Reason Study of Collision Between Valves and Piston of Diesel Engine Valve Train

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Abstract. Thermal-mechanical coupled finite element simulation of valve train for 265 diesel engine is carried out by using CREO and ANSYS softwares. The temperature field, thermal stress, thermal strain and thermal deformation re obtained for the system. Meanwhile, the cause of the collision between the valves and the piston is also got. The results of this paper will provide a certain theoretical basis for the further optimization design of valve system of the diesel engine.

Keywords: Valve train · Thermal-mechanical coupled ·
Finite element simulation · Collision reason

1 Introduction

Diesel engine is an important power supply device in rail transition, and the reasonable clearance between components of diesel engine is an important index to ensure the normal operation of diesel engine. At present, many scholars have conducted in-depth research on the clearance between the piston and the valves. Chen [1] used the mathematical function to calculate the clearance between the valve and piston of the 4160A diesel engine. Liu et al. [2]. Constructed a new algorithm for the extreme motion clearance between the valve and the piston, and edited the analysis program of valve piston clearance using Excel software. By establishing a mathematical model, Shi et al. [3]. Calculated the thermal expansion and dimension chain tolerance of piston and valve, so as to derive the minimum clearance between piston and valve. Li [4] used the method of changing the cam phase to analyze the minimum clearance between the piston and the valve. Wang et al. [5]. used UG software to couple and assemble the single cylinder and obtained the minimum clearance between the piston and valve. Wang et al. [6–8] used Pro/E software to establish a multi-body kinematics simulation model of valve and piston motion system, and measured the real-time motion clearance between the valve and the piston. Zhang [9] simulated the kinematics of the whole valve train and got the reasonable clearance between the piston and the valve. In the above literature, the clearance between valve and piston is analyzed without considering the thermal effect of diesel engine. However, there is no relevant report on the clearance change caused by the deformation of piston and valve due to the thermal effect. In this paper, the 265 diesel engine is taken as an example to perform the related

analysis. The whole valve train is systematically modeled by CREO and ANSYS software. The interaction between the thermal expansion of the fittings is fully considered. The thermal-mechanical coupled analysis of the valve train is carried out to obtain the temperature field, strain, stress and thermal deformation of the whole valve train. Thus, the reason of collision between the piston and the valve is derived. The research performed in this paper provides a certain theoretical basis for the further study of diesel engine valve train.

2   Basis of Theoretical Analysis

The theory of heat transfer defines that the temperature of a substance varies with time τ and space. The expression is as follows:

$$t = f(x, y, z, \tau) \tag{1}$$

where x, y and z represent the space Cartesian coordinates, respectively; and τ represents time.

As the basic theory of thermal theory, Fourier law can be expressed as:

$$q = -\lambda grad\, t = -\lambda \frac{\partial t}{\partial n} \tag{2}$$

where q represents the heat flux density with the unit of W/m^2; λ represents the thermal conductivity of the material with the unit of W/m °C; $\partial t / \partial n$ represents the derivative of the temperature in the n direction; the minus sign represents that the direction of Q is consistent with the direction of T reduction.

The radiation capacity of an object is related to temperature, and the radiation and absorption capacity of different objects are different under the same temperature condition. An ideal object is Imagined as a black body that absorbs all of the heat radiation energy applied to its surface.

The thermal radiation heat emitted by the black body in unit time is revealed by Stefan-Boltzmann law, and can be expressed as:

$$\Psi = A\sigma T^4 \tag{3}$$

where A is the radiation surface area; σ is the Stefan-Boltzmann constant and its value is 5.67×10^{-8} W/(m2 K4); T is the thermal-mechanical coupled temperature of the black body.

The thermal radiation heat of the actual object is modified by the empirical formula of Stefan-Boltzmann law and can be written as:

$$\Psi = \varepsilon A\sigma T^4 \tag{4}$$

where ε is the emissivity of the object, $\varepsilon \leq 1$.

In the light of classical thermal-mechanical coupling analysis, the governing equation of three-dimensional temperature field is derived by using finite element

method. The basic finite element solution equations of this kind of problems can be obtained as:

$$C\dot{\Phi} + K\Phi = P \tag{5}$$

This is a set of linear ordinary differential equations with time as independent variables. C is the heat capacity matrix, K is the heat conduction matrix, C and K are symmetric positive definite matrices; P is the temperature load array; Φ is the node temperature array; $\dot{\Phi}$ is the derivative matrix of node temperature to time. The elements of the matrix C, K, P are integrated by the corresponding matrix elements of the unit. That is:

$$K_{ij} = \sum_e \int_{\Omega^e} (k_x \frac{\partial N_i}{\partial x}\frac{\partial N_j}{\partial x} + k_y \frac{\partial N_i}{\partial y}\frac{\partial N_j}{\partial y} + k_z \frac{\partial N_i}{\partial z}\frac{\partial N_j}{\partial z})d\Omega + \sum_e \int_{\Gamma_3^e} hN_iN_jd\Gamma \tag{6}$$

$$C_{ij} = \sum_e \int_{\Omega^e} pcN_iN_jd\Gamma \tag{7}$$

$$P_i = \sum_e \int_{\Omega^e} \rho QN_id\Omega + \sum_e \int_{\Gamma_2^e} qN_id\Gamma + \sum_e \int_{\Gamma_3^e} h\Phi_aN_id\Gamma \tag{8}$$

The above formula has discretized the partial differential equation problem in time domain and space domain into the initial value problem of N node temperature $\Phi_i(t)$ ordinary differential equation in space domain. The core of solving temperature field problem by finite element software is to solve ordinary differential Eq. (5) by corresponding numerical method.

3 Thermal-Mechanical Coupled Finite Element Analysis of Valve Train

3.1 Model Establishment

In this paper, the thermal-mechanical coupled finite element analysis of the valve train of 265 diesel engine is carried out by using CREO3.0 and ANSYS Workbench software. The finite element analysis model is shown in Fig. 1. The material properties of the key parts in the model are shown in Table 1. In the finite element analysis, in order to improve the analysis accuracy, the model mesh is divided by the curvature control function, which generates 7315253 units and 10521715 nodes. The temperature points of the piston, valve and cylinder liner are shown in Figs. 2, 3 and 4. The specific values of the temperatures are shown in Tables 2, 3 and 4. The thermal-mechanical coupled analysis of the valve train carried out in this paper includes two kinds of transfer modes which are heat transfer and heat radiation. The external temperature of the system is 40 °C. The valve train is cooled using the water cooling. The water temperature is 72 °C after cooling. The system is set to be the exhaust stroke.
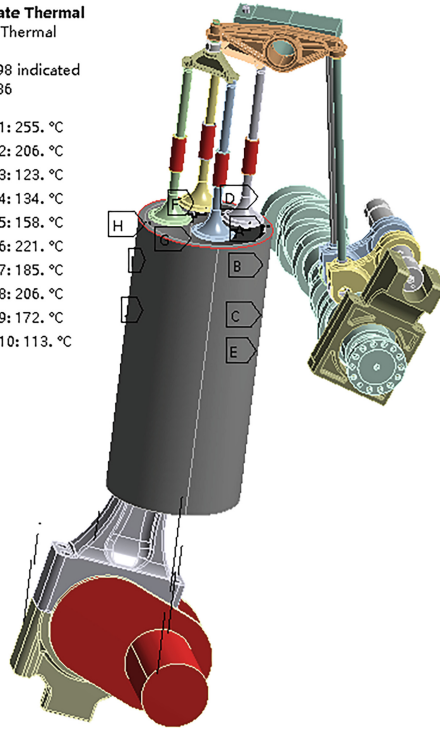
Fig. 1. Valve train of 265 diesel engine

Table 1. Material properties of each part

Components	Exhaust valve	Intake valve	Piston skirt	Piston top	Cam
Material	Nickel alloy	4Cr9Si2	Aluminum alloyLD11	42CrMoA	HT250
Density $\rho/(\text{g/cm}^3)$	8.22	7.70	2.70	7.83	7.8
Elastic modulus $E/(\text{GPa})$	214	206	72	207	130
Poisson's ratio	0.3	0.3	0.33	0.28	0.27
Thermal conductivity $CAL/(\text{W/(m.K)})$	12	16.	170	42	50
Thermal expansion coefficient $CTE/$ $((\mu\text{m/m})/°C)$	12.9 (21–93 °C) 14.0 (21–315 °C) 14.9 (21–538 °C) 16.0 (21–760 °C)	12.0 (20–500 °C)	22.0	11.0 (20–300 °C) 12.9 (300–400 °C) 13.5 (400–500 °C) 14.1 (500–600 °C)	12.1

(a) Exhaust valve   (b) Intake valve
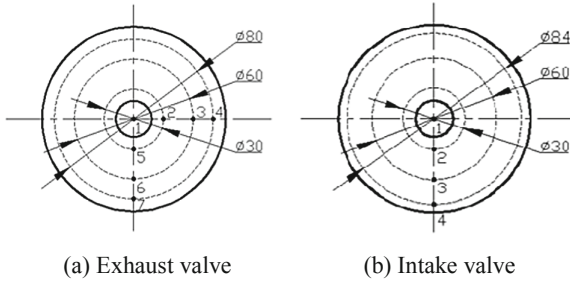
Fig. 2. Temperature measurement points distribution of Intake and exhaust valves
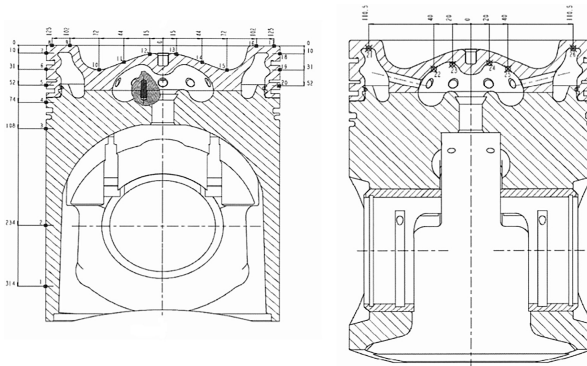
Fig. 3. Temperature measurement points distribution of Piston
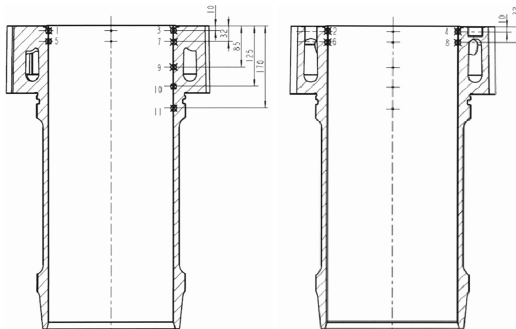
Fig. 4. Temperature measurement points distribution of Cylinder sleeve

Table 2. Measuring points temperature values of Intake and exhaust valve

Measuring point	1	2	3	4	5	6
Exhaust valve Q(°C)	399	408	399	363	\	\
Intake valve Q(°C)	537	543	541	\	543	536

Table 3. Measuring points temperature values of Piston

Measuring point	1	2	3	4	5	6	7	8	9
Piston Q(°C)	131	158	154	164	160	183	257	283	366
Measuring point	10	11	12	13	14	15	16	17	18
Piston Q(°C)	319	316	320	313	312	311	419	330	282
Measuring point	19	20	21	22	23	24	25	26	
Piston Q(°C)	180	164	308	260	257	259	253	284	

Table 4. Measuring points temperature values of Cylinder sleeve

Measuring point	1	2	3	4	5	6	7	8	9	10	11
Cylinder liner Q(°C)	206	216	255	221	172	179	206	185	123	134	158

3.2 Results of Thermal-Mechanical Coupled Analysis

3.2.1 Distribution of Temperature Field

After the simulation analysis, the temperature field of the valve train is shown in Fig. 5 (a). It can be seen that the highest temperature occurs at the top of the exhaust valve and the temperature is 540 °C, as shown in Fig. 5(b). This is because the high-temperature exhaust gas of the exhaust stroke of the diesel engine is exhausted through the exhaust valve, which has the effect of secondary heating to exhaust valve. The intake valve temperature is low and has the value of 438 °C as shown in Fig. 5(c). This is because the cold air flow outside the intake valve has a certain cooling effect on the intake valve. At the same time, the temperature drops significantly after the radiant heat transfer of the valve through the cooling surface, which indicates that it is necessary to consider the cooling effect for the thermal analysis of valve train. The distribution gradient of temperature at the top of the piston is small and its maximum temperature is 419 °C as shown in Fig. 5(d). This is because the four-stroke cycle in the cylinder is relatively stable, and the surface of the piston is only affected by the temperature of the oil and gas explosion.

3.2.2 Distribution of Equivalent Stress

The equivalent stress distribution of the valve train is shown in Fig. 6(a), and the maximum value and generation position are given in Table 5. The maximum equivalent stress occurs at the top of the piston near the exhaust valve side. Because the exhaust gas is stayed on the exhaust valve side for a period of time, it makes the temperature on this side relatively high as shown in Fig. 6(b). In this case, the maximum equivalent stress of the valve is at the tail end of the exhaust valve connected to the transverse arm of the valve as shown in Fig. 6(c). Because the valve cross arm pushes the exhaust valve to open, which results in the large stress on the interface between their contact surface.
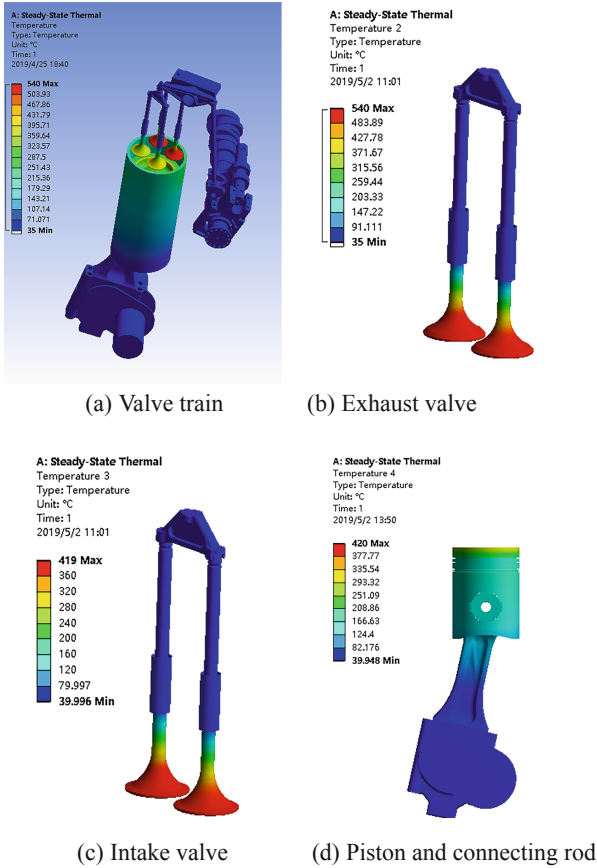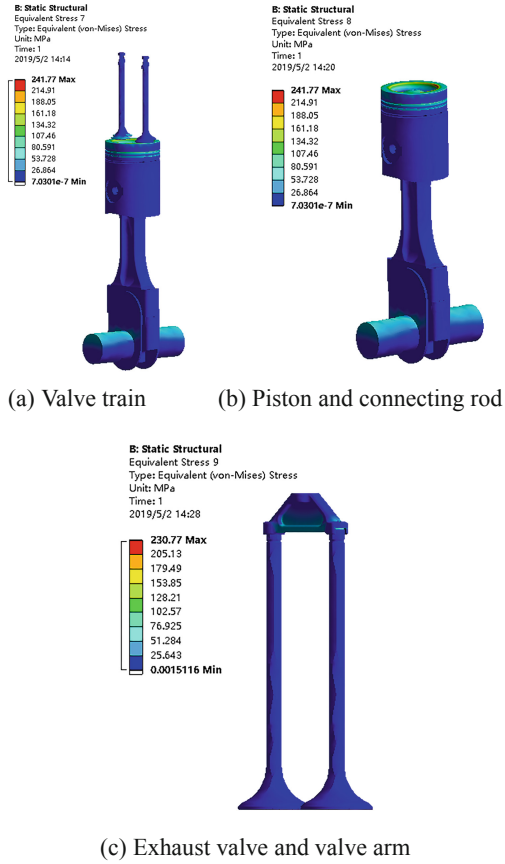
(a) Valve train

(b) Exhaust valve

(c) Intake valve

(d) Piston and connecting rod

Fig. 5. Distribution of Temperature Field

3.2.3 Distribution of Equivalent Elastic Strain

The equivalent strain of the valve train is shown in Fig. 7(a), and the maximum value and position of each component are shown in Table 6. It can be seen that the distribution law of the equivalent strain is the same as that of the equivalent stress. The maximum equivalent strain is located on the exhaust valve side as shown in Fig. 7(b). The equivalent strain of the valve is concentrated near the contact position between the valve and the valve cross arm. But the position of the maximum equivalent strain is slightly different from the that of the maximum equivalent stress, which occurs on the cross arm of the exhaust valve as shown in Fig. 7(c).

(a) Valve train   (b) Piston and connecting rod

(c) Exhaust valve and valve arm

Fig. 6. Equivalent stress distribution

Table 5. The values and position of the Maximum Equivalent Stress

Components	Valve train	Piston	Valve
Maximum stress/ (MPa)	241.77	241.77	230.77
Position	Top side exhaust valve side	Top side exhaust valve side	Connection between exhaust valve and valve arm

(a) Valve train   (b) Piston and connecting rod

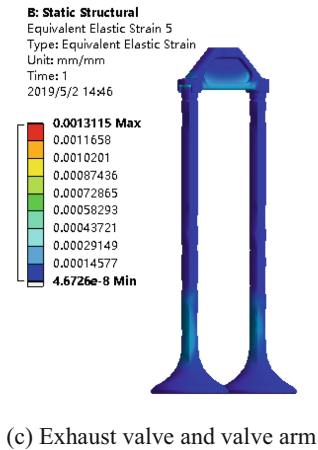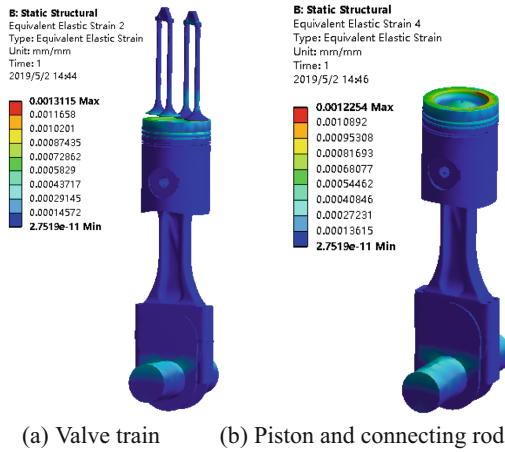
(c) Exhaust valve and valve arm

Fig. 7. Equivalent strain distribution

Table 6. Values and position of the maximum equivalent strain

Components	Valve train	Piston	Valve cross arm
Maximum strain/(mm)	0.0013	0.0012	0.0013
Position	Lower part of the valve	Top side exhaust valve side	Lower part of the valve

4   Cause Analysis of Collision Between Valve and Piston

4.1   Distribution of Thermal Deformation

The overall thermal deformation distribution of the valve train is measured in the direction of the combustion chamber and shown in Fig. 8(a). The values of thermal deformation and the minimum clearance reduction are shown in Table 7. The cam-

(a) Valve Train   (b) Piston and connecting rod

(c) Exhaust valve and valve arm
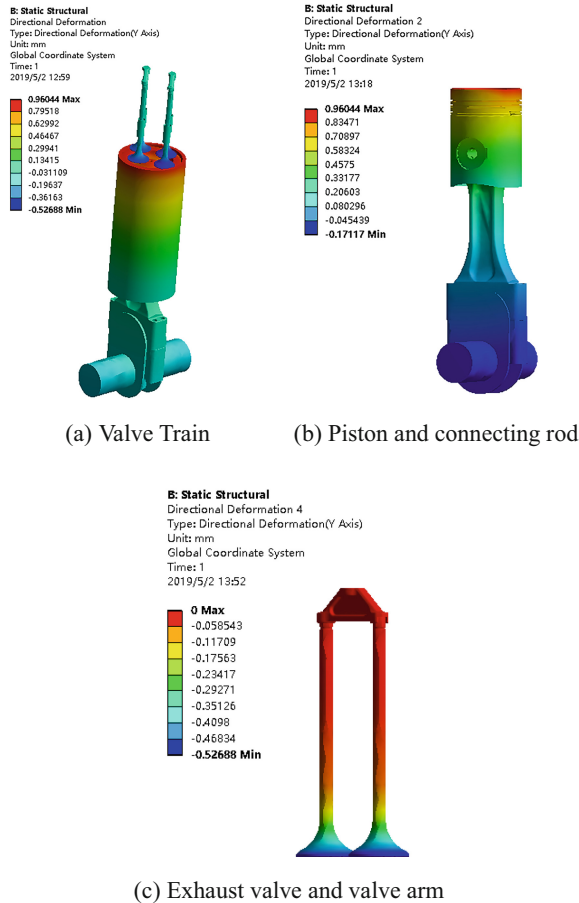
Fig. 8.   Heat distribution distribution

Table 7.   The amount of heat deformation and the minimum gap reduction of the valve train

Components	Valve train	Piston	Valve	
			Front end	Tail end
Maximum thermal deformation/(mm)	0.96044	0.96044	0.52688	0

connecting rod-piston structure of the system generate the thermal deformation. As shown in Fig. 8(b), the maximum thermal deformation of the piston top is 0.96044 mm. At this time, the maximum thermal deformation generates on the exhaust valve as shown in Fig. 8(c). Its thermal deformation is 0.52688 mm. The minimum clearance between the piston and valve is reduced by 1.48732 mm.

4.2   Collision Cause

During the analysis, it is found that if the cam is varied from 48.39° to 129.16°, the thermal deformation of part of the piston reaches a negative value, that is, its direction is downward along the axial direction of the piston. So it can be determined that the piston collides with the valve under this condition as shown in Fig. 9. As shown in Fig. 10, the contact stress between the exhaust valve and the piston surface is abruptly increased to 1203.2 MPa, which may induces the failure of the piston and the valve.
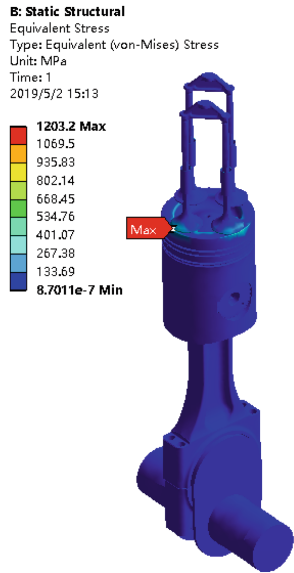

Fig. 9. Equivalent stress distribution in piston valve collision

B: Static Structural
Directional Deformation 5
Type: Directional Deformation(Y Axis)
Unit: mm
Global Coordinate System
Time: 1
2019/5/3 18:06

0.40489 Max
0.30233
0.19976
0.097204
-0.0053576
-0.10792
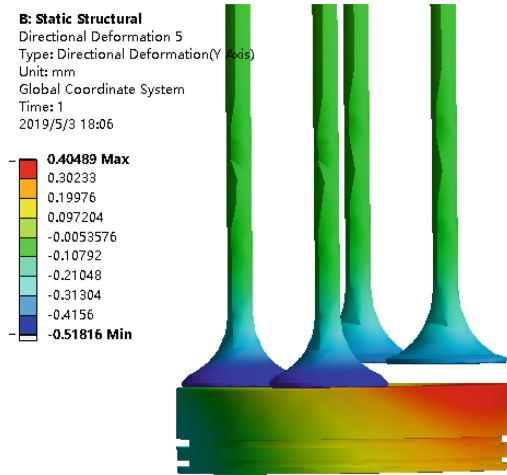-0.21048
-0.31304
-0.4156
-0.51816 Min

Fig. 10. Partial enlargement of piston valve thermal deformation

5   Conclusions

This paper focuses on the study of collision between valve and piston of 265 diesel valve train. From the analysis results, the following conclusions can be derived as: (1) under the stable temperature field of valve train, the maximum displacement of the piston is 0.96044 mm, the maximum equivalent stress is 241.77 MPa, and the maximum equivalent strain is 0.0012 mm; (2) the maximum displacement of the valve is 0.52688 mm, and the maximum equivalent stress is 230.77 MPa; (3) if the cam is varied from 48.39° to 129.16°, the piston collides with valve and their contact stress will be 1203.2 MPa.

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