Numerical Analysis On Fluid-solid Coupling Cooling Of Minimal Surface Lattice Structure

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Abstract: This paper established the minimal surface lattice structure cooling model, researched the fluid-solid coupling cooling properties in addition flow by interface function transmit and compared the cooling properties of different minimal surface lattice and bar lattice in the same density. The influence of cooling fluid velocity was considered. The thermal stress and impact stress of the structure was analyzed by sequential coupling method. The result showed that the minimal surface structure had better cooling properties. The bottom temperature decreased with the increase of coolant flow velocity. There was a threshold for different structures, when the flow rate exceeded this value, the bottom surface temperature will not decrease. Stress analysis showed that stress concentration occurred at the junction of lattice and panel. The overall stress decreased first and then increased with the increase of flow rate.

1. Introduction
Aerospace industry has entered a period of rapid development. According to statistics, when hypersonic aircraft fly at an altitude of 30km and the flight Mach number reaches 3, the surface temperature can reach about 600K because of aerodynamic hot, and when the Mach number reaches 5, the temperature is as high as 1200K[1]. The temperature in the scramjet combustion chamber can even reach 3500K[2]. The thermal stress caused by high temperature causes damage to the aircraft structure, and internal instruments and equipment are also prone to potential safety problems due to high temperature. Therefore, thermal protection structure becomes an indispensable link in aircraft design.

Lightweight lattice structure has high specific strength, heat insulation, vibration isolation and other functions[3]. The internally connected pore configuration makes the structure itself an excellent radiator[4]. At present, it has been used in the cooling system of spacecraft shell, aero-engine cooling panel and other cooling systems. Vermaak [5] found that the traditional cooling channel is prone to local overheating, which results in fuel coking and blockage and deteriorates the heat dissipation performance because of its long and narrow and disconnected configuration. A series of numerical analysis and experimental tests were carried out on the heat dissipation performance of pyramid, tetrahedron, Kagome and other lattice structures by Roper[6], joo[7] and lu [8]. and they found that compared with the traditional cooling channel, the lattice structure had better flow characteristics and better heat dissipation effect. Luo[9] compared the heat dissipation performance of common lattice structures and found that kagome lattice has the best heat dissipation effect under the same density.

In recent years, with the continuous development of additive manufacturing technology, the minimal surface lattice structures modeled by parameterized implicit functions have been used.
Compared with the Bar type lattice, it has larger surface-volume ratio, zero mean curvature at all points on the surface, smooth transition and good flow characteristics[11]. Some scholars have researched on its mechanical and thermal properties[12,13].

This paper took the commonly used Gyroid, Dimond and Primitive minimal surface lattice structure and the traditional bar type lattice Kagome lattice with the best heat dissipation performance as the research object. The fluid-solid coupled heat dissipation model of lattice sandwich cooling panel with temperature boundary condition was established based on the method of interfacial function transfer. And the heat dissipation performance of the structures with the same density was compared. The stress of the structure is analyzed by sequential coupling method.

2. Lattice heat dissipation structure model

In this paper, with heat dissipation structure of engine combustion chamber as the background, the commonly used Gyroid(G), Dimond(D), Primitive(P) minimal surface lattice and Kagome (K) bar type lattice heat dissipation model were established (figure 1). The element model is shown in table 1.

To facilitate horizontal comparison, the relative densities of the four structures are equal.

| Table 1. Lattice element configuration |
|--------------------------------------|
| Model | Gyroid | Diamond | Primitive | Kagome |

![Model Images]

Fig 1. Lattice structure heat dissipation model

The upper panel of the model is a heated layer, connected to the combustion chamber and subjected to continuous temperature boundary conditions. In the middle is the lattice heat dissipation layer, the cooling flow flows in from the left side and flows out from the right side after the lattice structure has fully heat exchange. The lower panel is insulated and connected to the instruments in the cabin. The temperature shall not be too high. The panel size is slightly larger than the lattice to allow the coolant to flow fully. The overall size parameters of the model are shown in table 2. Referring to the actual working condition of the engine combustion chamber, the heating surface temperature is 1000k, and the coolant inlet temperature is 300k[2]. Titanium alloy (TC4) was used for lattice materials, and the thermophysical parameters varied with the temperature, as shown in table 3.

| Table 2. Cooling model size |
|-----------------------------|
| Size of lattice cell | 4 |
| volume fraction of lattice | 0.18 |
| Thickness of panel | 1 |
| Length of model | 45 |
| Width of model | 9 |
Table 3. TC4 material parameters

| Temperature (°C) | heat conductivity (W/m.k) | thermal expansivity (10⁻⁶.°C⁻¹) | specific heat (J/(kg.°C)) |
|-----------------|-----------------|---------------------------------|---------------------------|
| 20              | 6.8             | 9.1                             | 611                       |
| 100             | 7.4             | 9.2                             | 624                       |
| 200             | 8.7             | 9.3                             | 653                       |
| 300             | 9.8             | 9.5                             | 674                       |
| 400             | 10.3            | 9.7                             | 691                       |
| 500             | 11.8            | 10.0                            | 703                       |

The coolant adopts aviation kerosene, and its density, viscosity coefficient, thermal conductivity coefficient and specific heat capacity at constant pressure are given by the following fitting function.

\[ \rho = 1087.47 - 0.9488 \times T \]
\[ \mu = 7.2444 \times 10^4 \times T^{-3.646} \]
\[ \lambda = 0.1993 \times 1.9705 \times T^{-4} \times T \]
\[ C_p = 705.55 + 4.03 \times T \]

3. Numerical calculation method

Due to the temperature difference between the upper and lower panels, the heat will be transferred from the heating surface along the lattice structure to the bottom surface, while the incoming coolant contact with the lattice structure and take away the heat. The heat transfer mechanisms involved include solid heat transfer, solid-liquid interface conjugate heat transfer and coolant flow heat transfer.

The heat transfer of solids follows Fourier law

\[ \rho C_s \frac{\partial T}{\partial t} = \frac{\partial}{\partial x} (k_s \frac{\partial T}{\partial x}) + \frac{\partial}{\partial y} (k_s \frac{\partial T}{\partial y}) + \frac{\partial}{\partial z} (k_s \frac{\partial T}{\partial z}) \]

Where \( \rho, C_s, k_s \) are density, specific heat capacity and thermal conductivity of solid respectively.

The coolant is regarded as viscous incompressible fluid, the \( k - \varepsilon \) standard turbulence model is adopted, and the continuous equation is

\[ \frac{\partial \rho}{\partial t} + \nabla (\rho U) = 0 \]

The momentum equation:

\[ \frac{\partial \rho U}{\partial t} + \nabla (\rho U \otimes U) - \nabla (\mu_{eff} \nabla U) = \nabla p' + \nabla (\mu_{eff} \nabla U)' + B \]

Where, \( B \) is the sum of volume forces, \( \mu_{eff} \) is the effective viscosity, and \( p' \) is the modified pressure. The expression is

\[ \mu_{eff} = \mu + \mu_t \]
\[ p' = p + \frac{2}{3} \rho k \]

Where \( \mu_t \) is turbulence viscosity, and the \( k - \varepsilon \) model assumes that turbulence viscosity is related to turbulent kinetic energy and turbulent kinetic energy dissipation

\[ \mu_t = C_p \rho \frac{k^2}{\varepsilon} \]

The value \( k, \varepsilon \) is directly solved from the turbulent kinetic energy and the turbulent kinetic energy dissipation equation, and the turbulent kinetic energy equation is

\[ \frac{\partial (\rho k)}{\partial t} + \nabla (\rho U k) = \nabla \cdot (\mu_t \nabla k) + \varepsilon \]

\[ \frac{\partial \varepsilon}{\partial t} + \nabla \cdot (\rho U \varepsilon) = C_1 \mu_t \frac{\varepsilon}{k} \nabla \cdot (\mu_t \nabla U) - C_2 \frac{\varepsilon^2}{k} + \varepsilon_{is} \]

Where \( \varepsilon_{is} \) is the artificial dissipation term.
\[
\begin{align*}
\frac{\partial (\rho K)}{\partial t} + \nabla \cdot (\rho \mu \nabla K) &= \nabla \cdot \left( (\mu + \frac{\mu}{\sigma_t}) \nabla \right) + P_t - \rho \varepsilon \\
\frac{\partial (\rho \varepsilon)}{\partial t} + \nabla \cdot (\rho \mu \varepsilon \nabla) &= \nabla \cdot \left( (\mu + \frac{\mu}{\sigma_t}) \nabla \right) + \frac{\varepsilon}{K} (C_p P_t - C_v \rho \varepsilon)
\end{align*}
\]

Where, $\sigma_t$, $\sigma_t^*$, $C_{t1}$, $C_{t2}$ is a constant.

$P_t$ is the turbulence product of viscous force and buoyancy, and its equation is

\[
P_t = \mu \nabla U \cdot (\nabla U + \nabla U^T) - \frac{2}{3} \nabla U (3 \mu \nabla U + \rho k) + P_{\rho b}
\]

For incompressible fluid, the value of $\nabla U$ is relatively small and has little influence on the results of the whole equation.

The fluid-solid coupling boundary is determined by the transient heat transfer relationship between the fluid and the solid. According to the continuity condition of temperature and heat flow

\[
T_s = T_f
\]

\[
k_s \frac{\partial T_s}{\partial n} = k_f \frac{\partial T_f}{\partial n}
\]

$T_s$ and $T_f$ are the temperature of solid and fluid at the boundary respectively.

In order to explore the influence of fluid velocity on heat dissipation effect, inlet velocity boundary condition was set, and the outlet was free flow boundary condition.

4. Results analysis

4.1 Heat dissipation performance analysis

For the convenience of description, the coolant flow direction is defined as x direction, the inlet coordinate is 0, and the vertical direction is z direction, as shown in figure 2. Figure 3 shows the temperature cloud in the z-direction of the four lattice structures when the flow rate is 1m/s. When the top surface temperature is 1000K, the bottom surface temperature of G, D and P lattice structures is 750, 728k and 773k respectively, and the cooling effect reaches 25%, 27.2% and 22.7% respectively. Kagome lattice structure has a temperature of 842K, and the cooling effect is only 15.8%.

Fig 2. Front view of lattice sandwich heat dissipation model

Fig3. Z section temperature cloud
Fig 4. Temperature cloud diagram of surface p structure (a) temperature distribution of coolant x-direction section z=0 (b) temperature cloud diagram of floor x-direction section

The temperature of the coolant increases continuously from the inlet to the outlet. Taking the p-curved structure as an example, the temperature increases from 300k to 375k, indicating that the coolant carries away heat through the lattice structure. The bottom temperature is higher in the place which is connected with the lattice and shows a series of hot circles in the temperature cloud. The temperature of the bottom plate increases gradually along the x direction, which is because the temperature of the coolant in this direction increases continuously, resulting in the decrease of heat transfer efficiency near the outlet.

Convection heat transfer coefficient and Nusselt number are introduced. The convection heat transfer coefficient is defined as the Heat exchange between solids and liquids per unit area per unit time when temperature change of 1K. Take P structure (figure 5 (a)) as an example, in the area near the inlet, the coolant does not flow sufficiently and the convection heat transfer coefficient is small. After stabilization, the convection heat transfer coefficient presents a regular horseshoe-shaped distribution and the coefficient around the pillar is larger. This is because the coolant flows around the pillar forming a vortex where the velocity of flow is larger than that of other regions, and the local heat transfer performance is improved. It also shows that the lattice structure has the potential to be an excellent heat transfer structure.

In order to make the comparison of heat dissipation performance more universal, nusselt number was used, which is defined as

$$Nu = \frac{h}{\lambda}$$  \hspace{1cm} (11)

Where, $h$ is the convection heat transfer coefficient, $\lambda$ is the thermal conductivity of the coolant, and $l$ is the characteristic length of the lattice element. Figure 6 shows the change of Nussel number on the fluid-solid coupling interface of the three structures along the x direction. It can be seen from the figure that the Nusselt number fluctuates within a stable range after reaching a steady state, D surface lattice structure has the largest Nusselt number, the strongest fluid-solid heat transfer performance, followed by G and P surfaces, and Kagome is the smallest.
Fig 5. Convection heat transfer coefficient of p-curved structure and strong cloud diagram of cooling hydraulic pressure (a) convection heat transfer coefficient (b) pressure

Fig 6. Nussel number changes along the x direction

4.2 The influence of flow rate
Figure 7 statistics the average temperature of the bottom surface of the three structures at different flow rates. When the flow rate is close to 0, the bottom temperature is close to the 1000K, which applied on the top surface. The larger the flow rate is, the less obvious the heat dissipation effect is improved by increasing the flow rate. When the flow rate is greater than a certain threshold, the bottom temperature will not decrease. On the one hand, the increase of flow velocity strengthens the flow of local eddy current and enhances the heat transfer effect. On the other hand, the thickness of the boundary layer may increase. Since the velocity in the boundary layer changes exponentially, the proportion of coolant with relatively low velocity in the near-wall area will increase when the velocity is not very high, which has a negative effect on heat transfer. When the speed is large, the two influences can be coordinated to stabilize the temperature, and the increase of the flow rate is at the cost of consuming more power, so the appropriate flow rate should be selected to ensure effective heat dissipation while minimizing the power consumption. As can be seen from the figure, the optimal heat dissipation velocity of G, D and P structures is about 6m/s, 5m/s and 9m/s, respectively. Kagome structure does not reach the maximum heat dissipation efficiency at 10m/s.
4.3 pressure analysis
In addition to good heat exchange capacity, low pressure loss is another important performance index of coolant. Due to the shape resistance of the bar and the viscous resistance of the panel, the pressure of the coolant will be lost after heat exchange with the lattice structure. The lower the pressure loss is, the less the circulating pumping motion force is demanded. Figure 5 (b) is a cloud diagram of the coolant pressure of the P lattice, and the coolant pressure gradually decreases from the inlet to the outlet. Figure 8 showed the pressure of the three structures along the x direction. The pressure of the coolant from the inlet to the outlet presents a step-down. After entering the stable state, the pressure loss of each structural unit is constant, and the pressure loss of G, D and P structures is 238pa, 271pa and 216pa respectively.

4.4 stress analysis
Lattice heat dissipation structure stress mainly comes from two aspects: thermal stress caused by temperature rise and the impact stress caused by the impact of the coolant. We calculated them by applying the temperature and pressure of the fluid-solid coupling analysis results as boundary conditions to the structure field.

Figure 9 shows the thermal stress cloud diagram of the three structures. The stress distribution at the panel is relatively uniform, and the stress concentration is mainly at the contact between the lattice and the panel. This is because the longitudinal temperature gradient of the lattice structure is large, and the panel limits the longitudinal expansion of the lattice structure, resulting in a large plastic strain at the contact between the lattice and the panel. The thermal stress value decreases exponentially with the
increase of flow velocity, and its fitting relationship is shown as follows equation (12).

\[ p_h = 66.39v^{-0.25} \quad \ldots \ldots \quad G \]
\[ p_h = 105.8v^{-0.34} \quad \ldots \ldots \quad D \]
\[ p_h = 46.08v^{-0.28} \quad \ldots \ldots \quad P \]  

Figure 10 shows the impact stress cloud diagram of the structure. It can be seen that the stress of the lattice structure gradually decreases from the inlet to the outlet, which is caused by the continuous decrease of fluid pressure. The maximum stress is located at the contact point between the first element and the panel. The relationship between maximum impact stress and flow velocity is fitted as shown in equation (13).
Finally, the relationship between the structural stress and the coolant flow rate is obtained, as shown in Figure 11. It can be found that the structural stress value decreases first and then increases with the increase of the coolant flow rate. The stress value of G, D and P structures reaches the lowest when the flow rate is 3.4m/s, 4.7m/s and 5.3m/s, respectively. In addition, the maximum stress value of the structure within the flow rate range of the cooling fluid reaching the maximum heat dissipation efficiency is less than the yield strength of titanium alloy (860MPa), which indicates the strength safety of the lattice heat dissipation structure.

Fig 11. Relationship between structural stress and coolant flow rate

The heat dissipation performance, pressure loss and stress of the three kinds of surface lattice heat dissipation structure are comprehensively compared. Under the same Relative density, the heat dissipation effect of the d structure is the best, and the cooling fluid flow rate is the lowest when the maximum heat dissipation efficiency is reached, the effect of the p surface is the worst. The pressure loss of the p structural element is the least, and the power demand is the least in the cooling liquid circulation process. D surface structure has the maximum stress, up to 268Mpa, and P structure has the minimum stress, up to 104Mpa. In the process of heat dissipation, P structure has the minimum damage to the heat dissipation structure.

| Performance indicators                          | Gyroid | Diamond | Primitive |
|------------------------------------------------|--------|---------|-----------|
| Lightweight volume fraction                    | 0.18   | 0.18    | 0.18      |
| The average heat transfer intensity Nu         | 343    | 325     | 277       |
| Average bottom surface temperature             | 750    | 728     | 773       |
5. Conclusion

CFD simulation of fluid-solid coupling heat dissipation performance of minimal surface lattice structure and Kagome bar type lattice structure with equal density was carried out in this paper, and the thermal properties of the coolant and the high-temperature thermal properties of titanium alloy were taken into account. The results show that compared with the traditional bar type lattice, the minimal surface lattice structure has better heat dissipation performance due to its larger heat dissipation area and smooth surface configuration. For the commonly used G, D, P three minimal surface lattice structure, D surface heat dissipation performance is the best, but the maximum pressure loss. Before reaching the maximum heat dissipation efficiency, the bottom temperature decreases with the increase of coolant flow rate. The maximum stress is located at the junction of the first lattice element and the panel. The stress value decreases first and then increases with the increase of coolant flow rate. In the future, the influence of relative density and lattice element size on the heat dissipation effect will be further studied, the structure will be optimized and the fluid-solid coupling experiment will be carried out.

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