Preparation and Heat Transfer Mechanism of ZrO₂ Fiber Flexible Heat-Insulating Materials

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Abstract. The high temperature insulation material of zirconia fiber and carbon fiber (CZ) was prepared by wet molding process using chopped carbon fiber and zirconia fiber as raw materials. The thermal conductivity of the block was measured by high temperature flat plate thermal conductivity instrument. The effects of content of zirconia fiber, diameter of zirconia fiber and material density on CZ thermal conductivity were studied. The heat transfer mechanism of CZ was also studied. The results showed that the heat conductivity of CZ insulation material could be reduced with the reducing the diameter of zirconia fiber. The heat conductivity of CZ insulation material also could be reduced with increasing the content of zirconia fiber.

1. Introduction
With the development of modern aerospace technology, people are increasingly pursuing the speed of aircraft. Especially in recent years, major aerospace powers in the world have set off a climax of hypersonic aircraft research and development [1]. At present, the research and development of hypersonic flight technology is faced with many technical challenges, including aerodynamics, material and structure, propulsion, control and many other fields. Among them, the research and development of engine propulsion system, as the core of aircraft work, which is the top priority [2, 3]. The basic form of the aircraft was determined by the development level of engine propulsion technology. An appropriate engine propulsion system is the premise of hypersonic flight [4-6].

The thermal protection effect of ramjet hot end components is directly affected by the thermal insulation effect of high temperature thermal insulation materials. Thermal insulation effect of high temperature thermal insulation material is an important determinant of engine gas temperature selection, which further affects engine efficiency and aircraft speed. Heat is transferred to the insulation in the form of convection and radiation, which are used at high temperatures. As the temperature raised, there is a temperature gradient in different regions of the insulation material. In the fiber structure, heat is transferred in the form of solid phase heat conduction, convection of air in pores and heat radiation. The thermal insulation performance of zirconia fiber-carbon fiber insulation material is affected by the composition ratio and microstructure of the fiber material.

In this study, the thermal conductivity of the block was measured by high temperature flat plate thermal conductivity instrument. The effects of content of zirconia fiber, diameter of zirconia fiber and material density on CZ thermal conductivity were studied. The heat transfer mechanism of CZ was also studied.
2. Experimental

2.1. Materials.

The high temperature insulation material of zirconia fiber and carbon fiber (CZ) was prepared by wet molding process using chopped carbon fiber and zirconia fiber as raw materials. Firstly, the raw materials were stirred and mixed evenly in PAM aqueous solution. Monolayer fiber prefabricated was prepared by wet molding process. Then Multilayer fiber prefabrications were bonded using a certain concentration of aluminum phosphate solution as binder. High temperature thermal insulation materials of zirconia fiber and carbon fiber were obtained by means of plywood pressing and molding. The drying time was 10 h at 100°C. The size of sample was Φ180mm × 20 mm. The thermal insulation performance samples were prepared by the same preparation process as the thermal conductivity samples with a size of 100mm×100mm. The thermal insulation performance of zirconia fiber-graphite fiber is affected by many factors such as composition ratio, density and fiber diameter. In this experiment, three influencing factors including composition ratio, density and fiber diameter were selected as research objects, and a series of samples were prepared. The effects of the above four factors on the thermal insulation performance of zirconia fiber-graphite fiber were studied. The specific parameter combinations were shown in table 1.

| Level | Zirconia fiber content (wt%) | density (g·cm⁻³) | diameter of Zirconia fiber (μm) |
|-------|-----------------------------|------------------|-------------------------------|
| 1     | 97                          | 0.36             | 8                             |
| 2     | 95                          | 0.63             | 15                            |
| 3     | 93                          | 0.80             | —                             |
| 4     | —                           | 0.92             | —                             |

2.2. Testing

The morphology of zirconia fiber, carbon fiber and fiber composite heat insulation materials were observed with transmission electron microscope. The thermal conductivity of the sample was measured by a high temperature plate thermal conductivity apparatus. The thermal insulation performance of zirconia fiber-carbon fiber high temperature insulation material was tested in a flat plate furnace designed and developed in laboratory. By adjusting the power of the heater, the temperature of the SiC soaking plate was raised to 1150°C. The change of back temperature with time was measured to evaluate the thermal insulation performance of thermal insulation materials. The sample size was 100mm ×100mm ×7mm.

![Figure 1. The appearance of composite insulation material with different diameter of carbon (a) 8μm, (b) 15μm.](image-url)
3. Results and discussion

In this paper, the change curve of thermal conductivity with temperature was shown in figure 1. With the increase of temperature from 400°C to 1200°C, the thermal conductivity of heat insulation material with different components tended to increase. Taking the change of thermal conductivity of composite material with 93 wt% zirconia fiber as an example, when the temperature exceeded 800°C, the increasing trend of thermal conductivity was more obvious. Through the heat conduction mechanism of zirconia-carbon fiber super-high temperature insulation material at high temperature, this phenomenon was related to the action mechanism of conduction, convection and radiation at different temperatures. The content of zirconia fiber increased from 93wt% to 97wt%. At the ambient temperature of 400°C, the corresponding thermal conductivity was reduced by 30%. At other temperatures, with the increase of zirconia fiber content, the thermal conductivity of zirconia-carbon fiber high temperature insulation materials tended to decrease. At the same temperature, the thermal conductivity of zirconia was much lower than that of carbon fibers.

![Figure 2. The appearance of composite insulation material with different diameter of carbon (a) 8μm, (b) 15μm.](image1)

![Figure 3. The thermal conductivity coefficient of insulation material with different diameter of zirconia fiber (a) 8μm, (b) 15μm.](image2)

As shown in Fig.3, with the increase of temperature, the thermal conductivity increases rapidly. At the same ambient temperature, compared with the composite insulation prepared from zirconia fibers with diameters of 15μm, the thermal conductivity of the composites prepared with zirconia fibers with...
smaller diameter was reduced. Thus, the solid phase heat conduction of the composite insulation material was also reduced. On the one hand, the intrinsic thermal conductivity of zirconia fiber might be reduced by decreasing the diameter of the fiber. On the other hand, smaller pores were formed by interwoven zirconia fibers with smaller diameter. In the high temperature environment, convection and radiation heat transfer were inhibited due to the small pores. As a result, the thermal conductivity of composite insulation material was reduced. The high temperature insulation material of zirconia-carbon fiber is a porous material. The amount of solid phase composition inside the material is an important factor affecting the thermal insulation performance. The amount of solid material in the interior of zirconia-carbon fiber high temperature insulation material can be measured by the density of the material.

**Figure 4.** The thermal conductivity coefficient of insulation material with different diameter of zirconia fiber (a) 8μm, (b) 15μm.

**Figure 5.** The cold surface temperature of insulation material with different density (a) 0.36g·cm⁻³; (b) 0.63g·cm⁻³; (c) 0.80g·cm⁻³; (d) 0.92g·cm⁻³.

When the density of zirconia fiber-carbon fiber high temperature insulation material increased from 0.36 g·cm⁻³ to 0.63g·cm⁻³, and the back temperature of the corresponding material decreased from 680
The thermal conductivity of the corresponding material decreased from 0.148 W·m⁻¹·k⁻¹ to 0.103 W·m⁻¹·k⁻¹. When the density of zirconia fiber-carbon fiber high temperature insulation material was increased to 0.8 g·cm⁻³ and 0.92 g·cm⁻³, the cold surface temperature of the corresponding materials increased by 40°C and 130°C respectively. At this point, as the density of the insulating material increasing, the contribution of solid phase heat conduction will increase. That is to say, the total thermal conductivity of insulation material could be decreased with the increase of density. Therefore, when the density of zirconia fiber-carbon fiber ultra-high temperature insulation material is 0.63 g·cm⁻³, the best heat insulation performance was shown.

4. Summary
In a certain temperature range, certain measures can be taken to reduce the thermal conductivity of CZ insulation material. The measures include reducing the diameter of the zirconia fibers or increasing the density of the material. With the increase of temperature, the increase of thermal conductivity for porous fiber materials is mainly caused by the increase of convection heat transfer and radiation heat transfer.

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