lies in improving the fiber properties by increasing the diameter of the fibers and achieving better homogeneity in the material by using new additives such as CaO or Cr_2O_3. The awareness of thermal transport properties in this context is vital, because it helps to estimate the relevance of the use of the material in complex multilayer composite structures. Ceramic fibers are being used as reinforcement, because they possess the outstanding properties of today's modern refractory composites.

Conclusions

The investigation of thermal properties of three different types of ceramic fibers showed that all materials have good thermal insulation properties and that fibers produced by the steam blowing technique can be used as a substitute for more costly analogous materials obtained from the nozzle dissemination technique.

Acknowledgments

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