Journal of Theoretical and Applied Information Technology
20th February 2013. Vol. 48 No.2

ISSN: 1992-8645 www.jatit.org E-ISSN: 1817-3195

TEMPERATURE FIELD ANALYSIS TO GASOLINE ENGINE PISTON AND STRUCTURE OPTIMIZATION

[1]HONGYUAN ZHANG, [2] ZHAOXUN LIN, [1]JIAN XING,

[1]School of Automobile and Traffic, Shenyang Ligong University, Shenyang 110159, Liaoning, China

[2]General Assemble Workshop, Shanghai GM (Shenyang) Norsom Motors Co., Ltd. (SGM-NORSOM), Shenyang 110044, Liaoning, China

ABSTRACT

This paper introduces the principle of thermal analysis for the combustion engine piston, gets the heat exchange coefficient of the piston top and the heat exchange coefficient distribution of the piston and the cooling water through calculation, calculates the temperature field of the piston with the finite element method and modifies the calculation model by repeatedly comparing the result with the measured temperature. It is found out that the temperatures of the piston top and the first circular groove are relatively high after calculating the temperature field and based on the results the optimization scheme of adding the cooling oil chamber is applied to the piston structure. Results show that, after optimization, the maximum temperature of the piston top is decreased to 264 , and the temperature at the first ring is decreased to 204 , thus improving the working condition of the piston ring.

Keywords: *Engine, piston, Thermal Load, Optimization*

1. INTRODUCTION

As a kind of thermal power machine, the working environment for the engine is severe, as it has to bear the effect of the thermal load during operation. As the most critical part of the engine, the working condition of the piston can greatly influence the service life and performance of the engine, so it is particularly important to carry out the temperature field analysis to the engine piston. Nowadays, the temperature field analysis work for the piston includes:

Hidehiko Kajiwaraa, Yukihiro Fujiokab, Tatsuya Suzukia, Hideo Negishi[1]Using CFD tools to calculate the coefficient of heat transfer for the cooling gallery, which is influential in piston cooling. J.H. Ong [2] using the results of a finite element analysis for the prediction of the steady state temperature distribution in a high speed diesel engine piston.V. Esfahanian, A. Javaheri, M. Ghaffarpour [3] calculates the heat transfer to an engine piston crown. Three different methods for the combustion boundary condition are used. The results of different combustion side boundary condition treatments are compared and their effects on the thermal behavior of the piston are investigated. H.W. Wu, C.P. Chiu[4] study presents a finite element heat transfer model for the prediction of piston temperature distributions in a real time operation engine. The thermal boundary conditions are specified adequately in the model for various operations. Shu Yao Long, Xing Cheng Kuai, Jun Chen[5] calculate The temperature and thermal stress fields for the piston of a diesel engine are using triangular finite elements and constant boundary elements. Ravindra Prasad [6] proposes a numerical method is presented for calculating the temperature fields in a semi-adiabatic diesel engine piston having a cooling oil canal. Yuh-Yih Wu, Bo-Chiuan Chen, Feng-Chi Hsieh [7] proposes a heat transfer model using the Stanton number. Avinash Kumar Agarwal [8] Research time resolved numerical modeling of oil jet cooling of a medium duty diesel engine piston.

In this paper, we have calculated the temperature field of the piston with the finite element analysis software according to the basic theory of thermal analysis. We have compared the measured temperature of the piston at several key points with the calculated results and repeatedly modified the boundary condition for the temperature and the heat exchange coefficient. From the analysis results, we have found out that the temperatures of the piston top and the first circular groove zone are higher, and effectively improved the working condition for the piston top and the first circular groove with the structure optimization for the piston, obtaining obvious effects, thus decreasing the thermal load of the piston.

Journal of Theoretical and Applied Information Technology
20th February 2013. Vol. 48 No.2

ISSN: 1992-8645 www.jatit.org E-ISSN: 1817-3195

2. FINITE ELEMENT MODEL

2.1 Geometrical Model

The finite element analysis to the piston is to establish the reasonable and accurate finite element model first, thus carrying out analysis by marking cell grids to obtain the accurate results finally. According to the structural symmetry of the piston, in order to be convenient for calculation and decrease workload, cut the established piston model to maintain 1/4 and then import the model to the finite element software for the finite element analysis to the piston according to the fine interface between the modeling software and the finite element analysis software. During the importing process, some details have been omitted, such as the chamfer and the snap ring of the piston pin etc. The geometrical model for the piston is as shown in Figure 1.

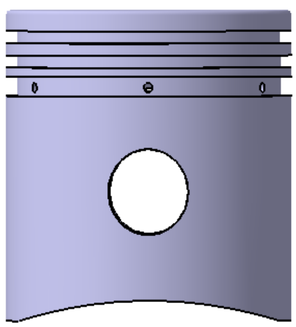

Figure 1: Geometrical Model For The Piston

2.2 Physical Properties of the Material

Table 1: Parameters Of The Piston Material

Parameters	Values of the parameters
Piston material	Aluminum alloy
Poisson ratio	0.32
Elastic modulus of the piston	$70\,GPa$
Material density	$2700\,kg/m^3$
Conductivity factor	$160\,w/(m^2\cdot K)$
Coefficient of thermal expansion	$21\times10^{-6}m/K$

2.3 Mesh Generation

During the mesh generation for the piston model, based on experiences and with several trials, the eight-node hexahedron cell SOLID70 is selected in this paper. Figure 2 shows the final finite element model after mesh generation for the piston.

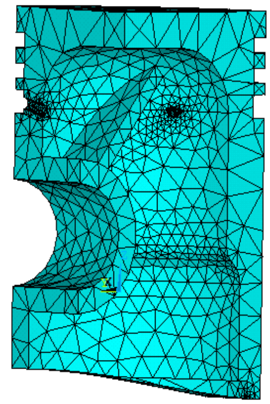

Figure 2: Mesh Generation For The Piston

3. FINITE ELEMENT ANALYSIS

3.1 Basic Theory for Thermal Analysis

To solve the temperature field of an object is the precondition necessary for the calculation of the thermal stress, thus obtaining the thermal strain and then carrying out the accumulation with the positive strain and shearing strain of the mechanical load.

Based on the basic theory for heat transmission, we can deduce the differential equation of the heat transmission for the object with the internal heat source and the transient temperature field:

$$\rho c\frac{\partial T}{\partial t}=k\left[\frac{\partial T^2}{\partial x^2}+\frac{\partial T^2}{\partial y^2}+\frac{\partial T^2}{\partial z^2}\right]+q_V \tag{1}$$

Where, T is the transient temperature value of the object, t is the time, k is the conductivity factor of the material, ρ is the material density, c is the specific heat capacity of the material and q_V is the internal heat source intensity of the material. Usually, k, ρ, c and q_V are treated as constants, while the stable thermal analysis has nothing to do with the time variable t, and no internal heat source has to be taken into consideration for the finite element analysis to the piston. So we can get

$$\frac{\partial T^2}{\partial x^2}+\frac{\partial T^2}{\partial y^2}+\frac{\partial T^2}{\partial z^2}=0 \tag{2}$$

Besides, to get the unique solution for the aforesaid differential equation, the initial condition and the boundary condition should be added, which are collectively called the definite condition. Then we get coupling solution for the differential equation. In this paper, the third boundary condition is applied for solving and analyzing the temperature field for the piston, which means that the temperature T_f and the heat exchange coefficient h

ISSN: 1992-8645 www.jatit.org E-ISSN: 1817-3195

of the fluid medium contacting the object is treated as the variables whose constants have been known. We can express in the equation as follows:

$$-k\frac{\partial T}{\partial n}=h(T-T_f) \tag{3}$$

Where, n is the exterior normal vector for the object boundary, h is the convection heat exchange coefficient and T_f is the temperature of the surrounding medium.

The finite element analysis for the temperature field of the piston is to get the extreme value the functional of the differential equation with the variation principle, based on the principle of the functional of the differential equation, thus solving the equation set with the node temperature as the unknown variable. Based on the variation principle, the functional equation for solving the node temperature is

$$I(T)=\frac{k}{2}\iiint_V\left[\frac{\partial T^2}{\partial x^2}+\frac{\partial T^2}{\partial y^2}+\frac{\partial T^2}{\partial z^2}+\rho C\frac{\partial T}{\partial t}T\right]dxdydz$$
$$-\iint_S h(T^2-T_fT)ds \tag{4}$$

Where, S is the piston boundary and V is the solution zone for the piston body.

The temperature function $T(x,y,z,t)$ of the piston temperature field meeting the boundary condition is obtained by carrying out variation to the aforesaid functional and obtaining the minimum solution as follows

$$\delta I=0 \tag{5}$$

After discrete the piston body with the finite element method, every element can be considered as the sub-domain of the integral computational domain, thus obtaining $I(T)=\sum I^e(T)$, where $I^e(T)$ is the sub-domain for every cell.

While the functional equation for the cells within the sub-domain can be expressed as:

$$I^e(T)=\frac{k}{2}\iiint_V\left[\frac{\partial T^2}{\partial x^2}+\frac{\partial T^2}{\partial y^2}+\frac{\partial T^2}{\partial z^2}+\rho C\frac{\partial T}{\partial t}T\right]dxdydz$$
$$-\iint_S h(T^2-T_fT)ds \tag{6}$$

The temperature value of any point within the cell applies the node temperature of the cell to carry out interpolation function and obtain with calculation:

$$T(x,y,z,t)=\sum_i^m N_iT_i \tag{7}$$

Where, N_i and T_i are the shape function and the of the temperature cell node respectively and m is the number of cell nodes。

3.2 Determination of the boundary condition

3.2.1 Calculation of the heat exchange coefficient for the piston top

When calculating as a stable temperature field, it is necessary to calculate the average temperature and the average heat exchange coefficient of the comprehensive gas within a working cycle. It is necessary to obtain the transient heat exchange coefficient and the transient gas temperature first, respectively.

Woschni formula is based on the similar principle and applies the cylinder diameter D and the average piston speed Re as the main representation amount. The equation for calculation is:

$$h_g=453.6D^{-0.214}(C_mP_g)^{0.786}T_g^{-0.525} \tag{8}$$

Where, P_g — the transient gas pressure, MPa .

T_g — the transient gas temperature, K;

C_m — the piston the average speed, m/s.

In order to get the average heat exchange coefficient, in the calculation of the thermal load of the combustion engine, the crank angle is pressed as the time and a working cycle is 720℃. Then we can get

$$h_m=\frac{1}{720}\int_{720}^{0}h_g\,d\varphi \tag{9}$$

Based on the computation as stated above, $h_m=474.58W/(m^2\cdot K)$, the average comprehensive gas temperature is the temperature based on gas. The expression of it with h_m is:

$$T_{res}=\frac{1}{h_m}\int_0^{720}h_gT_g\,d\varphi \tag{10}$$

Thus obtaining T_{res}=1369.19K.

3.2.2 Heat exchange coefficient between the piston and the cooling water

The heat absorbed from the gas by the piston is generally takes up 2-4% of the total heat of fuel burning. When the piston reaches the thermal equilibrium, the heat can be

(1) Transmitted from the piston ring zone and the skirt to the circulating cooling water within the water jacket through the cylinder sleeve wall;

Journal of Theoretical and Applied Information Technology
20th February 2013. Vol. 48 No.2

ISSN: 1992-8645 www.jatit.org E-ISSN: 1817-3195

(2) Transmitted to the fresh air through the head of the piston during the intake process;

(3) Transmitted to the oil mist and the cooling oil through the interior chamber and the oil chamber of the piston.

The heat exchange coefficient between the cylinder sleeve and the cooling water is $h_m = 3715W/(m^2 \cdot K)$.

As for the initial boundary condition of the piston ring zone, please refer to Table 2

Table 2: The Boundary Condition Of The Piston Ring Zone

Location	Symbol	Heat exchange coefficient
Piston junk	h_1	145
Top edge of the first circular groove	h_2	456
Inner edge of the first circular groove	h_3	375
Bottom edge of the first circular groove	h_4	2331
Top edge of the second circular groove	h_5	389
Inner edge of the second circular groove	h_6	244
Bottom edge of the second circular groove	h_7	389
Top edge of the third circular groove	h_8	387
Inner edge of the third circular groove	h_9	244
Bottom edge of the third circular groove	h_{10}	387
Bottom ring land of the first ring	h_{11}	145
Bottom ring land of the second ring	h_{12}	145
The piston skirt	h_{13}	532

3.2.3 Boundary condition for the piston temperature field calculation

From the heat exchange coefficient calculation for each part of the aforesaid piston, we can get that the boundary condition for the heat exchange coefficient calculation for each part, thus getting the piston temperature field calculation. In some parts, the original computational domain is subdivided according to the computation results, increased or decreased based on the different positions, thus meeting the actual condition better.

When determining the boundary condition, in order to get the analyzed results more close to the actual operation condition of the piston. based on the structure features and key parts, the piston surface can be divided into 18 boundary zones with the position of each part as shown in Figure 3.

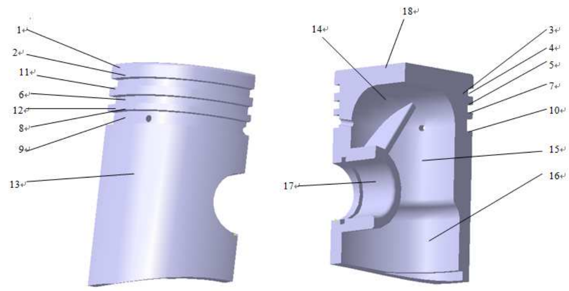

Figure 3: Dividing Diagram For The Thermal Boundary Zone Of The Piston

With the comparison to the experimental results and repeated computation adjustment of the experimental results, the heat exchange coefficient and the temperature of the piston boundary are as shown in Table 3.

Table 3: Heat Exchange Coefficient And Temperature Of The Piston

Location	Heat exchange coefficient	Ambient temperature
1	150	150
2	500	150
3	400	150
4	2500	150
5	450	130
6	350	130
7	450	130
8	400	120
9	350	120
10	400	120
11	150	150
12	150	130
13	700	110
14	1000	110
15	1000	110
16	500	110
17	400	110
18	474.58	1369.19

3.3 Computation and Result Analysis of the Temperature Field

Based on the established geometrical model and finite element model as well as the established boundary condition and with the stable thermal analysis module of the finite element analysis software, we can calculate and get results as shown in Figures 4&5.

Journal of Theoretical and Applied Information Technology
20th February 2013. Vol. 48 No.2

ISSN: 1992-8645 www.jatit.org E-ISSN: 1817-3195

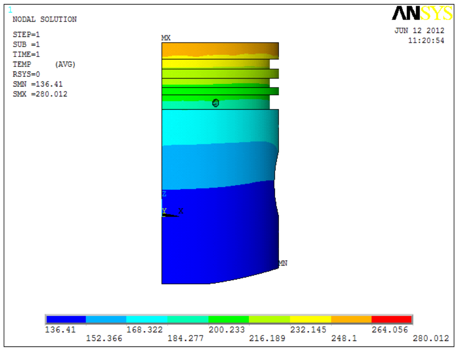

Figure 4: External Surface Temperature Field Of The Piston

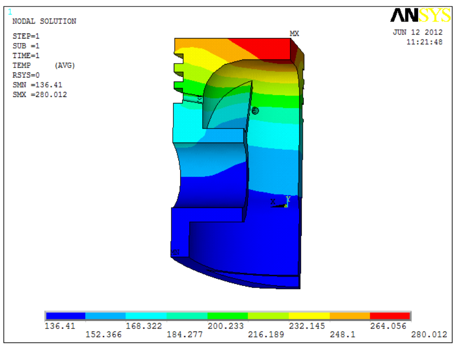

Figure 5: Temperature Field Of The Inner Chamber Of The Piston

From Figures 4&5, we can get:

(1) The piston temperature changes between 136.41 and 280.012 with the maximum temperature at the piston top and the minimum temperature at the lower part of the piston skirt.

(2) At the piston ring land, temperatures are distributed uniformly along the piston in the radial direction. We can see clearly that the temperature of the piston skirt is along the piston pin hole is higher than that perpendicular to the pin hole, thus causing the thermal deformation of the piston in the direction of the piston pin is greater.

(3) The piston temperature changes uniformly from the piston top to the bottom, without any sharp change phenomenon. The piston maximum temperature is at the piston top surface with the temperature of about 280 and the temperature of the upper surface of the first circular groove being about 230 . However, the allowable average temperature of the first circular groove of the aluminum piston is 180 to 220 and the temperature of the first circular groove is higher.

(4) The isothermal line of the circular groove zone is thicker than that of the skirt, indicating that the temperature of the circular groove zone of the piston changes greatly, so the thermal stress is relatively concentrated, causing it easy to be damaged. To assess the thermal condition of the piston, we should first pay attention to the maximum temperature of the piston top and the temperature of the first circular groove, the allowable average temperature of the aluminum piston top is 300 to 350 and the allowable average temperature of the first circular groove is 180 to 220 . This standard indicates that except the temperature of the first circular groove, the overall temperature of this piston is within the allowable average temperature, but the thermal load is severe. In high temperature, the material intensity will decrease and the high-temperature creep will occur. In the uneven temperature field, the piston in operation will cause great thermal stress, which will easily cause the piston cracked after long-time operation. The over-high temperature of the first circular groove will not only decrease the intensity of some materials of the circular groove, speed up the circular groove wearing, and influence the gaseous ring tightness, but also easily cause the piston ring cemented. So, it is necessary to take measures to carry out optimization design for the piston, so as to decrease the thermal load of the piston.

4. STRUCTURE OPTIMIZATION ANALYSIS OF THE PISTON

4.1 The Model after Optimization

From the temperature field analysis, we can get that the maximum temperature of the piston is below 280 , so no special materials are needed, but aluminum alloy will be acceptable. The temperature of the first piston ring is high, which can easily cause carbonization of lubricating oil, thus leading to the cementation of the piston ring which will cause the ring to lose mobility. So this can be the key point for optimization. We should apply the method of adding the cooling oil chamber to decrease the temperature of the first circular groove. The model after the structure optimization is as shown in Figure 6.

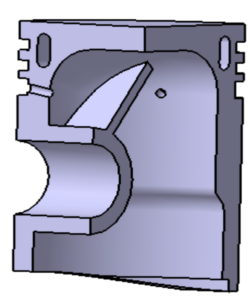

Figure 6: The Three-Dimensional Model Of The Piston After Optimization

ISSN: 1992-8645 www.jatit.org E-ISSN: 1817-3195

4.2 Comparison of the Temperature Fields before and after the Structure Optimization

With the boundary condition which is the same as that used for the stable thermal analysis before optimization, the heat exchange coefficient of the cooling oil chamber of 1300 $W/(m^2 \cdot K)$ and the ambient temperature of 130 , the analysis result is as shown in Figures 7&8.

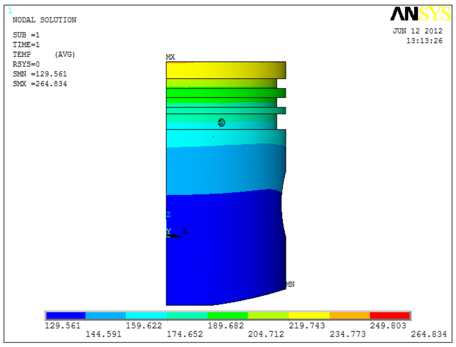

Figure 7: The Temperature Field Of The External Surface Of The Piston After Optimization

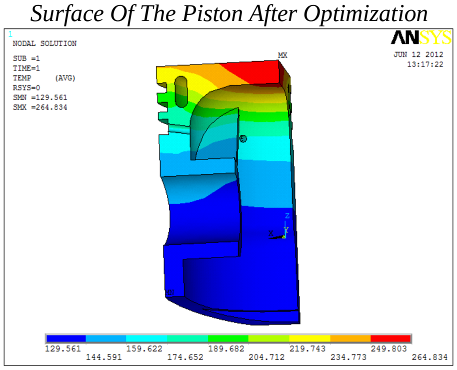

Figure 8: The Temperature Field Of The Inner Chamber Of The Piston After Optimization

Comparing the result in Figure 4 with that in Figure 5, we can get that the maximum temperature of the piston top after adding the cooling oil chamber is decreased to 264 , which is 16 lower than the maximum temperature of the original model of 280 . It has also been effectively relieved that the temperature of the piston skirt along the piston pin hole is higher than that perpendicular to the pin hole, thus decreasing the thermal deformation of the piston in the direction of the piston pin. From the figure, we can get that the maximum temperature of the first circular groove of the piston is 219 but the overall average temperature is about 204 , thus effectively improving the working condition of the first ring. The thermal load of the circular groove zone decreases and the thermal stress will also decrease accordingly, thus extending the service life of the piston ring, so the overall optimization result is satisfactory.

5. CONCLUSION

Result of the finite element analysis of the piston shows that, the maximum temperature of the piston before optimization is 280 which occurs at the piston top, the temperature of the first circular groove is about 230 ,and that of the first circular groove is relatively high so it needs to be optimized. With the optimization scheme of adding the cooling oil chamber, the maximum temperature the piston is decreased by 16 and the overall average temperature of the first circular groove is decreased to 204 , which conforms to the allowable average temperature of the piston. So the optimization scheme is effective.

REFERENCES:

[1] Hidehiko Kajiwara, Yukihiro Fujioka, Tatsuya Suzuki, Hideo Negishi, "An analytical approach for prediction of piston temperature distribution in diesel engines", *JSAE Review*, Vol. 23, No. 4, 2002, pp. 429–434.

[2] J.H, "Ong.Steady state thermal analysis of a diesel engine piston", *Computers in Industry*, Vol. 15, No. 3, 1990, pp. 255–258.

[3] V. Esfahanian, A. Javaheri, M. Ghaffarpour, "Thermal analysis of an SI engine piston using different combustion boundary condition treatments", *Applied Thermal Engineering*, Vol. 26, No. 2-3, 2006, pp. 277–287.

[4] H.W. Wu, C.P. Chiu, "Finite element model for thermal system in real time operation diesel piston", *Computers & Structures*, Vol. 32, No. 5, 1989, pp. 997–1004.

[5] Shu Yao Long, Xing Cheng Kuai, Jun Chen, " Boundary element analysis for axisymmetric heat conduction and thermal stress in steady state", *Engineering Analysis with Boundary Elements*, Vol. 12, No. 4, 1993, pp. 293–303.

[6] Ravindra Prasad, "Investigation of heat transfer in an oil cooled piston with and without ceramic insulation on crown face", *International Journal of Mechanical Sciences*, Vol. 31, No. 10, 1989, pp. 765–777.

[7] Yuh-Yih Wu,Bo-Chiuan Chen, Feng-Chi Hsieh, "Heat transfer model for small-scale air-cooled spark-ignition four-stroke engines", *International Journal of Heat and Mass Transfer*, Vol. 49, No. 21-22, 2006, pp. 3895–3905.

ISSN: 1992-8645 www.jatit.org E-ISSN: 1817-3195

[8] Avinash Kumar Agarwal, “Time resolved numerical modeling of oil jet cooling of a medium duty diesel engine piston”, *International Communications in Heat and Mass Transfer*, Vol. 38, No. 8, 2011, pp. 1080–1085.
[9] M. Spaniel, J. Macek, M. Divis, R. Tichanek , “Diesel engine head steady state analysis”, *International Journal of Middle European Construction and Design of Cars*, Vol. 2, No. 3, 2003, pp. 34–41.
[10] R. Tichanek, M. Spaniel, M. Divis , “Steady state heat analysis of engine head”, *International Journal of Széchenyi István University of Applied Sciences*, Vol. 20, No. 3, 2003, pp. 74–75.