Optimization and Application Technology of Reflective Foils Using in Zirconia Fiber Insulation Materials

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Abstract. Graphite paper was used as reflective foils in the zirconia fiber insulation materials system, the effects of the number, spacing and emissivity of reflective foils on the thermal insulation properties of zirconia fiber insulation materials were studied. It was found that when the number of reflective foils is 10, interlayer spacing was 1 mm, the minimum thermal conductivity of the insulation materials was obtained. Zirconia superfine powder was used to reduce the emissivity of reflective foils, the modified reflective foils was used in the zirconia fiber insulation materials system, it was found that when the emissivity of the modified reflective foils was 0.37, the minimum thermal conductivity of insulation materials was obtained.

1. Introduction
Multi-layer insulation materials is alternately made of high reflectivity reflective foils and low thermal conductivity spacer layers, and commonly applied in high-temperature environment in order to keep the temperature of underlying structure within an acceptable limit. The high reflectivity reflective foils such as gold foil, silver foil, copper foil, aluminum foil and graphite paper are used as the reflective screens, which can resist the thermal radiation. The low thermal conductivity spacer layers such as alumina fiber, silica fiber and carbon fiber possess a very low thermal conductivity which can resist the heat conduction. Note that both foils and spacer materials have to be capable of operating at high temperature. During the last several decades, the developments and use of multi-layer insulation materials have extended the range of applications from industry manufacture [1] into planetary atmospheres [2].

The radiation heat flux \( q \) between two parallel planes is related to their surface emissivity [2-4]. There are two infinitely parallel gray body planes with the same surface emissivity, \( \epsilon \), the radiation heat flux \( q \) between the two planes is:

\[
q = \frac{\sigma(T_1^4 - T_2^4)}{\frac{2}{\epsilon} - 1}
\]

Where, \( \sigma \) is the Boltzmann constant, \( T_1 \) is the temperature of the high temperature surface, \( T_2 \) is the temperature of the low temperature surface, both in K.

If \( N \) layer reflective screens are inserted between the two parallel gray body planes, then the radiation heat flux \( q \) is:
\[ q = \frac{\sigma(T_1^4 - T_2^4)}{(N + 1)(\frac{1}{\epsilon} - 1)} \]  

(2)

It can be seen that the reflective screens play an important role in thermal insulation property, the radiation heat flux \( q \) is reduced to \( \frac{1}{N+1} \) times of the original after the \( N \) layer reflective screens are inserted.

Moreover, the number and the location of the foils, the density of spacers, and the emissivity of the surface of foils also have a significant effect on the thermal insulation property \([3]\). There exist an optimal number of insulation layers for the best thermal insulation property, and the layout of radiation foils also has an effect on the thermal insulation property, when the foils are located near the cold boundary, the temperature of the cold boundary is lower, and the density of spacers and the reflectivity of foils are higher, the thermal insulation property is much better.

At present, the research of multi-layer insulation materials has been more mature. Miao\([5]\) prepared a novel multi-layer insulation material with alternately arranged parallel layers of aluminum silicate fiber and metal foils, metal foils were copper, stainless steel, titanium, zirconium, tantalum and molybdenum foil, respectively. The result shown that the thermal insulation property of the multi-layer aerogel composites is better than the pure aerogel composites and the traditional multi-layer insulation composites. Wei \([6]\) studied the heat transfer characteristics of the multi-layer insulation system through numerical simulation, the influence of the parameters such as reflecting screens number, reflecting screens emissivity, the extinction coefficient of thermal insulation material, the gas-solid coupled thermal conductivity of thermal insulation material on the thermal insulation layer thickness were analyzed. The results also show that the reflecting screens have more significant effect on the insulating layer when the extinction coefficient, the gas-solid coupled thermal conductivity of the insulation material, as well as the reflecting screens emissivity is small.

In this report, multi-layer insulation material was prepared with parallel layers of zirconia fiber. Zirconia fibers thermal insulation materials are considered as an important high temperature thermal protection materials due to their high temperature resistance (above 2000°C), low thermal conductivity, oxidation resistance, high strength and toughness, and other excellent properties. Graphite paper was used as reflective foils in the zirconia fiber insulation materials system. In order to further reduce the emissivity of the reflective foils, zirconia superfine powder was coated on the surface of the graphite paper. Finally, multi-layer insulation material with low thermal conductivity was prepared.

![Figure 1. Schematic diagram of multi-layer insulation materials.](image)

2. Experiment

Multi-layer insulation material was prepared with alternately arranged parallel layers of zirconia fiber and reflective foils, the reflective foils were graphite paper. The thickness of the graphite paper as reflective screens were 0.01 mm. Firstly, zirconia fiber were dispersed in polyacrylamide aqueous solution, wet zirconia sheet was prepared by vacuum filter forming process, then reflective foils were
inserted between fiber sheets, aluminium phosphate gel was used as adhesive to bond the wet fiber sheet with reflective foils. The preform was obtained after multilayer fiber sheets were glued with reflective foils. At last, the multi-layer insulation composite was obtained by drying the preform at 180°C for 12 h in oven, and the structure was shown in Figure 1.

The thermal conductivity coefficient of composite materials with different number of foils was determined by water flow plate method (YB/T4130-2005). The thermal insulation property was tested at a hot plate furnace, two thermocouples were placed on the heating-surface and the cold-surface of the sample, respectively, in order to record the temperature of the cold surface in response to the heating-surface temperature. Here, the hot side temperature was set at 1000 °C. All the samples were 10 mm thick.

| Table 1. Multi-layer insulation materials with different number of layers and layer spacing. |
|---------------------------------------------|-----|-----|-----|-----|-----|
| Number of layers                          | 6   | 8   | 10  | 12  | 14  |
| Layer spacing (mm)                        | 1.67| 1.25| 1   | 0.83| 0.71|

![Figure 1](image1.png)

![Figure 2](image2.png)

3. Results and discussion

3.1. Effect of the number of reflective foils on the thermal insulation property of multi-layer insulation materials

Five kinds of Multi-layer insulation materials with different number of layers were prepared as shown in Table 1, the thickness of all the samples was 10 mm, and number of layers were 6, 8, 10, 12 and 14, respectively, layer spacing were 1.67, 1.25, 1, 0.83, 0.71 mm, accordingly. In response to the change of the heating-surface temperature, the temperature of the cold surface was recorded in Figure 2 (a).

From equation 2, it can be seen that the thermal insulation property is better when the density of the layers is greater. However, because of the presence of spacer fibers, there is a contact heat transfer between the reflective screens, and the contact heat transfer increases rapidly with the increase of layer density. Therefore, there is an optimal layer density to make the thermal insulation property of the multi-layer insulation material achieve the best.

As can be seen from Figure 2 (a), when the number of foils was 6, the cold surface temperature was steady at 297.4°C, the thermal conductivity coefficient was 0.062 W/(m·K) which was recorded in Figure 2 (b). When the number of foils increased to 8 and 10, the cold surface temperature was steady at 280.8°C and 268.8°C, the thermal conductivity coefficient was 0.054 W/(m·K) and 0.049 W/(m·K),
and continue increased the layer numbers to 12 and 14, the steady cold surface temperature increased to 320.5°C and 334.8°C, the thermal conductivity coefficient increased to 0.053 W/(m·K) and 0.056 W/(m·K). When the number of foils was less than 10, the cold surface temperature decreases with increasing the layers. This shows that the insulation property of composite increased, this is because that with the number of layers increasing, the foils as reflective screens and the value of the radiant heat transfer decreasing greater than the value of the contact heat transfer increasing, so the total heat transfer is reduced. With the number of foils increasing, the contact heat transfer is also increasing rapidly. As shown in Figure 2, when the number of foils is more than 10, with the number of layers continue to increasing, the value of the contact heat transfer increased.

| Sample No | ZrO₂ powder(g) | Emissivity | Thickness(mm) |
|-----------|----------------|------------|---------------|
| 1#        | 3              | 0.51       | 0.80          |
| 2#        | 5              | 0.44       | 0.91          |
| 3#        | 8              | 0.37       | 1.15          |
| 4#        | 12             | 0.35       | 1.75          |

3.2. Effect of the emissivity of the foils on the thermal insulation property of multi-layer insulation materials

Zirconia powder was used to reduce the emissivity of the graphite paper foils, different quality of powder was coated on the surface of the foils with aluminium phosphate gel. When the graphite paper was coated with 3 g zirconia powder, zirconia powder is a thin coating on the surface of graphite paper, the emissivity was reduced to 0.51 compared with the emissivity of graphite paper, and the emissivity was further reduced to 0.44, 0.37 to 0.35 when 5 g, 8 g, 12 g zirconia powder was used, as can be seen from Figure 3, the foils was gradually turn to white and the thickness increased.

The above modified graphite paper was used as foils in the thermal insulation materials, the number of foils was 10. The effect of the emissivity of the foils on the property of the insulation materials was recorded in Figure 4. As shown in Figure 4 (a), when the emissivity of foils was 0.51, the steady cold surface temperature of the insulation materials was 263°C, in Figure 4 (b), the thermal conductivity coefficient was 0.056 W/(m·K). After the emissivity of foils reduced to 0.44 and 0.37, the steady cold surface temperature was 254°C and 240°C, the thermal conductivity coefficient was 0.047 W/(m·K) and 0.040 W/(m·K), respectively. This results was consist with equation (2), the thermal insulation property of the materials with lower emissivity was better, but in Figure 4, the thermal insulation property of the materials with emissivity of 0.35 was not the best, because more zirconia powder was coated on the surface of the foils, which results in the thickness increasing, and the contact heat transfer also increasing.
4. Conclusions

In conclusion, a new type of insulation materials was prepared using zirconia fiber as spacing layer and graphite paper as foils, and the thermal insulation property was investigated. The thermal insulation materials was best when the number of foils was 10. Zirconia powder can be used to reduce the emissivity of the graphite paper from 0.8 to 0.35. The thermal insulation property of the materials can be further improved by using the modified graphite paper foils.

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