Insulation performance analysis of novel high-temperature vacuum insulated panels with 2D and 2.5D braided structures

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Abstract
In this paper, the thermal insulation performance and mechanism of novel High-temperature vacuum insulated panel (HTVIP) with 2D and 2.5D braided structures shell were compared and analyzed extensively. The effective thermal conductivity of 2.5D HTVIP ranged from 0.326 W m$^{-1}$·K$^{-1}$ to 0.748 W m$^{-1}$·K$^{-1}$ within the temperature from 25 °C to 900 °C is 12.4%–27.2% lower than the value of 2D HTVIP ranged from 0.368 W m$^{-1}$·K$^{-1}$ to 1.027 W m$^{-1}$·K$^{-1}$. The infrared images of both 2D and 2.5D HTVIP were also examined, which showed the 2.5D HTVIP has better thermal insulation performance. The thermal flow dynamic simulation of the HTVIP shows that the values of temperature at the center of the lower surface of the 2D and 2.5D HTVIP calculated by thermal simulation are 471 °C and 386 °C, respectively. And the heat flux density on the side of the 2.5D HTVIP is significantly lower than that of the 2D structure, the highest values are 163 kW m$^{-2}$·K and 105 KW m$^{-2}$·K, respectively.

1. Introduction

With the development of hypersonic vehicle, the speed is getting significantly faster, and the surface temperature of the aircraft rises sharply due to aerodynamic heating [1–5]. As a counter measure, thermal protection system (TPS) covering the vehicle surface is developed using metallic materials [6, 7] to ceramic matrix composite material [8, 9] to resist the higher temperature and stronger heat flow. However, metal-based TPS has limited high temperature resistance and cannot be used for a long time at high temperature, while ceramic-based TPS has high thermal conductivity and often needs a bigger size to meet the thermal insulation requirements, which undoubtedly increases the weight of TPS. Based on this, a novel high temperature vacuum insulated panel (HTVIP) with high strength, low density and low conductivity is a new concept, which was first proposed by Wang et al. [10–12] few years ago. This material with core–shell structure is composed of insulating porous core material and a sealed C/C-SiC composite shell. The most important is that it has a vacuum inside, which can diminish or eliminate heat conduction and convection of internal gas, thus greatly reducing the thermal conductivity. The sealed C/C-SiC composite shell can be used to withstand high temperatures and high velocity airflow, while the porous core material can not only effectively isolate the heat flow, but also greatly reduce the overall weight of TPS. Thus HTVIP material is lightweight with excellent high temperature resistance and anti-airflow characteristics, which has a great potential to be used as a TPS material in high temperature insulation fields.

For HTVIP materials, different structures have different properties, especially for the C/C composite shell. Since the thermal conductivity of the C/C composite shell is much higher than that of the SiC foam core, heat is not only transferred downward from the inside of the core, but also transferred along the surface of the C/C shell due to thermal bridge effects. Therefore, reducing the thermal conductivity of the HTVIP C/C shell plays an important role in reducing the thermal bridge effect. Because the thermal conductivity of carbon fiber is much higher than that of carbon matrix [13], so the overall thermal conductivity of composite is highly sensitive to the...
carbon fiber braided structure [14, 15]. How to design and optimize the braided structure of the carbon fiber preform shell will have an important influence on the heat flow path in the C/C shell, thus ultimately changing the effective thermal conductivity of the HTVIP material.

In this research, two kinds of HTVIP with 2D and 2.5D braided structures shell have been prepared. By comparing and analyzing the 2D and 2.5D C/C shells, the influence of the thermal bridge effect of the C/C shells on the overall thermal insulation performance is discussed. The heat transfer analysis model of HTVIP material is also constructed to simulate the heat transfer in HTVIP material. This paper provides a theoretical basis for the potential design and practical application of HTVIP.

2. Experimental details

Raw materials, including SiC foam core material, carbon fiber cloth and carbon fiber bundle of T300 and 3 K types (prepared in Changsha, PR China) were used in this study. SiC foams in dimension of 150 mm × 150 mm × 22 mm (Suzhou DeXin Advanced Ceramics Co., LTD) produced by the replica method are used as the core materials with a porosity of 83% and a density of 0.42 g cm$^{-3}$.

Figure 1 describes the main manufacturing steps of HTVIP composites. In order to analyze the heat transfer performance of HTVIP with different braided structures, the carbon fiber preforms were prepared by 2D wrapping technology and 2.5D braiding technology, respectively.

The thickness and volume fraction of both preform outer shells were 3 mm and 40%. Then, pyrolytic carbon (PyC) deposited into the fiber preform by Chemical Vapor Infiltration (CVI) method to increase the density of the outer shell. To further densify the outer shell, polymer infiltration and pyrolysis (PIP) method was
performed. In the first three PIP cycles, a 40% solubility phenolic resin solution was selected. As the pores in the C/C shell became denser, the solubility of the phenolic resin in the subsequent PIP cycle decreased to 30%. The pyrolysis process must be very slow to obtain glassy carbon matrix with extremely low gases permeability \[16, 17\]. Such glassy carbons filled the small pores in the specimens to enhance its density. In the final step, Chemical Vapor Deposition (CVD) SiC coatings were performed in low pressure (1–10 Pa) on the entire units. In this step, the pressure inside the HT-VIP sample was in accordance with the pressure in CVD furnace. After 5 cycle of CVD process, the SiC coating acted as an outmost sealing layer to further densify the outer shell to prevent air from penetrating into the interior, thereby ensuring a vacuum inside. The specific densification process was previously reported \[12\]. 2D and 2.5D structure HTVIP sample images are shown in figure 1.

In order to compare the heat transfer performance of 2D and 2.5D HTVIP, an infrared thermal imager (FLIR-A320) was used to record the instantaneous temperature distribution in the surface of HTVIP. The infrared radiation observation schematic diagram is shown in figure 2. The HTVIP specimens were put on a copper plate with a constant temperature of 300 °C. The infrared thermal imager then records in real-time the variations of the temperature on HT-VIP upper surfaces. The thermal conductivities of the outer shells were
determined by a laser flash thermal analyzer (Netzsch, LFA457) and the effective thermal conductivities of HTVIP materials were determined measured via water flow plate method, according to ASTM standard E422–05 [18]. Additionally, the simulations of temperature and heat flux distributions in HTVIPs were also computed by ANSYS finite element software.

3. Results and discussion

3.1. 2D and 2.5D braided structure analysis of HTVIP

Figure 3 shows the basic structural schematic diagram of HTVIP, the above figure (a) shows the 2D or 2.5D weaving direction at the top of outer shell, and the right figure (b) is the right figure is 2D or 2.5D weaving direction on the side of outer shell. The inside is SiC foam core and the outside is the sealing outer shell. It can be seen clearly that the braided structures of outer shells between the top and bottom and the four sides are different.

For the 2D woven fabric structure, the carbon weft and warp yarns are both arranged parallel alone the x and y directions, respectively on the top and bottom surface, while on the side face, the warp yarn is distributed along the vertical direction, i.e., Y-axis distribution, and the weft is distributed along the X-axis. Also for the 2D structure, the

Figure 4. 2.5D braiding process in outer shell of HTVIP. (a) Initial stage of weaving; (b) Transition stage of weaving; (c) Development stage of weaving.

Figure 5. SiC Foam with different pore sizes.
ratio of warp and weft is 1:1. So a half of the carbon yarns are arranged vertically in the sides, resulting in a high thermal conductivity. Structurally, the arrangement of 2.5D fabric is completely different from 2D fabric. For the 2.5D woven fabric structure, on the top and bottom, the weft is neither distributed along the \(X\)-axis nor distributed along the \(Y\)-axis. It is distributed along the circle from the center outward radially, as shown in figure 4.

Figures 4(a)–(c) shows the different stages of weaving for the outer shell. It can be seen the warp yarn is expanding outward continuously, while the weft yarn is encircled in a circle. The main purpose of this structure design is to ensure that all weft yarns are distributed along the \(X\)-axis and all warp yarns along the \(Y\)-axis on the side of the outer shell. It is because that in 2.5D fabric the ratio of warp and weft should be controlled to decrease the quantity of carbon fiber bundles in the vertical direction as much as possible to reduce the heat conductivity of the sides. So in this paper, the ratio of warp (radial axes) and weft (circumferential axes) was designed to 1:2 in 2.5D structure. According to the characteristics of 2.5D structure, the wrap yards is much more curving than the wrap yards in 2D structure, leading to the extension of its heat transfer path in structure, which further reduces the thermal conductivity of the sides.

3.2. Properties of SiC foam cores

In order to investigate the influence of SiC foam parameters on thermal conductivity, SiC foams with different pore sizes were studied. Figure 5 shows the photo of SiC foam with 10 PPI, 20 PPI, and 30 PPI pore sizes. It can be seen that the 10 PPI SiC foam has a larger pore size and a thicker foam skeleton. For the 30 PPI SiC foam, the single pore size is smaller and the foam skeleton is finer. And the 20 PPI SiC foam has the appropriate pore size and skeleton fineness.

The SiC foam core not only has thermal insulation properties, but also supports outer shell. The diameter size SiC foam skeleton play a decisive role in its compression resistance. Figure 6(a) shows the compressive strength of SiC foams with three different pore sizes (10 PPI, 20 PPI, and 30 PPI). The maximum load for 10 PPI SiC foam is 3.5 KN and the compressive strength is approximately 8.75 MPa. For 20 PPI SiC foam, the maximum load is 3 KN and
the compressive strength is 7.5 MPa, and the strength drop is not large. While for 30 PPI SiC foam, the maximum load is only 1.8 KN, the compressive strength is only 4.5 MPa. This is mainly because the SiC foam skeleton with a pore size of 30 PPI is too thin and the skeleton is easy to break, resulting in its poor compressive strength.

Figure 6(b) compares the thermal conductivity of SiC foam with different pore sizes. It can be seen that the thermal conductivity increases with the temperature, which is mainly due to the fact that the radiation heat transfer gradually dominates with the increase of temperature. For SiC foam with 10 PPI, the thermal conductivity is the highest, owing to the largest the pore size in SiC foam. Conversely, the smaller the pore size, the higher the extinction coefficient and the lower the thermal conductivity. Therefore, the 30 PPI pore size SiC foam has the lowest thermal conductivity. In summary, although 10 PPI SiC foam has sufficient strength, its thermal conductivity is high and its thermal insulation performance is poor. The 30 PPI SiC foam has the lowest thermal conductivity and the best thermal insulation, but its strength is too low and the skeleton structure is easy to break. While 20 PPI SiC has proper thermal conductivity and strength, it is suitable to be used as the core of HTVIP.

3.3. Effect of 2D and 2.5D structures on thermal conductivity of HTVIP

The thermal properties of outer shells have big differences between 2D HTVIP and 2.5D HTVIP. Figure 7 shows the thermal conductivity of outer shell with 2D structure and 2.5D structure at different directions. It should be noted that the thermal conductivity of outer shell at any direction increases first and then decreases. It is because the phonon mean free path decreases with the temperature rises. In low temperature range, the increase of heat capacity is greater than the decrease of the free path, so the thermal conductivity increases with the rise of temperature at the first stage [13]. However, at higher temperatures, lattice defects begin activated and increased, the scattering effect of phonons is strengthened, resulting in the decrease of thermal conductivity.

Figure 7(a) shows the thermal conductivity of 2D outer shell at different direction. The thermal conductivity at X-Y direction reach 17.01 W m$^{-1}$ K$^{-1}$ at 500 °C, which is 3–4 times higher than that at Z direction, thus resulting in large heat flux and severe thermal bridge effect in the sides. Figure 7(b) shows the thermal conductivity of 2.5D outer shell at different direction. Even though the thermal
conductivity at X-axis is the highest, it wouldn’t make contribution to the heat transfer in vertical direction. In Z direction, the thermal conductivities of 2D and 2.5D structure are almost same, the highest value is about 4 W m$^{-1}$ K$^{-1}$. While in Y direction (along the side vertical direction), the highest thermal conductivity is only 10.69 W m$^{-1}$ K$^{-1}$ at 400 °C, which is significantly less than the thermal conductivity of 2D structure. So for the 2.5D structure, it is beneficial to reduce the heat flow along the sides.

In the Y direction, the difference in thermal conductivity is mainly caused by the different braided structure. The heat transfer path of 2.5D structure along the warp fiber is much more flexuous than 2D structure, leading to the lower thermal conductivity. Figure 8 exhibits the difference of heat transfer between 2D structure and 2.5D structure clearly. Because the heat flow is much faster in the fiber direction than in the carbon matrix, the thermal conductivity of C/C composites is mainly determined by the carbon fiber content and their structure [13]. So extending the length of carbon fiber can help reduce the overall thermal conductivity of C/C.

Figure 9 shows the surface infrared images of SiC foam, 2D HTVIP and 2.5D HTVIP. SiC foam as core material is analyzed first in figure 9(a). It can be seen the upper surface color of SiC foam changed from black to blue and then to red in 10 min, which meant the surface temperature was rising constantly. After 20 min, the maximum surface temperature reaches 200 °C. Figure 9(b) shows the surface infrared images of 2D HTVIP, it can be seen clearly that the heat flow is the fastest transmission on the edge and the temperature near the edge is significantly higher than the center temperature after 10 min. It is because the thermal conductivity of the side shells is much higher than SiC foam core. While compared with the 2D HTVIP, the heat transfer of 2.5D HTVIP through the edge of outer shell is effectively alleviated, as shown in figure 9(c). Even though the temperature near the edge is still higher than the center temperature, the temperature is lower in same time. Because the thermal conductivity of the 2.5D C/C outer shell in the Y direction is very low, the surface temperature rises slowly.

Figures 10(a)–(c) are the detected variation curve of highest and lowest temperature in the surface of SiC foam, 2D HTVIP and 2.5D HTVIP, respectively. It can be seen from figure 10(a), the difference of both curves...
is very small in the first 5 min. Then as the temperature rises, the gap between the two curves starts to widen. It might be caused by the air convection in different surface positions. For SiC foam, the heat transfer mode is mainly composed of gas heat convection and conduction, solid skeleton heat conduction and the thermal radiation, which leads to a high surface temperature. So after 10 min later, the highest and lowest temperature reach as high as 201 °C and 176 °C, respectively. As shown in figure 10(b), the highest temperature is mainly distributed at the edge of the sample, while the lowest temperature is mainly distributed in the middle of the sample surface. The strong thermal bridge effect has a certain influence on the thermal insulation performance of the material. After 20 min later, the highest and lowest upper surface temperature are 147 °C and 88 °C, respectively, which are obviously lower than that of SiC foam, owing to the restrictions of gas heat convection and thermal radiation inside the HTVIP. While in figure 10(c), the upper and lower surfaces temperature of the sample has become flat after 20 min of measurement, which is close to equilibrium state. The highest and lowest temperatures in the surface of 2.5D HTVIP are only 126 °C and 78 °C after 20 min, which are lower than the 2D HTVIP, showing 2.5D structure HTVIP has superior thermal insulation properties than 2D structure.

In order to evaluate the thermal insulation of the two HTVIP, it was necessary to compare the effective thermal conductivity of 2D and 2.5D HTVIP. Figure 11 illustrates the results of measurements. It can be seen the both thermal conductivities increased with the temperature. It is because the radiation in HT-VIP is the dominant heat transfer mode in high temperature due to the high porosity and relativity big pore size of foam.
And the radiation makes a contribution to the thermal conductivity is a relation of the temperature $T$ to the third power. It can be estimated by the expression

$$\lambda_r = 4\sigma_B \varepsilon n^2 d T^3$$  \hspace{1cm} (1)$$

In which $\sigma_B$ is the Stefan–Boltzmann constant, $\varepsilon$ the emissivity, $n$ the refraction index and $d$ is the pore diameter.

On the experiments shown in figure 11, the effective thermal conductivity of 2.5D HTVIP ranged from 0.326 W m$^{-1}$K$^{-1}$ to 0.748 W m$^{-1}$K$^{-1}$ within the temperature from 25 °C to 900 °C, which is 12.4%–27.2% lower than the value of 2D HTVIP ranged from 0.368 W m$^{-1}$K$^{-1}$ to 1.027 W m$^{-1}$K$^{-1}$. It indicates that the difference of outer shell structure has important influence on the overall effective thermal conductivity of HTVIP. This result is also consistent with the previous analysis. Compared with 2D outer shell, the outer shell with 2.5D structure is more conducive to reducing the effective thermal conductivity of HTVIP.

Figure 10. The variations of highest and lowest temperature in the surface: (a) SiC foam; (b) 2D HT-VIP; (c) 2.5D HTVIP.
3.4. Heat flow dynamic simulation

In order to simulate the transient thermal simulation of HTVIP, the upper surface is set to have a heat flow of $10^6 \text{ W m}^{-2}$, a surface emissivity of 0.9, and a load time of 300 s for analysis. The geometric parameters of HTVIP and the parameters of outer shell have been listed in tables 1 and 2.

In the model, the SiC coating is very thin compared to the C/C shell, so the effect of SiC coating on the whole heat transfer is ignored. It is assumed that the outer shell layer and the core material are in contact with each other, and the outer surface of the outer shell has no heat exchange with the outside, and the heat transfer coefficient between the bottom surface of the material and the outside is set to 38 W m$^{-2}$ K$^{-1}$.

### Table 1. Geometric parameters of HTVIP used in the simulation.

| Parameter      | Value  |
|----------------|--------|
| Core material  |        |
| Length, $L_1$ | 150 mm |
| Width, $L_2$  | 150 mm |
| Thickness, $h$| 22 mm  |
| Outer shell    |        |
| Thickness, $\delta$ | 2 mm |

### Table 2. The parameters of outer shell.

| Temperature ($^\circ\text{C}$) | Density (Kg m$^{-3}$) | Specific heat (J Kg$^{-1}$.$^\circ\text{C}$) | 2D C/C (W/(m-K)) X-Y direction | Z direction | 2.5D C/C (W/(m-K)) Y direction | Z direction |
|-------------------------------|-----------------------|------------------------------------------|--------------------------------|-------------|-------------------------------|-------------|
| 25                            | 1720                   | 720                                      | 7.42                          | 2.17        | 5.91                          | 2.38        |
| 100                           | 1720                   | 920                                      | 8.43                          | 3.36        | 6.85                          | 2.94        |
| 200                           | 1720                   | 1180                                     | 11.55                         | 4.51        | 8.52                          | 4.07        |
| 300                           | 1720                   | 1430                                     | 13.18                         | 5.16        | 9.38                          | 4.53        |
| 400                           | 1720                   | 1600                                     | 15.73                         | 5.08        | 10.69                         | 5.39        |
| 500                           | 1720                   | 1760                                     | 17.01                         | 4.34        | 10.11                         | 6.06        |
| 600                           | 1720                   | 1860                                     | 16.21                         | 3.91        | 8.87                          | 4.74        |
| 700                           | 1720                   | 1935                                     | 14.89                         | 3.52        | 8.02                          | 4.52        |
| 800                           | 1720                   | 1980                                     | 13.74                         | 2.42        | 6.94                          | 3.11        |
| 900                           | 1720                   | 2010                                     | 11.82                         | 1.7         | 5.35                          | 2.15        |

3.4.1. Temperature simulation

Figure 12 shows the simulated transient temperature changes of the lower surface of 2D and 2.5D HTVIP. On the lower surface, as shown in figure 12(a), the temperature rises relatively slowly. After 100 s, the center temperature is still low, then the center temperature rises slowly. After 300 s, the center temperature rises to 471 $^\circ\text{C}$, showing its excellent thermal insulation properties.
It can be seen from the figure that the temperature rises faster at the edge and the temperature rises relatively slowly at the center, which is determined by the structure of the HTVIP material. Because the thermal conductivity of the outer shell is much higher than the thermal conductivity of the core, the heat flow on the sides is faster, so the temperature at the edge is higher, which is consistent with the infrared images observed in the previous part. Figure 12(b) shows the transient temperature change of the lower surface of the 2.5D structure HTVIP. The temperature change trend is consistent with the 2D structure, but the temperature is slightly decreased. After 300 s, the center temperature is only 386 °C. This is because the outer layer of the 2.5D structure has a lower thermal conductivity on the side than the 2D structure, resulting in lower heat transfer through the sides than 2D HTVIP.

Figure 13 shows the temperature versus time at the center of the upper and lower surfaces of the 2D and 2.5D HTVIP, respectively. It can be seen that the temperature of the upper surface of the two structures rises rapidly to about 1800 °C within 40 s and reaches a steady state, and the temperature does not rise any more. The lower surface temperature is almost constant at the initial stage, and the temperature starts to rise after 70 s, as shown in figure 13(b). This shows that the two HTVIP both have excellent thermal insulation properties and high heat capacity. Figure 13(b) shows that the surface temperature of the 2D HTVIP is slightly higher than the 2.5D structure after 100 s. As time goes by, the temperature difference at the bottom gradually increases. After 300 s, the values of temperature at the center of the lower surface of the 2D and 2.5D HTVIP are 471 °C and 386 °C, respectively. It can be seen that the 2.5D HTVIP has superior thermal insulation performance compared to the 2D HTVIP.

Figure 12. The simulated transient temperature (°C) changes of the lower surface: (a) 2D HTVIP; (b) 2.5D HTVIP.
Figure 13. 2D and 2.5D structure HTVIP temperature change curve: (a) upper surface; (b) lower surface.

Figure 14. 2D and 2.5D HTVIP heat flow (KW m$^{-2}$K) distribution after 300 s.
3.4.2. Heat flow simulation

Figure 14 shows the heat flow distribution of the 2D and 2.5D HTVIP after 300 s. By comparison, the heat flux density on the upper surface of the two after 300 s is not much different and tends to be stable. The surface heat flux density at the lower surface of the 2D HTVIP is significantly higher than the 2.5D HTVIP at the edge of the material, and it is constantly moving toward the center. This means that the heat flow through the side in the 2D HTVIP is significantly higher than the 2.5D structure, which is consistent with the results of the previous analysis.

Figures 15(a) and (b) show the simulation results of transient heat flux on the sections of 2D and 2.5D HTVIP, respectively. It can be seen from the figure that the highest part of the heat flux density is mainly...
concentrated on the sidewall, and the heat flux density on the core material is small, indicating that the HTVIP material has a relatively obvious thermal bridge effect. Therefore, the influence of the thermal bridge effect can be effectively reduced by controlling the thermal conductivity of the sidewall and reducing the thickness of the outer shell layer. By comparing figures 15(a) and (b), the heat flux density on the sidewall of 2.5D HTVIP is significantly lower than that of 2D structure, indicating that the thermal bridge effect in the 2.5D structure is less affected.

Figure 16 shows the heat flux density versus time at the 2D and 2.5D HTVIP shell sides. It can be seen that in the first 70 s, the heat flux density in the two structures increases sharply, and then the heat flux density tends to decrease slowly. This is because the thermal conductivity of the C/C shell rises with increasing temperature in the initial stage, causing the heat flow to increase rapidly at the beginning. After a period of time, the thermal conductivity of the C/C shell decreases due to the continuous rise of the temperature of the sidewall, and the temperature difference between the upper and lower surfaces of the HTVIP decreases, resulting in a gradual decrease in the heat flux density on the sidewalls and eventually stabilizes. It can be seen from the comparison that the heat flux density on the side of the 2.5D HTVIP is significantly lower than that of the 2D structure, and the highest values are 163 kW m$^{-2}$K and 105 kW m$^{-2}$K, respectively. Compared with the 2D structure, the thermal bridge effect of the 2.5D structural shell has a lower impact on the thermal insulation performance, so the 2.5D HTVIP thermal insulation is better.

4. Conclusions

In this study, the insulation performance of HTVIP with 2D and 2.5D braided structure outer shell has been compared and analyzed. For the C/C shell, the thermal conductivity of 2.5D structure is significantly less than that of 2D structure in the Y direction, which is beneficial to reduce the heat flow along the sides. The heat transfer path of 2.5D structure alone the warp yarn is not only much more flexible, but also less than 2D structure, leading to that the thermal bridge effect of the 2.5D structural shell has a lower impact on the thermal insulation performance. The infrared images also show the upper surface temperature of 2.5D HTVIP is lower than that of 2D HTVIP. The effective thermal conductivity of 2.5D HTVIP is 12.4%–27.2% lower than the value of 2D HTVIP within the temperature from 25 °C to 900 °C. HTVIP heat flow dynamic simulation indicates that the structural differences of outer shell have a great influence on the thermal performance of the whole HTVIP, and the 2.5D HTVIP has superior thermal insulation performance compared to the 2D HTVIP.

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