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Research on the Thermal Insulation Performance of High Temperature Gradient Composite Insulation Material

Xiankai Sun, Shichao Zhang, Haoran Sun, Kai Fang, Dachen Yan, Yufeng Chen
China Building Materials Academy, Ceramic Research Institute, China, Beijing, 100024
sunxiankai2008@163.com

Abstract. In this study, the high temperature gradient composite insulation material (SGIM) was prepared by using zirconia fiber and carbon fiber (CZ), high temperature phase-change material (HPCM), microcellular thermal insulation material of calcium silicate (CS/AS), insulation material of nano-silica(NP) and radiation shielding material as raw materials. The thermal insulation performance was simulated by using the finite element software. The heat insulation performance of the material was tested by oxy-acetylene ablation experiment. The thickness of the insulation material was also set to 32 mm. The temperature of hot surface was controlled at 2000°C. After 600 seconds, the material of cold temperature was 54°C. The excellent performance of SGIM insulation is demonstrated.

1. Introduction
At present, active thermal protection and passive thermal protection are mainly used as ultra-high temperature thermal protection measures of scramjet combustion chamber [1, 2]. Air film cooling, transpiration cooling and heat absorbing fuel are all classified as active thermal protection mode. The disadvantages of complex structure, heavy weight and poor structural stability are often found in ramjet engines with active cooling system [3]. Passive thermal protection system is mainly composed of ceramic matrix composite material, flexible heat insulation material and high strength metal material. Compared with the active thermal protection system, the ramjet engine using this mode has the advantages of higher combustion efficiency, higher thrust coefficient and higher specific impulse [4]. The thermal insulation materials used in passive thermal protection systems are required to have excellent thermal insulation performance.

Ablative composite heat insulation materials are commonly used as thermal protection materials for solid ramjet engines. Such materials mainly include glass - silicone resin, organic materials, glass-aldehyde, carbon-phenolic and so on. Such materials are used to offset the heat transferred by combustion through phase transition and material consumption. When it is used for a short time, it has excellent thermal protection performance. When used for a long time, the material will be decomposed or ablated. The wall temperature of the combustion chamber was sharply increased, which could not meet the working time requirements of the scramjet engine [5-7]. The wall temperature of the combustion chamber was sharply increased, which could not meet the working time requirements of the scramjet engine.
In this study, the high temperature gradient composite insulation material (SGIM) was prepared. The thermal insulation performance was simulated by using the finite element software. The heat insulation performance of the material was tested by oxy-acetylene ablation experiment.

2. Experimental
High temperature gradient insulation materials are used above 2000°C. The ultra-high temperature multilayer thermal insulation material structure designed in this paper was composed of high temperature thermal insulation material, medium temperature thermal insulation material, low temperature thermal insulation material and radiation shielding layer material.

![Figure 1. The schematic diagram of gradient heat insulation material under high temperature.](image)

The high temperature gradient composite insulation material (SGIM) was prepared by using zirconia fiber and carbon fiber (CZ), high temperature phase-change material (HPCM), microcellular thermal insulation material of calcium silicate (CS/AS), insulation material of nano-silica (NP) and radiation shielding material as raw materials. The specific parameter combinations were shown in table 1.

| Structure   | Composition Material | Thickness (mm) |
|-------------|----------------------|----------------|
| The first   | CZ                   | 8              |
| The second  | HPCM                 | 4              |
| The second  | AO                   | 5              |
| The second  | CS/AS                | 5              |
| The second  | NP                   | 10             |

The following boundary conditions are followed in the simulation calculation. (1) The heat transfer calculation was based on one-dimensional model. That is, the heat transfer in the direction of material thickness was considered, the heat transfer between different sections in the length direction was not considered. (2) The contact thermal resistance between ablative layer and insulation layer was ignored. The heat was directly loaded on the high temperature surface of SGIM. The loading temperature was 1800°C. and the loading time was 600s. (3) The heat transfer calculation is carried out by using the transient heat transfer mode. (4) The average thermal conductivity of the materials in each layer of SGIM is taken as shown in Figure 2. (5) The heat transfer between the cold surface of SGIM and air was carried out in the form of convective heat transfer. The ambient temperature was 25°C. The convective heat transfer coefficient was 22W·m²·°C⁻¹.
The morphology of CS/AS and NP were observed with transmission electron microscope (Tecnal G2 20, FEI Co. Ltd, America). The thermal conductivity of the sample was measured by a high temperature plate thermal conductivity apparatus (PBD-15-7, LUOYANG Antelier Instrument Sci. Tec. Co., China). The heat insulation performance of the material was tested by oxy-acetylene ablation experiment.

3. Results and discussion
As shown in Figure 2, three types of pores with different sizes were found in the CS/AS material structure. The surface of the composite is porous, which mainly includes nano-scale pore of microporous calcium silicate itself, 2-10μm pore formed between agglomerated particles, and larger pore formed by the phase distribution of aluminium silicate fibers and calcium silicate particles. The pore size extended from nanometer to micron. Up to 85% of the pores were found in the NP thermal insulation structure, and the pore diameter was mainly distributed between 30nm and 80nm. The thermal conductivity of material could be reduced by first two kinds of pore. The thermal insulation performance could be improved.

Figure 2. SEM images of CS/AS material and NP material.

Figure 3. Thermal conductivity of component materials.
The change rule of the thermal conductivity of four different components with the increase of temperature was shown in Figure 3. As the increasing of temperature, the thermal conductivity increased rapidly. When the temperature was below 600°C, the thermal insulation performance of NP material was excellent.

The calculation results of SGIM thermal insulation material are shown in Figure 4. Heat was transferred to the high temperature surface of SGIM by heat conduction. After 30 seconds, the high temperature surface of SGIM reached the design checking temperature, which takes less time to simulate the heat conduction process in the ignition stage of engine combustion chamber. After 600 seconds, the CZ insulating layer with thickness of 8 mm achieved a large temperature drop of nearly 650°C due to the shielding effect of graphite paper in the CZ layer on infrared radiation at high temperature. The radiation heat transfer was restrained effectively. The hot surface temperature of HPCM with a thickness of 4 mm was 1150°C, which was nearly 100°C away from the solid-liquid phase transition temperature of the high-temperature phase change material. It showed that HPCM still exists in the form of solid phase or solid-liquid two-phase coexistence. If the heating time was prolonged, heat absorption space was still in HPCM material. Thanks to the design of CZ layer thickness, the phase change endothermic effect of HPCM had been maximized. The overall thermal insulation performance of the material was improved. During the 600 s continuous heating process, the thermal surface temperatures of CS/AS and NP layers are all below 990°C and 680°C respectively. This gave full play to the low thermal conductivity of NP material at low temperature, as shown in Figure 2, which had the advantage of high thermal insulation performance. The thickness of the insulation material was set to 32 mm. After 600 seconds, the material of cold temperature was 50°C. In other words, up to 1750°C temperature drop was realized.

![Figure 4. Curve of relationship between SGIM each layer temperature and heating time.](image)

The test results of SGIM thermal insulation material by using oxyacetylene are shown in Figure 5. The thickness of the insulation material was also set to 32 mm. The temperature of hot surface was controlled at 2000°C. After 600 seconds, the material of cold temperature was 54°C. The excellent performance of SGIM insulation was demonstrated.
4. Summary
In this paper, a new type of super-high temperature gradient flexible thermal insulation material (SGIM) was designed, and a finite element model was established. The thermal insulation performance of SGIM thermal insulation material was calculated and evaluated. The main conclusions are as follows.

(1) The new super-high temperature gradient flexible insulation material (SGIM) is composed of CZ, HPCM, AO, CS/AS and NP. When the temperature of SGIM thermal insulation layer is controlled at 1800°C, the temperature drop of 1750°C can be achieved within 600s. This material has excellent thermal insulation performance.

(2) It was verified that the model construction, boundary condition selection and material parameter selection was reasonable in the simulation calculation of thermal insulation performance of insulation material. The simulation calculation method was effective.

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