Thermal Conductivity of Ceramic Fibres at High-temperatures

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Abstract

Three ceramic fibres VK-60, ABK and Nextel/VK-80 produced by the steam blowing and nozzle dissemination methods have been investigated for the effect of press load per unit area and temperatures using the advantageous transient plane source (ATPS) method in air. It was noticed that with the increase of the aluminium oxide content in the composition of the ceramic fibres, the thermal conductivity of the material decreases and the isolation properties improved. The Nextel/VK-80 fibre has the lowest and VK-60 the highest value of thermal conductivity at room temperature. The application of a press load results in an increase in the value of the thermal conductivity for all the fibres analysed. ABK fibres showed the least increase and Nextel/VK-80 registered an increase of about 10% in the value of thermal conductivity within the load increase from 0.6 to 6.6 kN m–2. However, above 6.6 kN m–2 the thermal conductivity of all the samples increased almost linearly. The thermal conductivity measurements as a function of temperature indicated the same trend for an increase in thermal conductivity for all the samples.

Keywords: Ceramic Fibers, Advantageous Transient Plane Source (ATPS), Thermal Conductivity, Steam Blowing, Nozzle Dissemination, Applied Load, High Temperature

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 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. 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. 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 investigated [1,2]. 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 size 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.

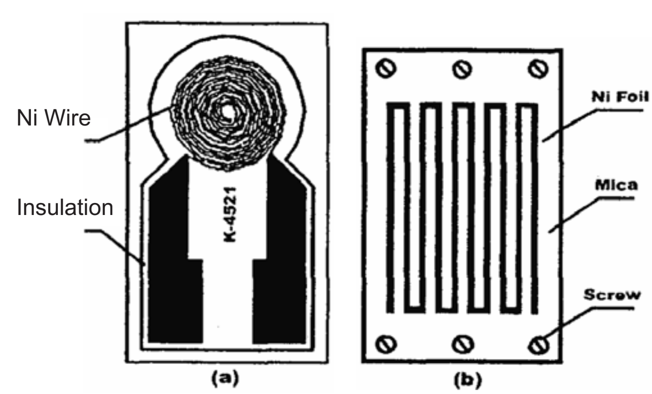

Fig. 1. Design of TPS hot disk (a) and TPS hot strip (b)

Table 1. Properties of the ceramic fibers.

Fiber Type	Chemical Comp. (wt. %)			Application Temperature Limit (K)	Density (gcm^{-3})	Content of nonfibrous particles	Thermal Conductivity ($Wm^{-1}K^{-1}$) at 298K	Method of Production
	Al_2O_3	SiO_2	B_2O_3					
VK-60	60	40	-	1623	2.94	51.6%	0.055	Steam Blowing Method
ABK	70	28	2	1673	3.05	0%	0.053	Nozzle Dissemination
Nextel/ VK-80	80	20	-	1723	3.20	0%	0.046	Nozzle Dissemination

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 advantageous transient plane source (ATPS) 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. l(a)), or strip (hot strip) shown in Fig. 1(b). The hot disk can be insulated by mica or kapton. For room and cryogenic temperatures, kapton 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 a special sample holder 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 kNm^{-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 [9-12].

Results and discussion

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 [1]. The main advantage of these fibers is their low cost and suitability for use at high temperature [13]. 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 nozzle dissemination process [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. 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.

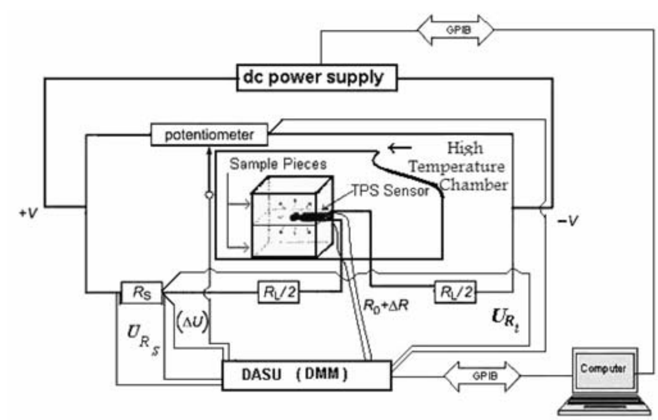

Fig. 2. The electrical circuit of ATPS method

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 kNm^{-2}.

Based on the results obtained, a correlation between the thermal conductivity and the applied pressure (press load) was obtained (Fig. 3). 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 kNm^{-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 kNm^{-2}. Above this value, the applied pressure showed no effect on thermal conductivity, which has a constant value of 0.051 $Wm^{-1}K^{-1}$. 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.

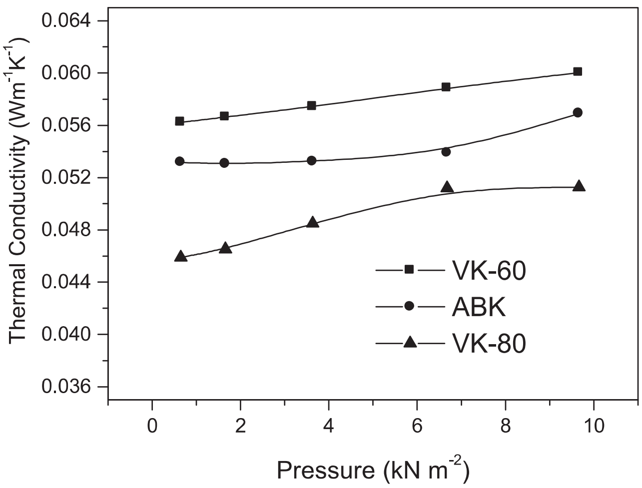

Fig. 3. Impact of pressure on thermal conductivity

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 0.026 $Wm^{-1}K^{-1}$ [14].

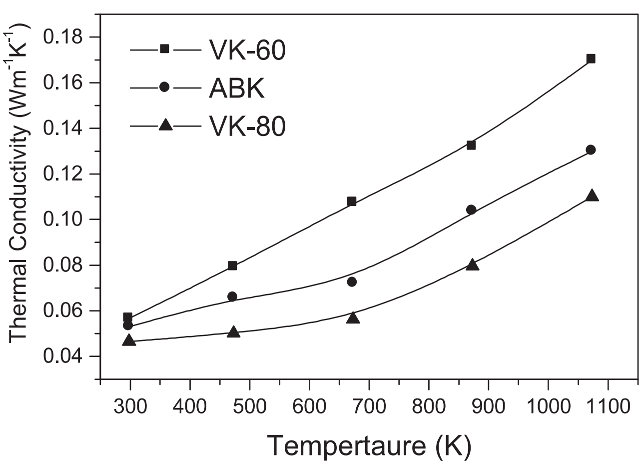

Fig. 4. High-temperature thermal conductivity of ceramic fiber

High-temperature measurements showed that thermal conductivity of all three fibers increased gradually with temperature. Fig. 4 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 non-fibrous particles. The purity of the fibers is one of the aspects that influence the thermal conductivity. The Content of non-fibrous particles in analyzed materials was measured at "NPO Stekloplastic"[1,2] and is given in Table 1.

The effect of the percentage of non-fibrous particles on thermal conductivity for VK-60 fibers is shown in Table 1. These fibers were produced by the steam blowing method and have 51.6% of non-fibrous particles. For fibers produced by the nozzle dissemination method, the absence of non-fibrous 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 non-fibrous materials can be reduced by applying different purification techniques or by using stabilizing admixtures [14]. A set of additional stabilizing additives Cr_2O_3, CaO may be used to achieve better oriented structure [15] 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.

Conclusion

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.

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.

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