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THERMAL PROPERTIES OF HIGHLY POROUS FIBROUS CERAMICS

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ABSTRACT

Highly porous fibrous ceramics were fabricated by vacuum-molding the fiber slurry and sintering the dried felt. The materials comprised of a random network of ceramic fibers and air, with the pore sizes on micron scale. The effects of binder content and porosity on the microstructure and room-temperature thermal conductivity of fibrous ceramics were investigated. It was found that the room-temperature thermal conductivity increased with increasing binder content. In addition, the thermal conductivity decreased from 0.18 to 0.06 W/(m·K) when porosity increased from 73% to 90%, showing nearly a linear relationship. The high-temperature thermal conductivity in the range of 200-1200℃ for three different porosities were also investigated. The thermal conductivity increased as temperature and density increased. Furthermore, the porous ceramics were impregnated with silica aerogel to further lower the thermal conductivity. The room-temperature thermal conductivity decreased from 0.049 to 0.040 W/(m·K), and the back temperature decreased from 870℃ to 750℃ after the aerogel impregnation, showing better high-temperature insulation performance.

1 INTRODUCTION

Porous ceramic have been widely used for many applications including fuel-cell electrodes, ceramic filters, catalyst supports and thermal barriers [1,2]. Recently, fibrous ceramics with highly-porosity have drawn more attention, because such bird’s nest-like structure has the advantage of low density, low thermal conductivity and reasonable high mechanical strength, which can be used as thermal insulations. Heat transfer through the porous material involves multiple energy transport mechanisms, including heat conduction through solid and gas phases as well as heat radiation. The silica fibrous rigid thermal insulations have been extensively studied and successfully used on the shuttle vehicles [3,4]. In this work, highly porous fibrous alumina or silica ceramic were investigated for the thermal insulation application. The effects of binder content, porosity and aerogel impregnation on the materials’ microstructure, room-temperature and high-temperature thermal conductivities were investigated.

2 EXPERIMENTAL

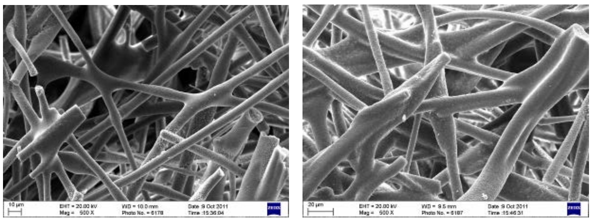
The porous material was formed by mixing the slurry of fibers and a binder to form a uniform slurry. The fibers were alumina or silica fibers, with a diameter in the range of 5~10 μm. Then the slurry was vacuum-molding to remove excess water and to form a soft felt. After drying in an oven at 100-150℃ for 24-72h, the dried billet was placed in a furnace to sinter at high temperatures between 1200-1500℃. Finally, the sintered tile was machined to desired shape and size.

The sample’s microstructure was examined by a ZEISS scanning electron microscopy. The thermal conductivity at room temperature (λ_{RT}) was measured using a EKO analyzer, with a sample size of 150×150×20 mm. The high-temperature thermal conductivity in the temperature range of 200-1200℃ was measured according to the Chinese standard of YB/T4130-2005, with a sample size of ϕ180×20 mm. The hot surface' temperatures were set as 200, 400, 600, 800, 1000 and 1200℃ The back temperature test was carried out for 30min, with a hot surface temperature of 1200℃ The sample's cold surface temperature was recorded and the sample's size was 150×150×20 mm.

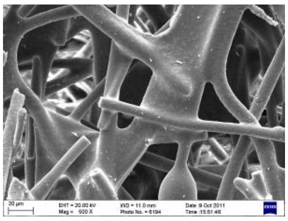
3 RESULTS AND DISCUSSION

3.1 room-temperature thermal conductivity vs. binder content

The thermal and mechanical properties of fibrous porous samples are greatly determined by the bonding between fibers. The effects of binder content on the microstructure and room-temperature thermal conductivity were studied. Fig. 1 shows the SEM micrographs of the fibrous alumina ceramics, with the binder content of 5wt%, 10wt% and 15wt%. It was found that the fibers were bonded together mainly at the fiber junctions. Such microstructure is desirable to obtain low thermal conductivity as well as high mechanical property. In addition, as expected, the bonding area increased with increasing binder content. The room-temperature thermal conductivity for the above three ceramics increased from 0.065, to 0.072 and to 0.080 W/(m·K), respectively. This can be explained by the higher solid-phase heat conduction in the samples with more binder content. A 10 wt% binder was chosen for the further study, because it had a good balance between low thermal conductivity and high mechanical strength.



(a) 5wt% binder (b) 10wt% binder



(c) 15wt% binder

Fig.1 SEM micrograph of three samples with different binder contents.

Fig. 2 gives a picture of the fabricated hilgy porous fibrous ceramics (150×150×20 mm), indicating good handleability due to the relatively high mechanical properties.

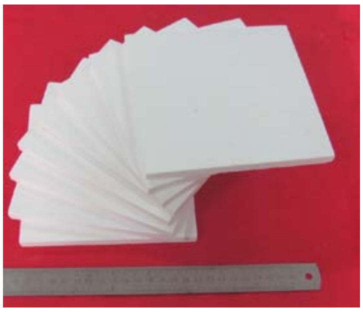


Fig. 2 Picture of the fabricated higly porous fibrous ceramics.

3.2 room-temperature thermal conductivity vs. porosity

Porosity plays an important role in determining the thermal properties of the porous materials [5,6]. Table 1 summarizes the room-temperature thermal conductivities (λ_{RT}) of the fibrous alumina ceramics as a function of porosity. It is clear that the thermal conductivity decreased with increasing porosity. λ_{RT} decreased from 0.18 to 0.058 W/(m·K) as porosity increased from 73% to 90%. In general, when decreasing porosity, the ceramics' solid-phase heat conduction increases drastically, while the deduction of gas-phase heat conduction and thermal radiation is less, thus the overall thermal conductivity at room temperature increases [7,8]. Fig.3 depicts the λ_{RT}-porosity relation in the porosity range of 70-90%, which can be fitted using a linear equation of y=Ax+B. In order to evaluate the validity of equation, correlation coefficient (R) was also calculated (the more R is closer to "1", the more the linearity). Here, the values for A, B and R were -0.0069, 0.674 and 0.989, respectively. The similar linear relationship has been observed previously for silica fibrous insulation materials [4], and for the highly porous zirconia and mullite materials [9,10].

Table 1 The samples' thermal conductivity as a function of porosity.

Porosity (%)	Density (g/cm^3)	λ_{RT} W/(m·K)
73	0.82	0.18
77	0.70	0.14
79	0.62	0.12
81	0.56	0.10
83	0.51	0.093
85	0.44	0.079
87	0.40	0.073
87	0.38	0.067
88	0.36	0.066
90	0.30	0.058

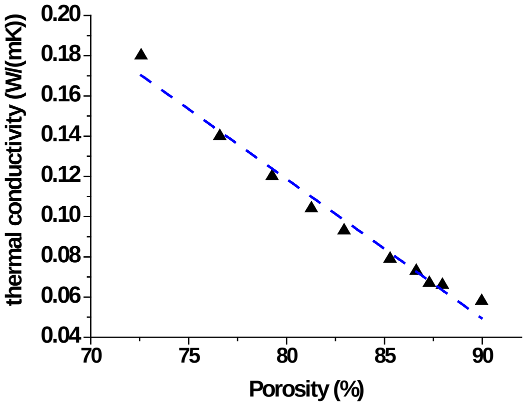


Fig.3 The variations of the samples' thermal conductivity as a function of porosity.

3.3 High-temperature thermal conductivity vs. porosity

The variations of thermal conductivity as a function of temperature is important for the high-temperature insulation applications. Fig. 4 illustrates in the temperature range of 200 to 1200℃, the variations of thermal conductivity for the fibrous alumina ceramics with three porosities of 87%, 79% and 73% (i.e. density=0.4, 0.61 and 0.82 g/cm3, respectively). It was found that the thermal conductivity for the three samples increased with increasing temperature. This is probably due to the increased convection conduction and radiation conduction with increasing temperature. In addition, the ceramics of less porosity (i.e. higher density) had bigger thermal conductivity in the whole temperature range, indicating porosity is a critical factor for the high-temperature thermal conductivity.

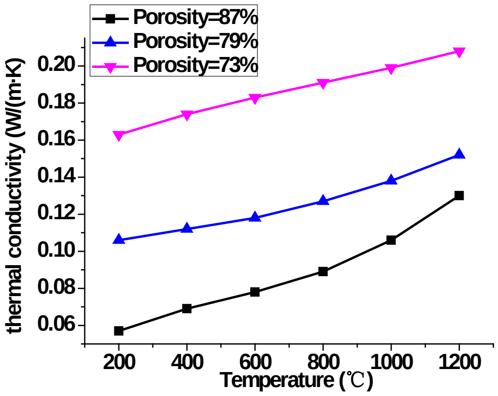
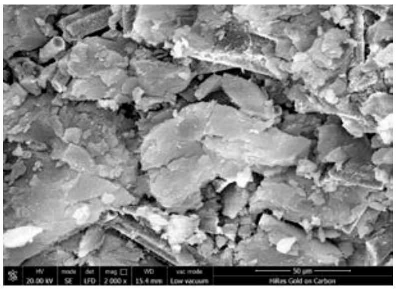


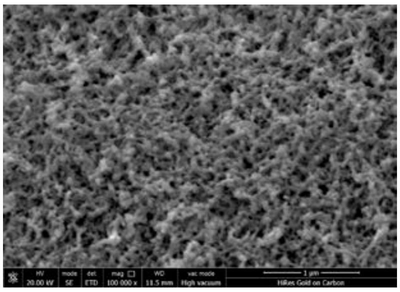
Fig. 4 The thermal conductivity vs. temperature for the ceramics with different porosities.

3.4 Aerogel impregnation

Aerogel is a kind of ideal thermal insulation materials, due to the extraordinary properties, such as ultralarge specific surface area (500-1200 m^2/g), ultralow density (0.003-0.35 g/cm^3), ultralow thermal conductivity (0.012-0.1 W/(m·K)) [11,12]. In order to further decrease the thermal conductivity as well as to improve thermal insulation performance, silica aerogel was impregnated into the porous fibrous silica ceramics. The microstructure for the ceramics after the aerogel impregnation is shown in Fig.5. Fig.5(a) shows that the silica aerogel occupied most of the pores between the fibers, resulting a significant decrease in pore size. Fig. 5(b) shows that aerogel was nanostructure material with nanosized particles and nanosized pores.



(a) ceramics (500x)



(b) aerogel (100kx)

Fig. 5 SEM micrographs of the porous ceramics after the aerogel impregnation.

The room-temperature thermal conductivity of the silica ceramics decreased from 0.049 to 0.040 W/(m·K). In general, although the solid-phase heat conduction is expected to increase slightly after the aerogel impregnation, the convection conduction should be restrained much more by decreasing the ceramic's pore size by aerogel, thus a lower λ_{RT} is achieved.

The back temperature tests were carried out on the fibrous silica ceramics before and after aerogel impregnation, in order to evaluate the high temperature performance for the thermal insulation applications. As shown in Fig. 6, for the hot surface temperature of 1200℃ for 30min, the back temperature of the fibrous silica ceramics decreased from 870 to 750℃ after the aerogel impregnation. This results confirmed the improved high-temperature thermal insulation performance of the aerogel impregnation, which is attributed to the special microstructure of the aerogel material.

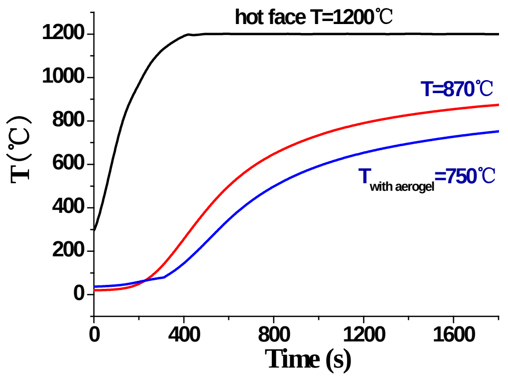


Fig. 6 The back temperature tests for the ceramics before and after the aerogel impregnation.

4 CONCLUSIONS

The thermal properties of fibrous alumina or silica ceramics of high-porosity were investigated. The effects of binder content and porosity on the microstructure and room-temperature thermal conductivity of fibrous ceramics were studied. It was found that the room-temperature thermal conductivity increased with increasing binder content. The thermal conductivity decreased from 0.18 to 0.06 W/(m·K) when porosity increased from 73% to 90%, showing nearly a linear relationship. In addition, the high-temperature thermal conductivity also increased as temperature and density increased. Furthermore, the fibrous ceramics were impregnated with silica aerogel to further lower the thermal conductivity. The room-temperature thermal conductivity and high-T thermal performance both improved after the aerogel impregnation.

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