Optimization and Design of Regenerative Cooling Channel for Scramjet Engine

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Abstract. In this paper, the optimization model and numerical calculation verification model of the regenerative cooling channel structure of the scramjet engine are established, and the structural parameters of the regenerative cooling channel of the scramjet engine are optimized and numerically verified. The results show that the established optimization model of the regenerative cooling channel structure of the scramjet engine can meet the design requirements; after the structure optimization, the wall temperature change trend is basically the same as the original design change trend, and the overall temperature is low; the central flow calculated by the optimized configuration calculation, but the pressure loss of kerosene in the cooling channel is small. The oil temperature and convection heat transfer coefficient are large; the inner wall and fins of the optimized configuration are thinner, the channel height is higher, and the width is narrower, which can effectively increase the convection heat transfer efficiency of the cooling channel, which can ensure that the material temperature is not exceeding its maximum allowable temperature can make the pressure loss relatively low.

1. Introduction

Aiming at the particularity of the thermal protection conditions and working thermal environment of scramjet engines, regenerative cooling has great advantages compared with other types of cooling methods. First, the scramjet engine is filled with hot gas inside and outside at high Mach number, and it cannot be introduced into the external cooling. Secondly, according to the working characteristics of the scramjet engine, fuel injection is required to burn during the work process. During the regenerative cooling process, the engine casing is cooled by its own endothermic hydrocarbon fuel. The fuel is first used as a coolant, and after being burned, it is used as a propellant and injected into the combustion chamber for cooling.

An engine with a regenerative cooling structure is composed of heat exchange panels, and the flowing fuel flows as a coolant in the channel. Fuel flows from the cooling channel, flows through the combustion chamber wall of the engine, and then is injected into the combustion chamber for combustion. The cooling channel is coated with a catalyst to promote the cracking of the fuel when the fuel heats up, generate a hot gaseous hydrocarbon component and absorb a large amount of heat. This design can not only cool the high-temperature combustion chamber, but also can pre-heat the fuel to convert it into a hot gaseous hydrocarbon component, which can increase energy by more than 10% compared with the liquid state.

The structural parameters of the cooling channel have a great influence on the regenerative active cooling effect of the scramjet engine. There are many factors that affect the cooling structure: the thickness of the inner wall surface, the thickness of the fins, the width-to-height ratio of the channels,
and the number of channels. Each factor has a greater impact on the regenerative cooling effect. The thinner inner wall thickness corresponds to a lower wall temperature, while the heat flux density is larger, and the kerosene temperature and pressure change little; the thin ribs correspond to the higher wall temperature and oil temperature, but the pressure loss of kerosene in the cooling channel is small. For thicker fins, the maximum wall temperature and maximum oil temperature are smaller, but the pressure loss is larger; the channel with a larger aspect ratio has better cooling effect, and the wall temperature and oil temperature are relatively low, but the aspect ratio cannot be selected. An excessively large cooling channel is because after the aspect ratio is greater than 1, the pressure loss in the channel increases as the aspect ratio increases; reducing the channel cross-sectional area can increase the flow rate, thereby increasing the convection heat transfer coefficient, making the maximum wall temperature and oil temperature lower, but the kerosene with a too small channel area has a larger flow resistance in the channel, and the effective heat exchange area also becomes smaller; the increase in the number of channels can strengthen the heat transfer under certain circumstances. When the material temperature allows, multiple cooling channels can be arranged to give full play to the kerosene heat sink and fin effect to enhance the cooling effect [1].

Through analysis and analysis, it can be found that the change of the channel geometry has a great influence on the cooling effect of the regenerative cooling channel. Increasing the heat exchange capacity of the regenerative cooling channel and reducing the flow pressure loss in the channel have always been one of the goals pursued by the regenerative cooling structure design of scramjet engines. Based on this concept, this paper optimizes the design of the channel parameters under the constraints of improving heat exchange efficiency and reducing channel pressure loss.

2. Structure optimization and numerical simulation method of regenerative cooling channel

2.1 Geometric model and numerical simulation method

2.1.1 Geometric model

Due to the symmetry of the regenerative cooling channel, in order to simplify the calculation, only one half of the flow unit of one cooling channel is analyzed. Figure 1 is a cross-sectional view of the half of the regenerative active cooling channel. Where a is half the rib width, b is the height of the cooling channel, c is the half width of the channel, d is the thickness of the outer wall, and e is the thickness of the inner wall. The channel material is alloy steel, and the coolant is domestic aviation kerosene. Its physical properties are given in [2].

![Cross-sectional view of the regenerative active cooling channel flow unit](image)

Figure 1. Cross-sectional view of the regenerative active cooling channel flow unit.

2.1.2 Numerical calculation method

(1) Control equation

Control equations include mass continuity equation, energy equation, momentum equation, as shown in equations (1), (2), (3).
\[
\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_i} (\rho u_i) = 0
\]

\[
\frac{\partial}{\partial t} (\rho E) + \frac{\partial}{\partial x_j} (\rho (u_i \rho E + p)) = \frac{\partial}{\partial x_j} (k_{\text{eff}} \frac{\partial T}{\partial x_j}) - \sum_{j'} h_{j'j} J_{j'} + u_i \tau_{ji} + S_h
\]

\[
\frac{\partial}{\partial t} (\rho u_j) + \frac{\partial}{\partial x_j} (\rho u_j u_i) = -\frac{\partial p}{\partial x_j} + \frac{\partial}{\partial x_j} (\rho \tau_{ij}) + \rho g_i + F_i
\]

In formula (2), \( k_{\text{eff}} \) is the effective heat conduction coefficient: \( k_{\text{eff}} = k_i + k_t \), \( k_t \) is the turbulent heat conduction coefficient, which is determined according to the turbulence model. \( J_{j'} \) is the diffusion flow of component \( J_{j'} \), \( S_h \) contains the heat of chemical reaction and other user-defined volumetric heat source items, \( E = h - \frac{p}{\rho} + \frac{u_i^2}{2} \).

In formula (3), \( \rho g_i \) and \( F_i \) are the gravity volume force and external volume force in the i direction, respectively, and \( \tau_{ij} \) is the stress tensor: in formula

\[
\tau_{ij} = [\mu (\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i})] - \frac{2}{3} \mu \frac{\partial u_i}{\partial x_i} \delta_{ij}, \mu \text{ is the viscosity coefficient, } \mu_l = \mu_t + \mu_i, \mu_l \text{ is the laminar viscosity coefficient, and } \mu_t \text{ is the turbulent viscosity coefficient, Defined according to the turbulence model.}

(2) Meshing and boundary conditions

Simulation conditions: the inlet mass flow rate of coolant aviation kerosene is 0.01 kg / s, the calculation area is long \( 0.5 \text{m} \), wide \( 1 = 5 \text{mm} \), inner wall heat flux density \( 1 \text{MW/m}^2 \), and inlet pressure is 4 MPa. Channel parameters: half rib thickness 1mm, channel height 4mm, width 4mm, outer wall thickness 3mm, inner wall thickness 2mm.

To simplify the problem, the lateral heat transfer between adjacent channels is not considered, symmetry is used to reduce the number of grids, and the calculation time is shortened. The fluid-solid coupling interface is encrypted when dividing the grid, comparing the number of 200,000 grids and 600,000 grids The calculation result of the quantity, the temperature difference is within the range of 15K, so the calculation uses a grid of 200,000, and the grid division is shown in Figure 2.

Figure 2. Cooling channel meshing.

In numerical calculation, proper and correct boundary conditions are of great significance to the accuracy of the calculation. The selection of different boundary conditions results in different results.
The inlet AO is the mass inflow inlet boundary conditions, mass flow \( \dot{m} = \dot{m}_0 \), inlet pressure \( p = p_0 \), inlet temperature \( T = T_0 \), turbulent kinetic energy \( k = k_0 \), turbulent dissipation rate \( \varepsilon = \varepsilon_0 \),

where \( k_0 \) and \( \varepsilon_0 \) are shown in equations (4) and (5), respectively.

\[
\begin{align*}
  k_0 &= \frac{3}{2} \left[ \bar{u} (0.16 Re_{Dh})^{-1/8} \right]^2, \\
  \varepsilon_0 &= C_u \frac{k^{3/2}}{l}. 
\end{align*}
\]

Where \( \bar{u} \) is the average fluid velocity, \( DH \) is the hydraulic diameter, \( C_u \) is the empirical constant taken as 0.09, and \( l \) is the turbulence length scale, approximately 0.07D.

The upper wall surface, the outlet wall and the inlet wall surface are insulated wall surfaces, and the wall heat flux density is zero. The lower wall surface is the wall surface of the heating section, and the heat flux density is the heat flux density applied in the physical model. Both sides are set as symmetrical boundary conditions, and the axial speed, temperature and pressure are all zero. The outlet cross section is a pressure outlet, and the outlet back pressure is set to zero.

(3) Solving governing equation

Solve the control equation according to the incompressible and variable physical conditions. Fluent is used for numerical simulation, the turbulence model uses RNG \( k-\varepsilon \) model, the second-order upwind style is used to discretize the equation, and the pressure and velocity coupling solution is solved using SIMPLEC algorithm. The time and space dispersion of all variables in the control equation have second-order accuracy.

2.2 Structural optimization method

The size of the objective function value can be used to measure the pros and cons of the design scheme. It is generally written as:

\[
  f(\bar{x}) = f(x_1, x_2, ..., x_n)
\]

The purpose of optimal design is to require the selected design variables to make the objective function reach the optimal value, that is, to find the best \( \bar{x}^* \) and make \( f(\bar{x}^*) = \text{Opt} \). Usually the optimal value refers to the minimum or maximum value of \( f(\bar{x}) \).

In engineering design issues, the design goals can be varied. When the objective function contains only a minimum of design indicators, it is called a single objective function. If all design indexes are required to be minimized, it is a multi-objective optimization problem. However, due to the single index, it is easy to measure the quality of the design plan for the objective optimization design problem, and the solution process is relatively simple and clear. The problem of multi-objective optimization design is more complicated, because different evaluation goals are often opposed and affect each other. In this case, the common method is to compose them into a composite objective function for calculation [12].

For the design of the configuration parameters of the regenerative cooling channel of the scramjet engine, the goal should be pursued: in the given space range, the flow resistance of the coolant in the channel should be as small as possible and the channel The heat transfer coefficient should be as high as possible. Obviously this is a multi-objective optimization problem.

Objective function 1: The largest average heat transfer coefficient.

\[
\text{max} \overline{\theta}(X)
\]

\[
\overline{\theta}(X) = \frac{q_w}{T_w(X) - T_0}
\]
Among them, \( q_w \) is the wall surface heat flux density, \( T_w \) is the wall surface temperature, and \( T_0 \) is the total temperature of the channel inflow;

Objective function 2: minimum flow resistance coefficient.

\[
\min \bar{c}_f(X) = \frac{p_1 - p_2}{L} \frac{1}{0.5 \rho_1 v(X)^2}
\]

In the formula, \( p_1 \) is the inlet static pressure, \( p_2 \) is the outlet static pressure, \( L \) is the channel length, \( d_h \) is the hydraulic diameter, \( \rho_1 \) is the inlet density, and \( v_1 \) is the inlet velocity.

Because the problem of solving single-objective optimization design is relatively simple, so often multi-objective function problems are converted into single-objective problems for solution. The two objective functions selected in this paper belong to the same type of objective functions, that is, they both appear as the objective function to seek the extreme value, so the multiplication and division method can be used to unify the total objective function, and the minimum value can be found within the working range, that is:

\[
f(X) = \frac{\bar{c}_f(X)}{\bar{h}(X)}
\]

The optimal design variables are taken as:

\[ X = [e, a, h, w]^T = [x_1, x_2, x_3, x_4]^T \]

Among them,
- \( e \) —— Inner wall thickness
- \( a \) —— Half rib thickness
- \( h \) —— Cooling channel height
- \( w \) —— Cooling channel width

According to the design requirements, take the following constraints:

\[
\begin{align*}
0.5mm & \leq e \leq 4.5mm \\
0.5mm & \leq a \leq 3mm \\
2mm & \leq h \leq 8mm \\
1mm & \leq w \leq 6mm
\end{align*}
\]

The purpose of regenerative active cooling of the scramjet engine combustion chamber is to ensure that the solid wall temperature of the engine combustion chamber is within the allowable range of the material when the coolant mass flow rate is constant and the pressure drop and temperature rise meet certain conditions. Therefore, there is also a temperature constraint:

\[
T_w \leq T_{Material \ allowable \ temperature} = \text{Const}
\]

Here the maximum allowable temperature of the structural material is set to 800K.

The heat transfer process of the regenerative cooling channel includes heat conduction through the chamber wall, convective heat exchange between the chamber wall and the coolant, and radiative heat exchange. Here, the simplified calculation does not include the influence of heat radiation.

The heat flow through the wall of the combustion chamber is:

\[
q_{wi} = \frac{\lambda_w}{e} (T_{wg} - T_{wi})
\]

Among them, \( \lambda_w \) is the thermal conductivity of the inner wall surface, \( e \) is the thickness of the inner wall, \( T_{wg} \) the side wall temperature of the fuel gas, and \( T_{wi} \) the side wall temperature of the coolant.
The convective heat transfer between the side wall of the coolant and the coolant can be expressed by the following formula:

\[ q_{w2} = h(T_{w2} - T_i) = \frac{\lambda}{d_h} \eta_f Nu_f (T_{w2} - T_i) \]  

(15)

Among them, \( T_i \) is the average coolant temperature, and \( \eta_f \) is the rib efficiency. Since the heat transfer in the channel is dominated by turbulent flow, the Mihayev formula can be used:

\[ Nu = 0.021Re^{0.8}Pr^{0.43} \left( \frac{Pr}{Pr_w} \right)^{0.25} \]  

(16)

Hydraulic diameter:

\[ d_h = \frac{4A}{C} \]  

(17)

Where A is the wet cross-sectional area and C is the wet circumference of the channel.

3. Channel parameter optimization design

The above optimization problem of regenerative cooling channel parameters can be reduced to a multi-variable function nonlinear programming problem, which uses a mixed penalty function method. The specific optimization program flow chart is shown in Figure 3. The mixed penalty function combines the advantages of the outer penalty function (the initial point can be taken arbitrarily) and the advantage of the inner penalty function (which can approximate the optimal solution), and can be used to solve optimization problems that contain both equality constraints and inequality constraints.

Bring the original channel parameters into the optimization model. Table 1 for a comparison between the optimized design and the original design.
Table 1. Comparison of optimization results with original data

| design          | Inner wall Thickness (mm) | Rib thickness (mm) | Channel height (mm) | Channel width (mm) |
|-----------------|---------------------------|-------------------|---------------------|-------------------|
| original design | 2                         | 1                 | 4                   | 4                 |
| Optimized value | 1.57                      | 1.52              | 5.27                | 2.29              |

4. Verification of optimization design results

According to the optimization results, the channel configuration parameters are adjusted, and the optimized configuration is meshed and numerically simulated and analyzed. The average oil temperature, the inner wall surface centerline temperature distribution and the convection heat transfer coefficient are distributed along the channel as shown in the figure 4. It can be seen from the figure that the optimized wall temperature change trend is basically the same as the original design change trend, but the overall temperature is lower; the center flow oil temperature and convective heat transfer coefficient calculated by the optimized configuration are larger.

Table 2 shows the comparison between the optimized configuration and other groups of configurations. From the table, it can be seen that the inner wall and ribs of the optimized configuration are thinner, the channel height is higher, and the width is narrower. This design is generally consistent with the previous analysis. This design can effectively increase the convection heat exchange efficiency of the cooling channel, not only to ensure that the material temperature does not exceed its maximum allowable temperature, but also to make the pressure loss relatively low.

Table 2. Comparison of simulation results between optimized configuration and other configurations

| Structure | Inner wall thickness (mm) | Channel width (mm) | Channel height (mm) | Rib thickness (mm) | Wall temperature (K) | Oil temperature (K) | Pressure loss (MPa) |
|-----------|----------------------------|--------------------|---------------------|-------------------|----------------------|----------------------|---------------------|
| 3         | 3                          | 4                  | 4                   | 1                 | 940                  | 737                  | 1.797               |
| 7         | 2                          | 4                  | 4                   | 2                 | 886                  | 771                  | 1.801               |
| 9         | 2                          | 2.3                | 6.9                 | 1                 | 857                  | 748                  | 2.150               |
| 14        | 2                          | 2                  | 2                   | 1                 | 796                  | 668                  | 3.419               |
| Optimized configuration | 1.57                      | 2.29               | 5.27                | 1.52              | 798                  | 691                  | 1.808               |
Figures 5-7 are the comparison charts between the design configuration and the previously analyzed configuration wall temperature, central flow oil temperature, and heat transfer coefficient. It can be seen from the figure that the optimized configuration can meet the maximum temperature allowed by the material, the wall temperature is low, and the temperature rise of the oil in the channel is large, which is due to the increase of the convection heat transfer coefficient. Therefore, the optimized design method can meet the design requirements.

5. Summary
In this paper, the optimization model and numerical calculation verification model of the regenerative cooling channel structure of the scramjet engine were established. The structural parameters of the regenerative cooling channel of the scramjet engine were optimized and numerically verified. The results show that:

(1) The mixed penalty function method was used to establish the optimization model of the regenerative cooling channel structure of the scramjet engine, and the configuration was optimized. The optimized configuration was verified by the numerical verification model to achieve the pre-optimization design goal and meet the design. Claim.
(2) Judging from the distribution of the average oil temperature, the temperature distribution of the inner wall centerline and the convection heat transfer coefficients along the channel, the optimized wall temperature change trend is basically the same as the original design change trend, but the overall temperature is lower; optimized configuration calculation The resulting central flow oil temperature and convective heat transfer coefficient are larger.

(3) The comparison between the optimized configuration and other groups of configurations shows that the inner wall and fins of the optimized configuration are thinner, the channel height is higher, and the width is narrower, which can effectively increase the convection heat transfer efficiency of the cooling channel. It can not only ensure that the temperature of the material does not exceed its maximum allowable temperature, but also make the pressure loss relatively low.

(4) The optimized configuration can meet the maximum temperature allowed by the material, the wall temperature is lower, and the temperature rise of the oil in the channel is larger, which is due to the increase of the convection heat transfer coefficient. Therefore, the optimized design method can meet the design requirements.

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