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Thermal Conductivity of Ceramic Fibrous Insulators at High Temperatures[1]

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The temperature and bulk density dependence of the thermal conductivity of commercial aluminosilicate fibrous insulators were studied by using the transient hot wire method. The thermal conductivity of ceramic fibrous insulators in both air and helium gas atmosphere increased with increasing bulk density. At high temperatures, however, the insulators with lower bulk density showed a higher thermal conductivity because of heat radiation. The following experimental relation between thermal conductivity λ and temperature θ was obtained for aluminosilicate fibruous insulators: $\lambda = a \exp(b\theta)$. Relationships are given between the constants a and b and the bulk density. From the relation, the optimum bulk density of ceramic fibrous insulators can be calculated for each working temperature.

KEY WORDS: aluminosilicate fibrous insulator; ceramic fiber; hot wire method; thermal conductivity.

1. INTRODUCTION

Ceramic fibrous insulators have recently come into use in place of refractory bricks as heat insulators for kilns or dryers because their low thermal conductivity and small heat capacity make it possible to save energy when the temperature of such apparatus is being raised or maintained [1]. In addition to these advantages, these materials are so light and easy in handling that a reduction in labor costs can be expected. However, ceramic

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fibrous insulators have a porosity greater than 80 vol %, so their microstructure has a great influence on their heat insulating properties and is subject to variation even when handling conditions change only slightly.

In the present paper, the temperature and bulk density dependences of the thermal conductivity of commercial ceramic fibrous insulators are investigated and data are provided for determining suitable handling conditions for these materials.

2. EXPERIMENTAL

2.1. Sample Characteristics

The chemical composition and the physical properties of the samples used in the determination of the thermal conductivity are given in Table I. These are two kinds of commercial aluminosilicate fibrous insulators; sample 2 was obtained by water-washing of sample 1, so that the shot content of sample 2 is less than that of sample 1.

2.2. Measurement of Thermal Conductivity

The transient hot wire method [2] was used for measuring the thermal conductivity of ceramic fibrous insulators. The apparatus for measuring the thermal conductivity of ceramic fibrous insulators with various bulk densities in various atmospheres is shown in Fig. 1. This apparatus has a jack for compressing the fibers as seen in the figure, so that the bulk density of the fibers can be changed without opening the bell jar for each measurement.

Figure 2 shows the sample holder for measuring the thermal conductivity at elevated temperatures. Ceramic fiber blankets in which a 0.3-mm-diameter Pt 13% Rh wire (hot wire) and a 0.3-mm-diameter Pt–Pt 13% Rh thermocouple were sandwiched were put into the sintered alumina sample holder. Then the sample holder was set in an alumina tube in order to obtain reasonable temperature uniformity along the tube furnace controlled by a PID program controller [3].

Table I. Chemical Composition, Mean Fiber Diameter, and Shot Content of Ceramic Fibrous Insulators

Sample	Composition (%)		Fiber diameter	Shot content
	Al_2O_3	SiO_2	(μm)	(%)
1	46	54	2.8	20
2	46	54	2.8	8
3	56	44	2.5	12

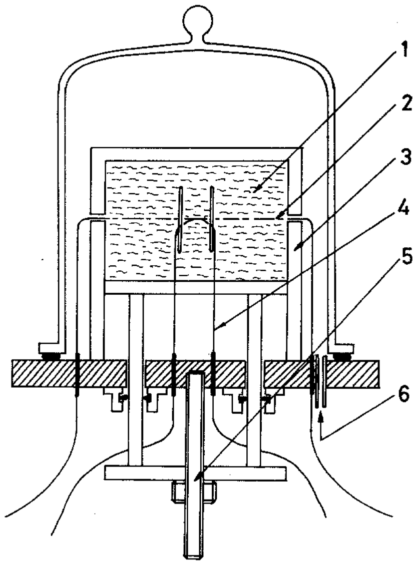

Fig. 1. Apparatus for measuring the thermal conductivity of ceramic fibrous insulators in various atmospheres. 1, sample; 2, hot wire; 3, container; 4, thermocouple; 5, jack for compressing sample fibers; 6, gas inlet.

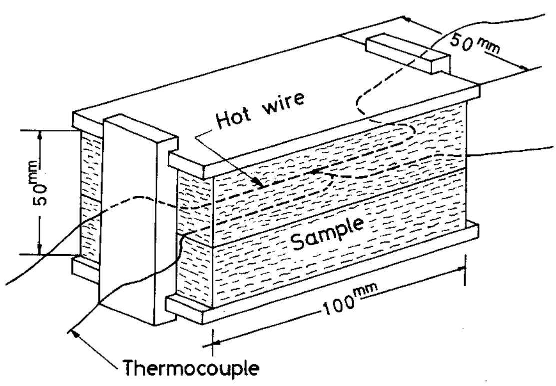

Fig. 2. A sample holder for measuring the thermal conductivity of ceramic fibrous insulators at high temperatures.

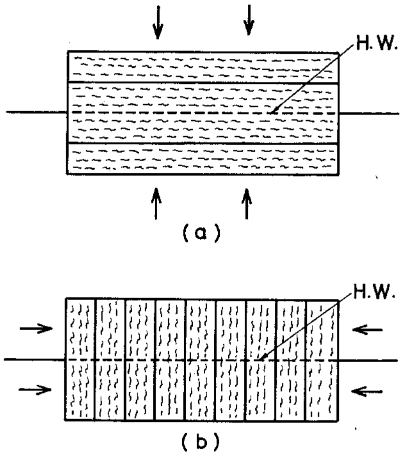

Fig. 3. Schematic view of arrangement of the hot wire in the specimens. H.W., Hot wire. Compressing direction indicated by arrows. (a) Parallel to the blanket surface. (b) Perpendicular to the blanket surface.

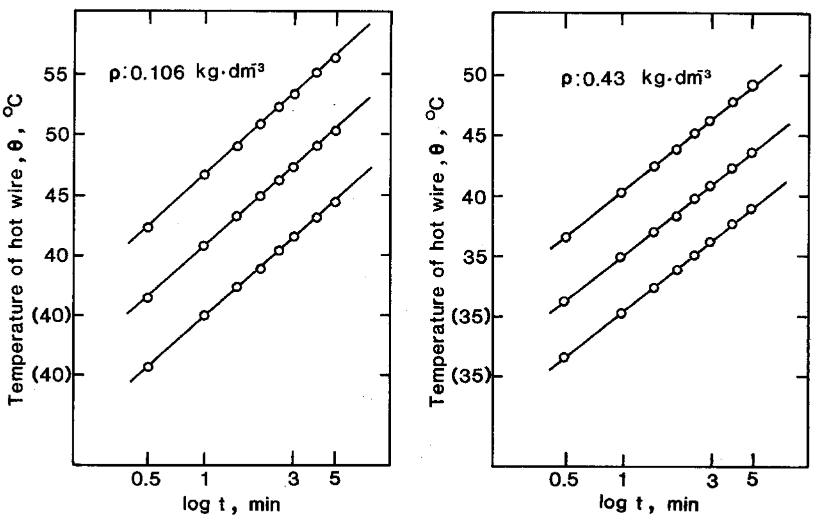

Fig. 4. Relation between the temperature of the hot wire and the logarithm of time.

3. RESULTS AND DISCUSSION

3.1. Validity of Applying the Transient Hot Wire Method

In order to check the validity of applying the transient hot wire method for the measurement of thermal conductivity of fibrous materials such as ceramic fibrous insulators, temperature increases of the hot wire in fiber compacts with various bulk densities were measured as a function of logarithmic time, and the thermal conductivity in the direction parallel to the fiber blanket surfaces was compared with that in the direction perpendicular to them as shown in Fig. 3.

Figure 4 shows the linear relation between the temperature increase of the hot wire and the logarithm of time, showing that this method is applicable for thermal conductivity measurements of fibrous materials. The difference in thermal conductivity values measured in the two different directions was less than 9%.

The thermal conductivity of ceramic fibrous insulators with various bulk densities was measured by the transient hot wire method at various temperatures between room temperature and 1200°C in various atmospheres.

3.2. Bulk Density Dependence of Thermal Conductivity of Ceramic Fibrous Insulators

The thermal conductivity of three kinds of ceramic fibrous insulators in both air and helium gas atmospheres increased with increasing bulk

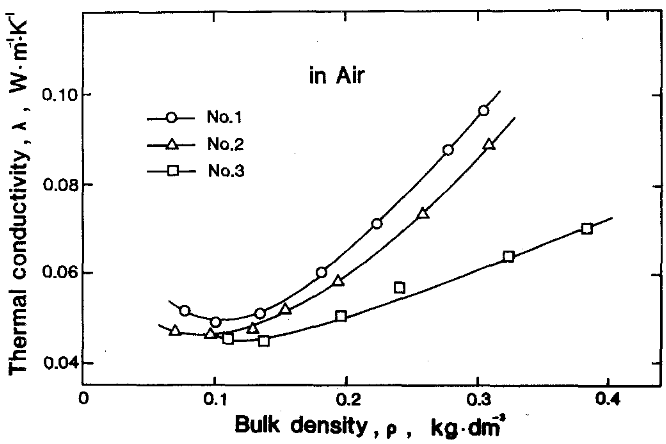

Fig. 5. Bulk density dependence of the thermal conductivity of ceramic fibrous insulators in air at room temperature.

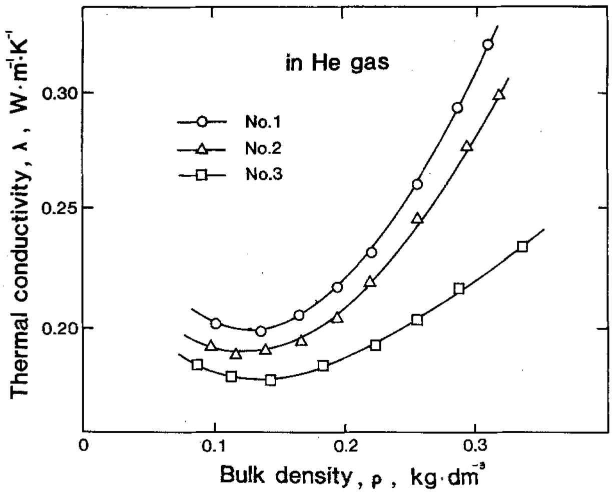

Fig. 6. Bulk density dependence of the thermal conductivity of ceramic fibrous insulators in helium gas at room temperature.

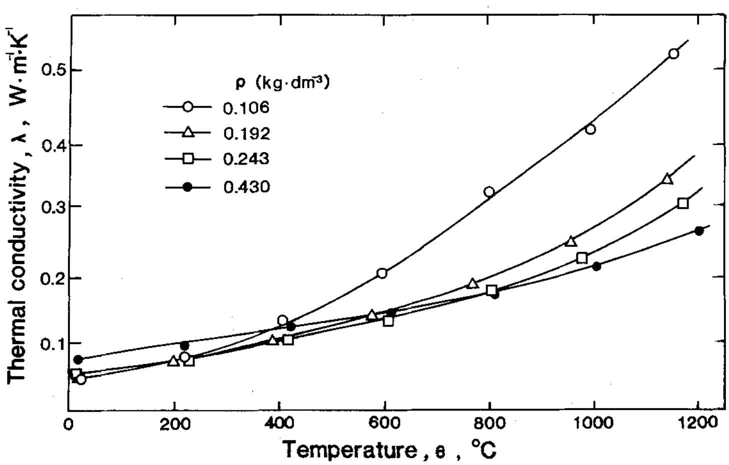

Fig. 7. Temperature dependence of the thermal conductivity of ceramic fibrous insulator no. 1 with various bulk densities in air.

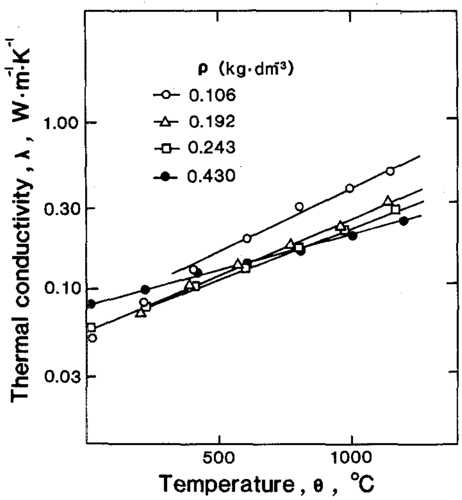

Fig. 8. Logarithm of the thermal conductivity for ceramic fibrous insulator no. 1 with various bulk densities versus temperature.

density as seen in Figs. 5 and 6. The difference in thermal conductivity between the samples is due to the difference in shot content and fiber dimension.

3.3. Temperature Dependence of Thermal Conductivity of Ceramic Fibrous Insulators

Figure 7 shows the temperature dependence of the thermal conductivity of sample 1 with various bulk densities in air. Generally speaking, the thermal conductivity of ceramic fibrous insulators increased with increasing bulk density, as mentioned in Section 3.1. At high temperatures, however, the ceramic fibrous insulators with lower bulk density showed higher thermal conductivity because of the contribution of heat radiation.

3.4. Estimation of Suitable Bulk Density for Ceramic Fibrous Insulators at Ambient Temperature

The logarithm of the thermal conductivity of sample 1 with various bulk densities is plotted as a function of temperature in Fig. 8. In aluminosilicate fibrous insulators, the following experimental relation between the thermal conductivity λ ($W \cdot m^{-1} \cdot K^{-1}$) and temperature θ (°C) was obtained:

$$\lambda = a \exp(b\theta) \tag{1}$$

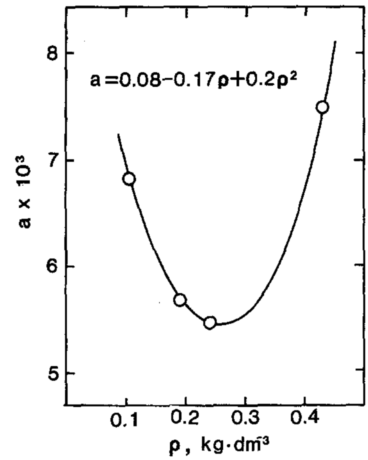

Fig. 9. Plot of *a* in Eq. (1) versus the bulk density of ceramic fibrous insulator no. 1.

Vishevskii *et al.* [4] measured the thermal conductivity of kaolin wool (corresponding to the present sample 1) with bulk densities of 0.2 and 0.35 $g \cdot cm^{-3}$ by the steady-state radial heat flow method and reported that the temperature dependence of the thermal conductivity is governed significantly by the heat radiation, which is proportional to the third power of temperature T^3.

The constants a and b in Eq. (1) that correspond to the results obtained in Fig. 8 are plotted as a function of bulk density ρ ($kg \cdot dm^{-3}$) in

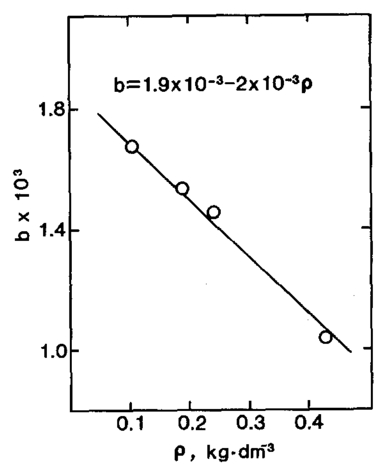

Fig. 10. Plot of *b* in Eq. (1) versus the bulk density of ceramic fibrous insulator no. 1.

Figs. 9 and 10, respectively. As seen in the two figures, a and b are related to ρ by the following equations:

$$a = 0.08 - 0.17\rho + 0.2\rho^2 \qquad (2)$$

$$b = 1.9 \times 10^{-3} - 2 \times 10^{-3}\rho \qquad (3)$$

Figure 11 shows the relationship between λ, ρ, and θ determined from expressions (1)–(3). It is obvious at a glance that the bulk densities at which the thermal conductivity of aluminosilicate fibrous insulators is to be a minimum vary with increasing temperature. Thus, at high temperatures a bulk density should be chosen that is larger than the one that is suitable at room temperature.

The thermal conductivity can be estimated from Eqs. (1)–(3) when the bulk density of an aluminosilicate fibrous insulator and the temperature at which it will be used as heat insulation have been decided. The bulk density dependence for each working temperature can also be estimated in a similar manner.

Thermal conductivity data for ceramic fibrous insulators have become very important in recent years because they are needed in such new industrial areas as helium gas-cooled nuclear reactors for the continuous

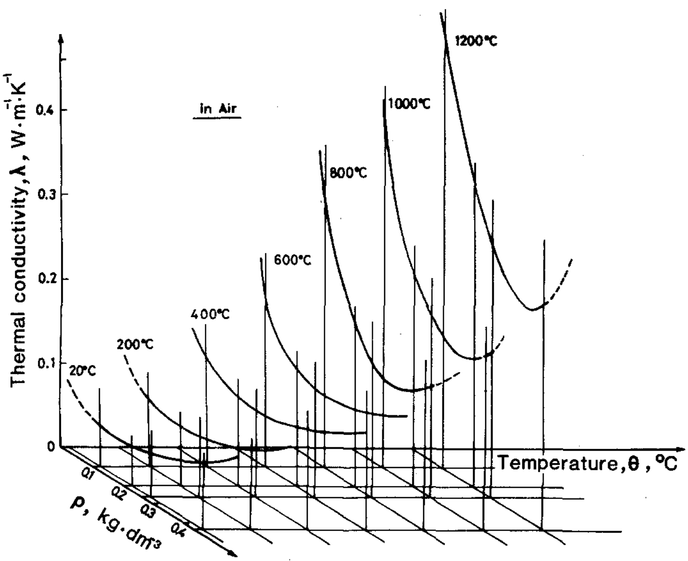

Fig. 11. Variation of the bulk density dependence of the thermal conductivity calculated from Eqs. (1)–(3) for an aluminosilicate ceramic fibrous insulator at elevated temperatures.

steel-making process [5] or manned aircraft and aerospace vehicles requiring complete heat insulation during reentry into the atmosphere [6].

4. CONCLUSIONS

The thermal conductivity of aluminosilicate fibrous insulators with various bulk densities was measured by the transient hot wire method between room temperature and 1200°C. The results obtained are as follows:

1. The thermal conductivity of ceramic fibrous insulators in both air and helium gas atmosphere increases with increasing bulk density.

2. At high temperatures, however, the ceramic fibrous insulators with lower bulk density show higher thermal conductivity because of the contribution of heat radiation.

3. In aluminosilicate fibrous insulators, the following experimental relation connects the thermal conductivity λ ($W \cdot m^{-1} \cdot K^{-}$), the bulk density ρ ($kg \cdot dm^{-3}$), and the temperature θ (°C):

$$\lambda = a \exp(b\theta)$$

where $a = 0.08 - 0.17\rho + 0.2\rho^2$ and $b = 1.9 \times 10^{-3} - 2 \times 10^{-3}\rho$. From this experimental relation, the optimum bulk density of aluminosilicate fibrous insulators can be calculated for each working temperature.

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