FINITE ELEMENT ANALYSIS OF THERMAL LOAD ON CYLINDER HEAD OF SMALL-SIZED PISTON ENGINE

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Due to low fuel consumption, small volume, light weight and many other advantages, small-sized piston engines are still applicable in many fields nowadays. With the military and civilian industries springing up, many new requirements have been put forward to the performance, structure, adaptability and reliability of small-sized piston engines as power devices, which means small-sized piston engines still have a very broad development prospect in the future. When the piston engine is under the working condition of high rotation speed and heavy load, the cylinder head may be subjected to over temperature and bad lubrication, frequently resulting in the scuffing of cylinder bore and the damage to the engine itself. In addition, the engine for special use has requirements for fuel oil. If it is necessary to change the fuel oil from gasoline to kerosene, the combustion flame of kerosene delays and keeps heating the cylinder wall, and it will lead to relatively high temperature of the inner wall of cylinder head, leading to the same bad situation as above. On this basis, the paper takes the cylinder head of small-sized piston engine as research object and utilizes the finite element analysis method to calculate and analyze the heating and thermal stress of the cylinder head of small-sized piston engine. Based on the research and analysis in this paper, the heating situation of cylinder head can be more accurately learned, providing a favorable basis for improving the structure of cylinder head in the future.

Key word: small-sized piston engine; cylinder head; the finite element analysis, heat load, thermal Stress

1. Introduction

With the science and technology developing rapidly, people's demand for vehicles has been increasing, meanwhile fast and comfortable ones lying in incessant updating and manufacturing. For the cylinder head is quite a crucial component of the piston engine, its reliability almost determines the reliability of the whole piston engine. However, the majority of various losses in the cylinder head result from thermal load, thermal fatigue, and hot corrosion. In order to improve the reliability of the entire piston engine, the engineering designers are

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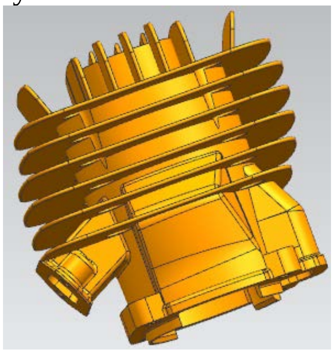
required to accurately conduct comprehensive analysis and calculation of the thermal load of the cylinder head at the design stage. In recent years, under the support of computer technology and numerical analysis method, the finite element analysis method has already provided an effective way to cope with this complex problem of analysis and calculation.

The application of the finite element analysis software ANSYS in the strength analysis of the main components of the piston engine makes the design and strength check of the parts quick and convenient [1]. Domestic and foreign scholars have used finite element simulation analysis methods to do a lot of research in engine thermal load analysis and parts design and development. For example, Yang Shusen used finite element analysis software ANSYS to analyze the thermal load and mechanical load of the piston of a diesel engine, analyzed the heat, force and deformation of the piston of the diesel engine, and checked the strength of the piston [2]. Wu Ji uses finite element analysis software ANSYS to perform finite element analysis on the thermal load, mechanical load and thermal load and mechanical load of diesel engine piston head [3]. Tian Jian uses software ANSYS to perform finite element analysis on the thermal load, mechanical load and coupling of the new ME-B piston head [4]. Zhou Xiaoyan uses finite element analysis software to calculate the transient temperature field of the piston and perform finite element contact analysis on its worst state [5]. Cocchi, Alessandro Federico et al. proposed a three-dimensional CFD numerical simulation method to study the temperature field of the air-cooled engine cylinder head, and gave reasonable optimization suggestions for the heat dissipation problem in the high temperature region [6].

The theme of this paper is to study the thermal stress distribution of the cylinder head when a small-sized piston engine is working under extreme working conditions. Besides, with regard to the area of stress concentration, some improved schemes have been proposed, to provide reference foundation for the optimization design of cylinder head in the future.

2. Processing of Cylinder Head's Geometric Model

The cylinder head material is ZL107, and its physical property parameters are shown in Table 1 and the original geometric model of the cylinder head, as shown in Fig. 1, some mounting holes and fillets can be seen in the exterior of cylinder head. Since this topic mainly analyzes the thermal load of cylinder head, the existence of mounting holes and fillets on the original model of cylinder head will bring great difficulties to establish the finite element model but will not bring significant influence to the results of thermal load analysis. Therefore, it is quite necessary to simplify the mounting hole and fillets on the geometric model. Furthermore, according to the point that the structural characteristic of the cylinder head's geometric model is axisymmetric, only half of the model needs to be processed. After processing, it is available to obtain the geometric model of the entire cylinder head through mirror operation, and half of the geometric model for the simplified cylinder head is shown in Fig. 2.



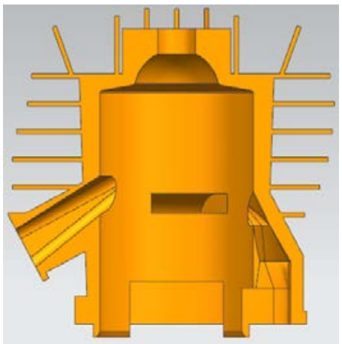


Fig. 1. 3D geometric model of the cylinder head

Fig. 2. Simplified 3D geometric model of 1/2 cylinder head

Table1

Material property parameter

Name	Material	Thermal Conductivity (W/(m^2·K))	Specific heat capacity (J/(kg·K)
Cylinder head	ZL107	109	963

3. Establishment of Finite Element Model of Cylinder Head

Simplify the model with 3D modeling software UG, after the 3D geometric model of the cylinder head is simplified, the file can be exported. Then, the hypermesh software is used to perform finite element mesh dividing on the simplified 3D geometric model. During the dividing process, the area from the top dead center to the bottom dead center on the inner wall of the cylinder head is divided into three parts. Besides, the entire exterior of the cylinder head is divided into the windward side and the leeward side; the top fin is divided into the ring groove on the windward side and the ring groove on the leeward side; the division of the ring fin is on the basis of its quantity from the top to the bottom in the manner of software automation dividing. As a result, the 3D finite element model of the cylinder head is obtained as shown in Fig. 3, with a total of 555573 elements and 144267 nodes.

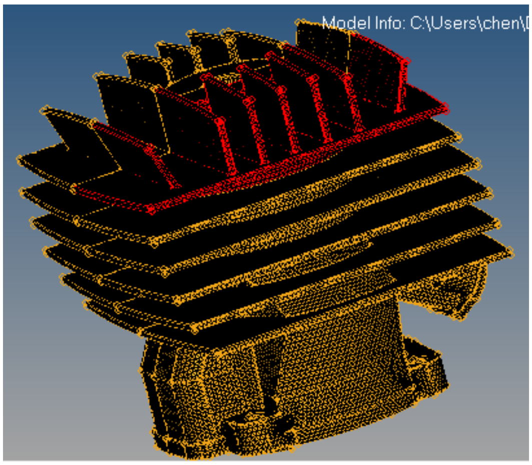


Fig. 3. Finite Element Model of Cylinder Head

4. Simulation Calculation and Result Analysis of in-Cylinder Fuel Gas Characteristics

In the occasion that the high-temperature and high-pressure in-cylinder fuel gas keeps heating the inner wall of the cylinder head, the thermal load of the cylinder head will be generated. For the fuel gas characteristics, they are obtained through simulation analysis of GT-power, a one-dimensional simulation analysis software and the version used here is GT-Power-v7.3.0 [7]. In addition, the one-dimensional simulation model for small-sized piston engine cylinder head in this paper has been established as shown in Fig. 4. In the cylinder assembly of the GT-power model, the instantaneous heat transfer coefficient of fuel gas and the instantaneous temperature of fuel gas are selected as the output data, while the crank angle is selected as the abscissa variable. Since this article mainly studies the thermal load of the cylinder head under extreme working conditions, the rotation speed is set to 7000 rpm in GT-power model. With the GT-power model running, the curves, as shown in Fig. 5 and Fig. 6 respectively, stand for that the instantaneous heat transfer coefficient of in-cylinder fuel gas changes with the crank angle and that the instantaneous temperature of in-cylinder fuel gas changes with the crank angle.

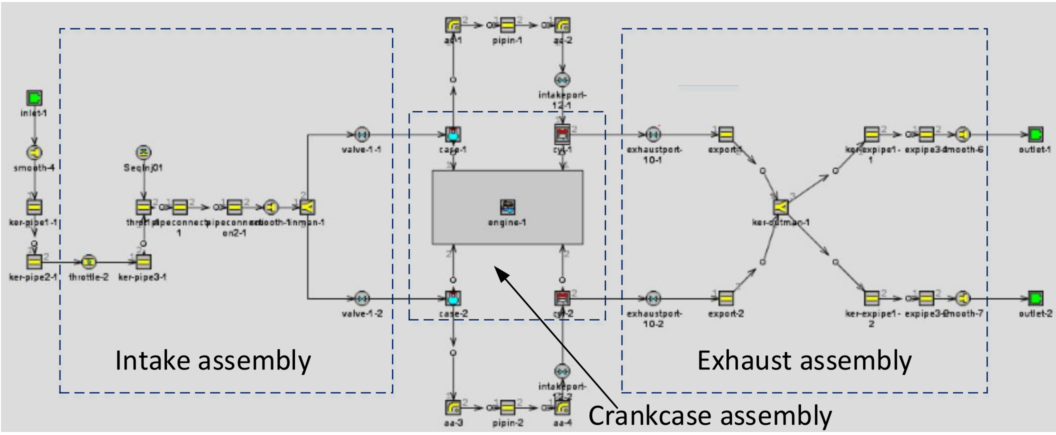


Fig. 4. One dimensional simulation model of the Cylinder Head

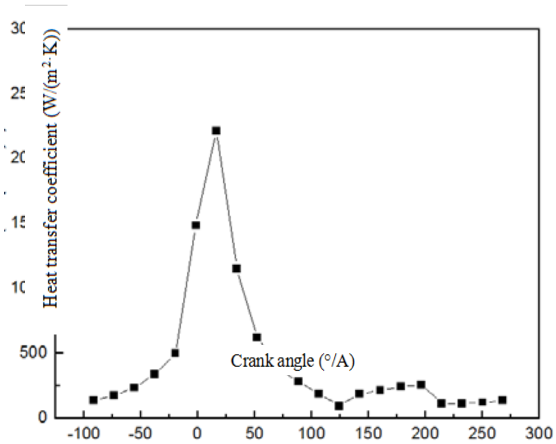


Fig. 5. Change curve of fuel gas heat transfer coefficient

As shown in Fig. 5, during the process crank angle turning from -180° to 0°, the gas heat transfer coefficient first increases slowly with the increase of crank angle, and then increases sharply when close to the top dead center and achieves the maximum value when reaching about 20° beyond the top dead center. Afterwards, the heat transfer coefficient decreases first sharply and then slowly. When the crank angle reaches 180°, its value is similar to that of the starting position of -180°.

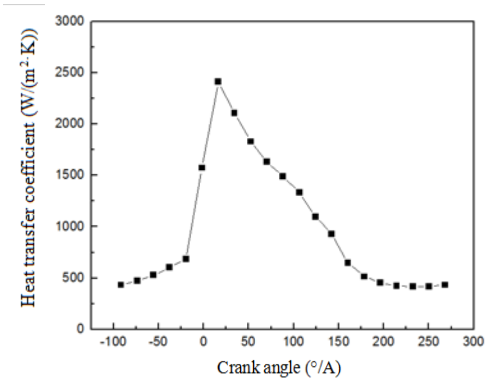


Fig. 6. Variable graph of the fuel gas temperature

As can be seen from Fig. 6, the fuel gas temperature increases slowly with the crank angle changing before the top dead center; it reaches the highest near the top dead center, and then decreases slowly.

5. Determination of Thermal Boundary Conditions

5.1 Heat Transfer Boundary Conditions of Fuel Gas Side

In terms of the heat transfer boundary conditions between the fuel gas and the cylinder head, the convection heat transfer boundary conditions are mainly adopted, and the influence of fuel gas on the radiation heat transfer of the cylinder head's inner wall is omitted. Regarding the conditions of calculating the convection heat transfer between fuel gas and cylinder head, it is necessary to obtain the curve that the in-cylinder fuel gas temperature changes with the crank angle and the curve that the instantaneous heat transfer coefficient of in-cylinder fuel gas changes with the crank angle. After obtaining these curves, the integration will be performed on them, so that the average temperature and average heat transfer coefficient of the in-cylinder high-temperature gas in one cycle can be obtained. Finally, according to the divided areas on the inner wall of the cylinder head, coupled with the empirical Equations, it is attainable to calculate the average temperature and average heat transfer coefficient of in-cylinder fuel gas in the entire piston area from the top dead center to the bottom dead center [8]. As follows, the detailed calculation process, calculating the average temperature $T_{res}(0)$ and average heat transfer coefficient of fuel gas in one cycle $\alpha_m(0)$.

$$T_{res}(0) = \frac{\int_{-180}^{180} \alpha_g T_g d\varphi}{\int_{-180}^{180} \alpha_g d\varphi} \tag{1}$$

$$\alpha_m(0) = \frac{\int_{-180}^{180} \alpha_g \, d\varphi}{360} \tag{2}$$

The steady-state heat transfer boundary conditions on the internal surface of the engine cylinder block has the following distribution law at height in the axial direction [8]:

$$\alpha_m(H) = \alpha_m(0) \cdot (1 + k_1\beta) \cdot e^{-\sqrt[3]{\beta}} \tag{3}$$

$$T_{res}(H) = T_{res}(0) \cdot (1 + k_2) \cdot e^{-\sqrt{\beta}} \tag{4}$$

In the Equations,

$\beta = H/S$, $0 \le \beta \le 1$;

$k_1 = 0.537(S/D)0.24$, $k_2 = 1.45k_1$;

H represents the distance to the top of the cylinder block;

α_m（0） represents the average heat transfer coefficient of the in-cylinder fuel gas ;

$T_{res}(0)$ represents the average temperature of in-cylinder fuel gas.

According to Equation (3), when the engine is under extreme working conditions, the average temperature of fuel gas and the average heat transfer coefficient at each height of cylinder sleeve in the cylinder can be calculated. Besides, the inner wall surface of the cylinder block is divided into three regions at height in the axial direction, and the average heat transfer coefficient and the average temperature of in-cylinder fuel gas at each region are shown in Table 2. Obviously seen, the average temperature of fuel gas in the combustion chamber is set to 1200 K; the average heat transfer coefficient is taken as 260 W/(m^2·K); the average temperature in the scavenging passage is set to 400 K, and the average heat transfer coefficient is 110 W/(m^2·K); the average temperature of fuel gas in the exhaust passage is 862 K, and the heat transfer coefficient is 230 W/(m^2·K).

Table 2

Heat Transfer Boundary Conditions of Fuel Gas Side

Position Number	H(mm)	α_m (W/(m^2·K))	T_{res} (K)
Area 1	9	266	1095
Area 2	18	241	1005
Area 3	27	221	993

5.2 Heat Transfer Boundary Conditions of Cooling Air Side

The calculation of the heat transfer coefficient between the external fins of the cylinder head and the cooling air is greatly related with the wind speed between the fins. Since the exterior of cylinder head is divided into the windward side and the leeward side, and the fins are divided into windward fins and leeward fins, so the flow velocity of cooling air between the fins is different. Moreover, the wind speed at the windward side is greatly different from that at the leeward side, and the Reynolds number characterizing the flow characteristics is also different. Therefore, based on the differences of flow velocity of cooling air, the air flow condition between the fins can be divided into three states: laminar flow, turbulent flow, and transitional flow. For these three flow conditions, a Equations suitable for each condition should be selected respectively to calculate the heat transfer coefficient of the cooling air between the fins [8-12].

laminar flow(Re＜2300):

$$\alpha_f = 1.86 \frac{\lambda_f}{d_e} \mathrm{Re}^{\frac{1}{3}} \mathrm{Pr}^{\frac{1}{3}} \left[\frac{d_e}{L} \right]^{\frac{1}{3}} \varepsilon_T \varepsilon_R \tag{5}$$

transitional flow（$\mathrm{Re} = 2300 \sim 10000$）:

$$\alpha_f = 0.116 \frac{\lambda_f}{d_e} \left[\mathrm{Re}^{\frac{2}{3}} - 125 \right] \mathrm{Pr}^{\frac{1}{3}} \left[1 + \left(\frac{d_e}{L} \right)^{\frac{2}{3}} \right] \varepsilon_T \varepsilon_R \tag{6}$$

turbulent flow(Re＞10000):

$$\alpha_f = 0.023 \frac{\lambda_f}{d_e} \mathrm{Re}^{0.8} \mathrm{Pr}^{0.4} \varepsilon_L \varepsilon_T \varepsilon_R \tag{7}$$

In the Equations,

ε_R represents correction coefficient of elbow pipe and $\varepsilon_R = 1 + 1.77 \frac{d_e}{R}$;

ε_T represents temperature correction coefficient and $\varepsilon_T = \left(\frac{T_f}{T_w} \right)^{0.3}$,Where

T_w is the wall temperature of the cylinder, T_f is the temperature of fluid;

ε_L represents correction coefficient of flow path length, and is set to 1.13;

d_e represents the equivalent diameter of the cooling fin slot, $d_e = 4F / U_f$;

Re represents the Reynolds number and $\mathrm{Re} = \frac{V_f d_e}{\nu_f}$;

F represents the passage section between the cooling fins;

U_f represents the length of the perimeter of the passage section;

ν_f represents the kinematic viscosity of air and $\nu_f = \eta / \rho$;

η represents the dynamic viscosity of air , and is set to $17.9 \times 10^{-6} Pa \cdot s$;

ρ represents the density of air, and is set to 1.235 kg/m^3;

λ_f represents the thermal conductivity coefficient of air, and is set to 0.02477 W/(m· K) ;

$\Pr$ represents the Prandtl number;

L represents the length of air flow channel;

V_f represents the average speed of the air passing between the fins.

The values for the exterior of cylinder head are obtained by using an empirical Equation. First, it is necessary to calculate the air flow velocity between the fins and then calculate the surface heat transfer coefficient. Next, the air flow velocity between the fins can be used to simulate the external flow field with Fluent, a fluid calculation software. Then, the boundary condition of cooling air flow velocity at the entrance should be set to be 45 m/s, and the pressure boundary condition should be adopted at the exit, meanwhile the pressure at the outlet boundary set to be atmospheric pressure 0.1 MPa, thus to obtain the external flow field distribution of the cylinder head and the cooling air flow velocity of the exterior of cylinder head. Later, substitute the cooling air flow velocity of the exterior of cylinder head into the above Equations, to calculate the heat transfer coefficient between the fins on the cooling air side. Meanwhile the air temperature of the external cylinder head is taken as 298 K and the calculated results are shown in Table 3.

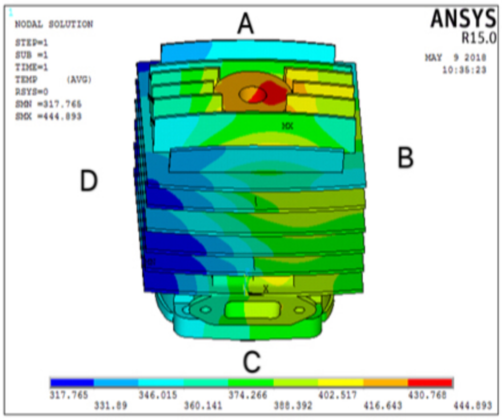
Table 3

External heat transfer boundary condition

Air velocity (m/s)	Wall Temperature (K)	Heat Transfer Coefficient (W/(m^2·K))
50	460	350
43	455	320
36	450	288
28	445	256
10	440	245
7	435	220
7	430	150

6. Finite Element Analysis of Cylinder Head's Thermal Load

Import the mesh file into ANSYS, a finite element analysis software and the version used here is ANSYS15.0 [13]. After setting up the material properties of the cylinder head material and applying the boundary conditions of the gas side and the cooling air side of the cylinder head, it is available to calculate and analyze the thermal load of the cylinder head, of which analysis results are shown in Fig. 7 and Fig. 8. In the Figs, B represents the leeward side and D represents the windward side [14-23].



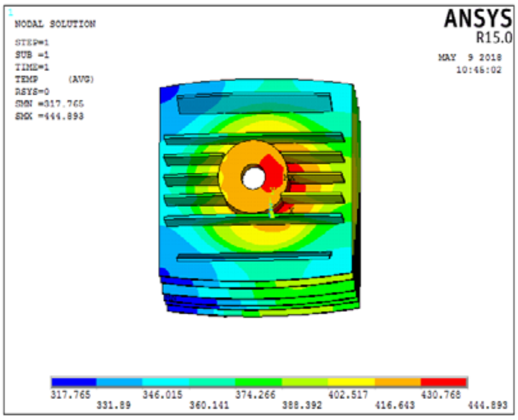


Fig. 7. Overall temperature distribution of the cylinder head

Fig. 8. Temperature distribution near the sparking plug

It can be seen from Fig. 8 that the temperature of the leeward side is significantly higher than that of the windward side, and the temperature near the mounting hole of sparking plug is the highest, up to 444 K. In order to verify the accuracy of the finite element simulation, the engine has been tested on a ground bench, to measure the temperature near the mounting hole of the sparking plug. When the engine is at 7000 rpm, the temperature near the mounting hole of sparking plug is 454 K. Compared with the numerical simulation results, the error value is 2.3%, satisfying the engineering demand.

For the sake of analyzing the thermal stress distribution of the engine cylinder head under extreme working conditions and checking its thermal strength, it is required to analyze its thermal stress. Thus, the method is first to constrain the displacement of nodes at the bottom surface of cylinder head in all directions, and the boundary conditions of displacement constraint are shown in Fig. 9.

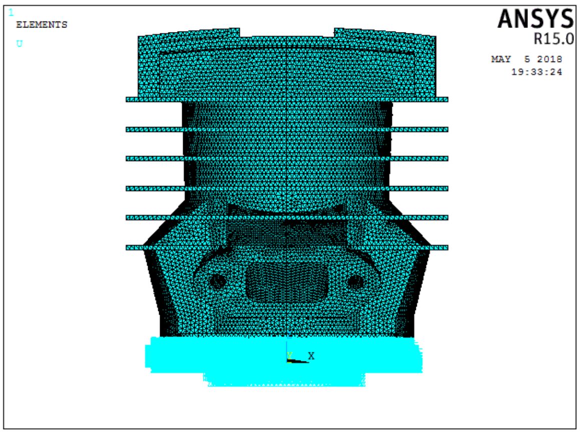


Fig. 9. Displacement constrained boundary condition of cylinder head

Then, the temperature field obtained by thermal load analysis will be act as a body load applied to the finite element mesh of cylinder head, so that the stress field distribution of the cylinder head under extreme conditions can be calculated, as shown in Fig. 10. Obviously seen, the stress of the exterior of cylinder head is relatively low, while the middle position at the bottom of cylinder head is slightly higher than the other positions, and the maximum thermal stress the cylinder head bears is 1850 MPa, which is used to constrain the displacement of nodes at the bottom surface of cylinder head in all directions. After removing the constraint part near the bottom surface of the cylinder head, the stress field of cylinder head obtained is shown in Fig. 11.

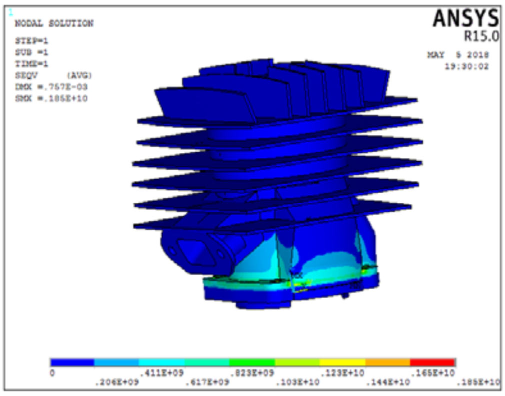


Fig. 10. Stress Analysis Results of Finite Element.

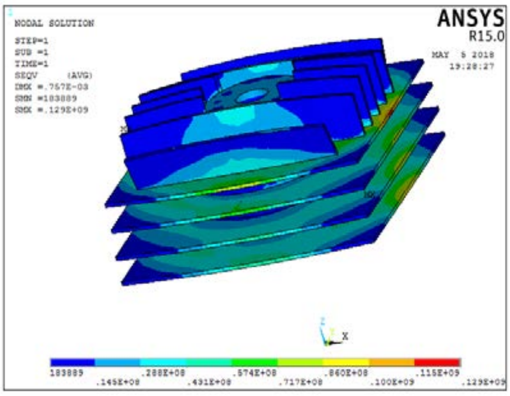


Fig. 11. Analysis Results of Local Stress

As shown in Fig. 11, the stress on the leeward side is more concentrated than that on other positions, which is caused by low cooling air velocity and poor heat dissipation on the leeward side. The maximum stress, up to 129 MPa, appears on the ring fin edge on the leeward side. Then, check the aluminum alloy material performance manual and list the mechanical properties of ZL107 aluminum alloy in Table 4.

Table 4

Mechanical Properties of ZL107 Aluminum Alloy

Alloy code	Casting method	Alloy state	Tensile strength (MPa)
ZL107	SB	F	165
	SB	T6	245
	J	F	195
	J	T6	275

As can be seen from Table 3, the maximum tensile strength of ZL107 alloy is 275 MPa. Obviously, the calculated maximum thermal stress is less than the maximum tensile strength, so the cylinder head meets strength requirements under the working condition of 7000 rpm.

On the analysis method of the steady-state temperature field of engine piston, cylinder head and other parts of the heating, the relevant scholars mainly determined the thermal boundary conditions to carry out some work. For example , when Yang Shusen and Wu Ji calculated the mechanical load and thermal load acting on the piston head, they mainly used the empirical formula and the indicator diagram of the diesel engine to calculate the boundary conditions [1~2]; Tian Jian also calculated the boundary temperature and heat transfer coefficient by using the indicator diagram of diesel engine and combining experience and semi-empirical formula [3]; Zhou Xiaoyan calculated the transient convection heat transfer coefficient of piston wall using CFD software, and analysed the transient temperature field of piston [4]; Zhao Yixian et al. coupled the cooling and heat transfer of the engine as a system and solved the problem by compiling a calculation program. The results obtained are in good agreement with the test results [9]; Gao Pengfei et al. calculated the temperature and heat transfer coefficient of each part of the piston through empirical formula, and carried out thermal analysis of the piston [16]; Shi Chao et al. calculated the average temperature and heat transfer coefficient of the cylinder gas by using the actual measured indicator diagram under the given working conditions of the engine [17]. Liu Jianmin et al. used empirical formula to calculate the thermal analysis boundary conditions of piston [18]; Liu Chao used three-dimensional CFD to calculate the boundary conditions of combustion exothermic process and heat dissipation in cooling oil chamber, and calculated the transient temperature field of piston by ANSYS [19].

By comparing with the research methods and results of relevant scholars on engine heating components, this paper mainly simulated and analysed the performance of the engine under given working conditions to get the instantaneous temperature and heat transfer coefficient of the gas in the cylinder, and calculated the average gas temperature and heat transfer coefficient in the designated area of the cylinder wall with the empirical formula. The thermal analysis module was used to calculate the steady temperature field of the cylinder head. The research methods are basically the same, but the difference is that this paper directly simulates the engine performance and gets the instantaneous characteristics of gas, including the instantaneous temperature of gas and the instantaneous heat transfer coefficient of gas. This method directly reflects the particularity of the research object in this paper and guarantees the accuracy of the calculation results. Thereafter, the calculation of average gas temperature and average gas heat transfer coefficient can be obtained by combining the empirical formula.

7. Conclusions

In this paper, the finite element analysis of the cylinder head thermal load of a small piston engine is carried out. The thermal stress of the cylinder head is calculated under given working conditions, and the strength of the cylinder head is checked. The conclusions are as follows:

(1) The temperature field distribution characteristics and the temperature values at the characteristic locations are consistent with the actual conditions of the engine, thus verifying the accuracy of calculating the boundary conditions.

(2) By analyzing the temperature field distribution of the cylinder head under given working conditions, it is found that the temperature value of the leeward surface near the spark plug position is the highest, reaching 454 K. The temperature at this position is too high and should be considered in the design of the engine cylinder head in the future.

(3) Analyze the thermal stress field of the cylinder head under given working conditions and find that the maximum thermal stress 129 MPa does not exceed the tensile strength of 275 MPa of ZL107 materials, which proves that the engine operation is safe under this condition.

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