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The evaluation of the stress-strain state for the cylinder heads of high-powered diesel engines using the multiphysics ANSYS technology

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Abstract

The researchers have built a calculation model for comparative assessments of the heat balance, heat and stress-strain state for the head and cylinder liner of forced diesel engine, which model takes into account the redistribution of the quenching fluid between the cylinder head and crankcase. Computational experiments have been performed. The trade-off approach to the design of a diesel engine cooling system has been demonstrated to find out that improved cooling of the cylinder head is accompanied by deteriorating thermal state of the crankcase and the cylinder liner.

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Keywords: diesel engine, cylinder head; crankcase; cylinder liner; cooling system; redistribution of coolant; FEA; thermal stress

1. Introduction

Increasing load to cylinder head (thermal, mechanical, hydraulic and gas-dynamic) on the forcing diesel engine can lead to warping fire surface, cracks in intervalvular crosspieces, in the sealing valve timing, disclosure gas joint and other factors that are indicative of the loss of its efficiency. Difficulties of estimate of the thermal state and the stress-strain state of cylinder head at the design stage are closely connected with the need of modeling interdependent non-steady thermodynamic movement processes of working gas, quenching fluid, heat exchange

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with the environment, the contact interactions with the other elements diesel engine. Existing methods solve the problem of modeling the thermal state and the stress-strain state cylinder heads with different fullness and need to be improved.

2. Review

Modern approaches to the computational estimate of temperature fields, the strain and stress of the cylinder head is usually limited to a non-steady three-dimensional formulation of heat conduction problems and deformable solid mechanics based on numerical finite element method (FEM), embodied either by researchers independently or into one of the commercial software packages. The accuracy and adequacy of such a calculation model directly depends on representation and reliability of the boundary conditions (BC).

The boundary conditions of the heat conduction problem on the surfaces of the firing bottom, the inner surface of inlet and outlet ports include the time-averaged heat transfer coefficient α_{rez} and the resulting temperature of the gas T_{grez} defined on the recommendations of [1]. The coefficient of heat transfer from the working gas is determined using [2] and its distribution across the hot surface of the cylinder head is determined using Z. Slivinski equation. Boundary conditions in the contact zone of valve seats are estimated taking into account the recommendations of [3]. Heat transfer boundary conditions in the cavities of the liquid cooling of the cylinder head are defined as the average time for the heat transfer coefficient and the average α_{Lrez} resulting coolant temperature T_{Lrez} [4].

The boundary conditions of the problem of elasticity [5, 6] by the bottom surface of the combustion maximum pressure P_{max} include gas in the cylinder during combustion. The gas pressure on the inner walls of the inlet and outlet channels in the head, respectively, is determined taking into account the parameters of charge air and exhaust gases. The pressure of the quenching fluid on the inner surface of the cavities is estimated from the water pump parameters. Loads of tightening nuts power pins are applied in the form of distributed force to the shim contact area with the surface of the cylinder head.

There are also works based on the modeling of unsteady transfer processes of momentum, energy, mass, density and turbulent combustion in the cylinder of the engine [18, 19]. The simulation results are the values of velocity and temperature at all points of the combustion chamber and the local heat fluxes into the walls of the chamber, in such way is reached a clarification of the boundary conditions of the local heat transfer and heat transfer coefficients determination in determining the thermal state of the piston. However, these studies have not analyzed heat-stressed state of the cylinder head.

Reliability of calculated results increased when comparing the results of numerical simulation of the temperature state of the cylinder head with the results of thermometry and refinement of boundary conditions for solving test problems [7, 8]. Using this approach is useful when checking the particular design of the cylinder head. However, the use of such approaches in the design and the search for the most effective design solutions is not always possible and economically feasible.

3. Problem definition

The purpose of work is to construct a computational model of the cylinder head and crankcase for comparative assessments of the thermal state and the stress-strain state with relatively small changes in the object of research and is focused on support of the design process of new technology and reducing time to market.

A distinctive feature of the proposed calculation model is the quantitative estimation for parameters of heat exchange of the cylinder head by the solution of connected problem of motion of the gas flows and the flows of quenching fluid. After determination of the three-dimensional temperature field of the cylinder head and the cylinder crankcase of a diesel engine, the import of these results to the analysis of strain state is performed.

Similar staging task used in [9, 10, 15, 16, 17]. The authors of [9] used the method of numerical simulation of fluid flow and heat transfer only in cavities cooling of the cylinder head of the forced diesel engines. In [10] is suggested the technique of mathematical modeling of the agreed boundary conditions for the calculation of temperature fields, field strains and stresses only the elements of the cylinder-piston (cylinder head, valves) diesel. In [15, 16] focuses on the state of thermal stresses crankcase of diesel and its impact on the performance of main bearings. The authors of [17] calculated the thermal state of the cylinder head and engine valves and left unattended the questions of the stress-strain state.

4. Model

A geometric model is represented by single-cylinder fragment (Fig. 1a) of six-cylinder V-type diesel dimension 15/16. As the main causes of stress in the component parts of the head housing unequal distribution of the volume of the head casing independent of the time component of the temperature (averaged over the cycle temperature) and the quasi-static force application of gas pressure in the cylinders are considered. Calculation model stress-strain state of head crankcase diesel engine considered in this paper focused on the selection of a preferred embodiment from the numbers involved compared to the limited number of distinctions. An analysis of the strengths and weaknesses of embodiment of the object of research is done by comparing the solutions of the stationary heat and power quasi-static problems.

Finite element method implemented in the application package Ansys v16.2 used for the settlement prediction of temperature distribution, thermal and mechanical stresses in the cylinder head. Numerical simulations were performed on workstation with six CPU and 64 GB of RAM.

Used interdisciplinary technology FSI (One-Way Fluid-Structure Interaction analysis), in which the actual constructional calculation of solid mechanics (Structural Analysis) precedes the solution to the problem of fluid dynamics CFD (Computational Fluid Dynamics). At the stage of solving CFD problems in geometric model of the object of the study was divided into four domains (Fig. 1a). There are two solid state domain (one of which includes a piston and connecting rod assembly, a fragment of the crankcase, the sleeve, the second - the cylinder head body fragments timing, intake and exhaust manifolds). There is gas domain representing the spatial region occupied by working gases while moving from the inlet manifold of the cylinder head into the cylinder and into the exhaust manifold (only used in CFD model). There is domain of quenching fluid communicating space formed of the regions occupied by the cooling fluid in the cylinder head, in the fragments of the crankcase, the outlet and inlet collectors (used only in the CFD model).

An algorithm for solving FSI tasks implemented in the package Ansys for the heat transfer problems and to determine the parameters of liquid and gas flow, involves the use of a non-deformable Eulerian grid finite element (FE) with the subsequent transfer of temperature fields in the Lagrangian deformable mesh to calculate the stress-strain state. Parameters FE models are shown in Table 1. Areas streaming domains in contact with the solid domains (parietal area) breaking-were five layers of prismatic elements, other areas broke tetrahedral with a typical size of 1 mm.

Power source of heat is determined by assessing the total irreversible heat loss of diesel. Flow of cooling fluid through a cylinder head performance was assessed by the power of a circulation pump. Airflow is determined by calculation of diesel engine working cycle.

For cylinder head domain used the properties of aluminum alloy AMX-605, and for the crankcase - ductile iron. For solid domains accepted model of continuous, homogeneous, isotropic material. When select a characteristic size of the finite element mesh for the structural calculation takes into account the heterogeneity of the structure-material-temperature case [13, 14]. For liquid-domain model used one- and two-phase medium (Homogeneous Binary Mixture), corresponding to the thermodynamic properties of water and steam. [20]

5. Results

Determination TNDS performed for two levels of heat dissipation from the diesel engine (see Table 2), and two variants of the cooling jacket (CJ). Differences between cooling jacket variants were reduced to open or closed the channels connecting the cavity cooling the head and intake manifold (Fig. 1b).

Heat flow Q in the domains of computational model (as a fraction of total heat loss) (Fig. 1c) for the examined cases are shown in Fig. 2a. Averaging of temperature for combined surface formed by the criterion of performance of similar thermal features reveals pronounced dependence of heating different parts of the model from the formation of the coolant flow the cooling jacket (Fig. 2b).

The differences in the formation of flow of coolant to CJ options under intense heat sink shown in Fig. 2c (the line intensity is proportional to the current flow rate of fluid through the corresponding spatial region of cooling jacket).

Table 1. FEA model data

Quantity	Computational Fluid Dynamics	Structural Analysis
Elements	8,78 mio	6,2 mio
Nodes	> 2 mio	> 9 mio

Table 2. Calculation options

Heat removal from the engine	Coolant flow, kg/s	Temperature, C°		
		coolant inlet	outside the crankcase	inside the crankcase
Intense	2	80	20	100
Hindered	0,2	95	120	220

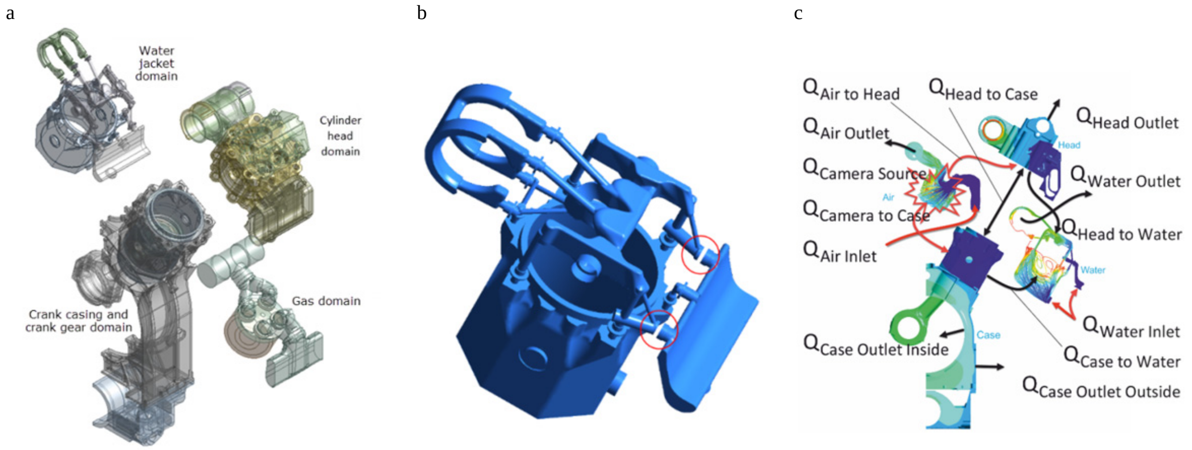

Fig. 1. (a) Components of the model, (b) Location connecting channels of cooling jacket, (c) Designation of heat flows between the components of the calculation model.

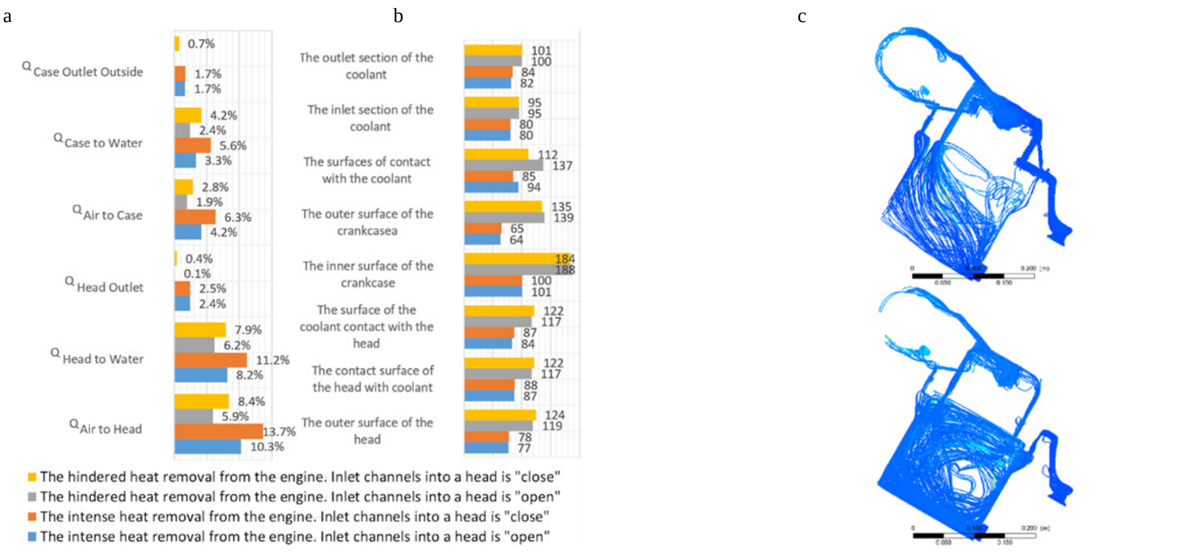

Fig. 2. (a) Thermal balance in the domains of the cylinder head and crankcase for different modes, (b) The average temperature (in C°) major surfaces CFD model, (c) Options for flow of coolant in the cooling jacket: at the top - the inlet manifold channels in the head is open;

Opening of the connecting channels between the intake manifold and the cylinder head intensify quenching fluid motion through a head. In the crankcase from the side of intake manifold is formed stagnation zone. There is boiling in the crankcase part of cooling jacket in case of the hindered heat removal from the engine and "open" channel between the intake manifold and the cylinder head (Fig. 3). Option "closed" channel in the head allows to intensify the movement of the coolant in the crankcase and to avoid virtually boiling coolant (Table 3).

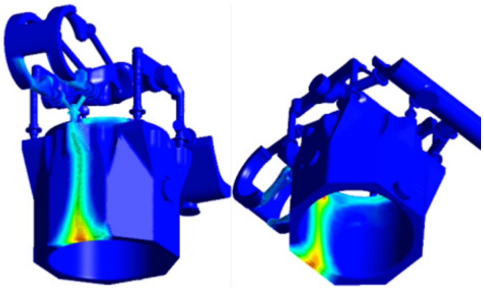

Fig. 3 Location zone boiling of coolant in the crankcase cooling jacket.

Table 3. Part of the boiling liquid in the volume of the cooling jacket

Heat removal from the engine	Open channels between the intake manifold and the cylinder head	Close channels between the intake manifold and the cylinder head
Intense	0	0
Hindered	0,134%	0,00102%

In Fig. 5b can be seen to what extent the movement of heat (the change of the inner surface of the cylindrical shape) of the sleeve connected with peculiarities of the cooling system. In the case of boiling coolant in the cooling jacket of crankcase the difference mutual displacements diametrically opposite points by the height of the cylinder liner is increased by 4.5 times.

a b c

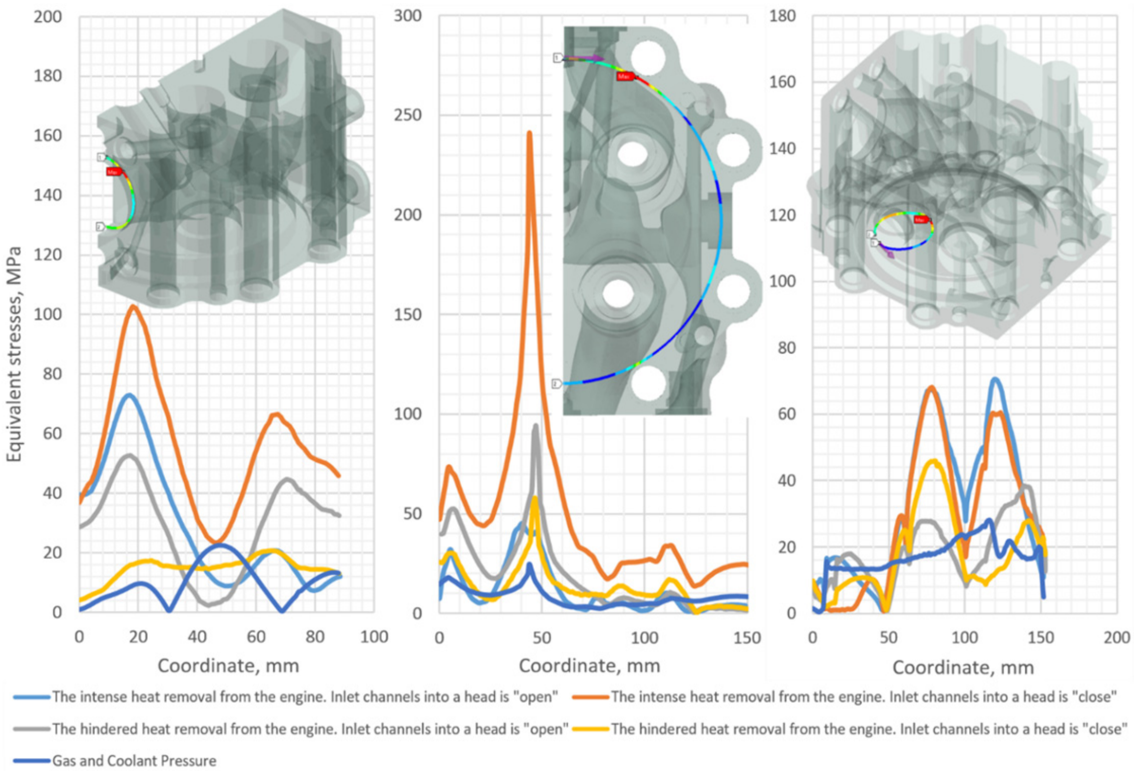

Fig. 4. The equivalent stresses in the elements of the cylinder head of a diesel engine: a) the edge of the window in the exhaust manifold; b) the edge of the cavity combustion chamber; c) the edge of the mounting surface of the exhaust valve seat.

The results of the calculations show the greatest stresses in cylinder head occur in the areas of the windows in the exhaust manifold, the rib groove in the head flange of the sleeve and the seat of the exhaust valve (Fig. 4 a, b, c).

Locking connecting channels between the intake manifold and the cylinder head intensifies the motion of the fluid in the crankcase reducing the temperature at the hottest points of the liner of more than 80 C $^{\circ}$. The decrease in the flow of coolant through the cylinder head temperature rises is reflected in its local zones 50 C $^{\circ}$.

The contribution thermal load to the total stresses for the analyzed areas of the head is the primary (Fig. 4). The maximum thermal stresses occur in the head at a low temperature in the engine compartment, maximum performance water pump and "closed" the input coolant channels in the cylinder head. Interestingly, this mode also corresponds to a maximum heat flow both from the combustor to the head and from the head to the coolant (Fig. 2a), but the average temperature of the outer surface of the head on the mode with the maximum heat stress is substantially (at 40 C $^{\circ}$) below than with the hindered heat removal from the engine. But with the hindered heat removal from the engine (as seen from the graphs of Fig. 4), the highest values of thermal stresses in the analyzed fragments of the head are significantly lower: the most loaded by heat stress area of the window into the exhaust manifold - almost 5 times, to the edge of the combustion chamber - in 5.3 times, for the edge of the seat of the exhaust manifold - 1.7 times.

Qualitatively this result was predicted: the thermal stresses is higher than the above temperature gradient. However, the established calculation fact such a significant relationship between the levels of maximum values of thermal stresses in the head on the conditions of the heat sink once again confirms the need for very careful attention to detail design of the cooling system.

The redistribution of the coolant flow to the head at the open front into the head coolant channels allows to significantly reducing thermal stresses in it (Fig. 4a). However, the simultaneous reduction in the flow of coolant through the cooling jacket of the crankcase reduces the efficiency of the cooling sleeve. The result of reduced cooling sleeve is to increase the danger of boiling coolant in the crankcase of the cooling jacket. One of considered calculation option leads to the boil (Fig. 3).

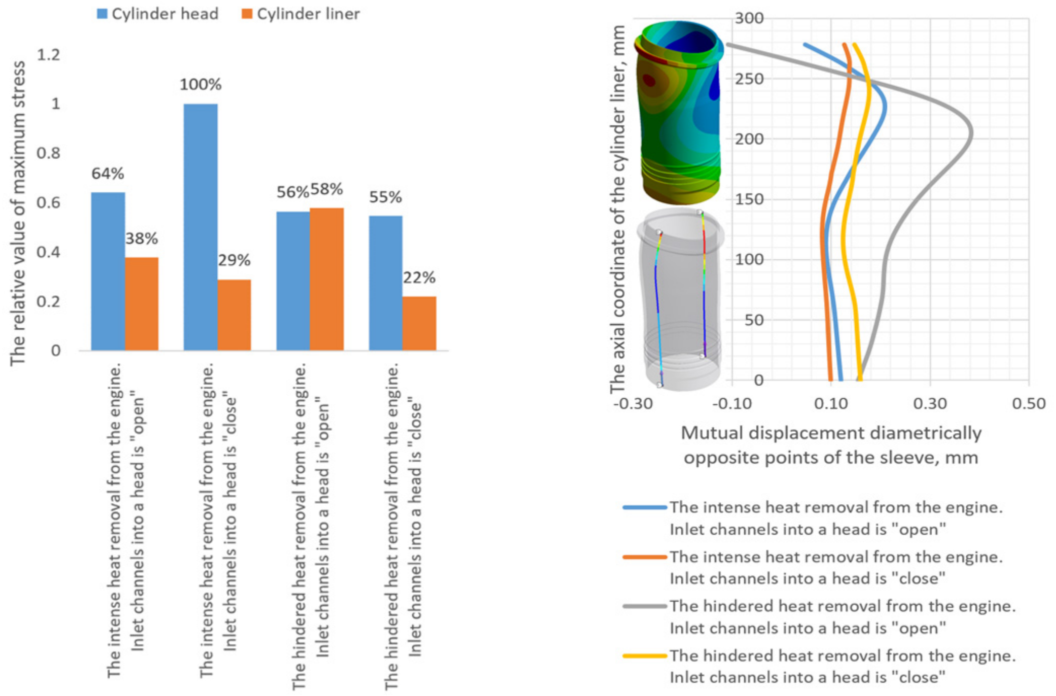

Fig. 5. (a) A comparison of thermal stresses in the cylinder head and cylinder liner, (b) Thermal displacement opposite points of the inner surface of the liner in a plane perpendicular to the axis of the crankshaft.

6. Conclusion

Using FSI technology for the computational analysis of the cooling system of a diesel engine has allowed estimating quantitatively the dependence of the stress state of the cylinder head and crankcase of a diesel engine on the operating conditions of the cooling system of the diesel engine.

It is shown that at the fixed level of power developed by the engine the maximum stresses in the cylinder head may vary up to 5 times depending on the cooling of the engine.

Showed compromise sense of the design of the cooling system of a diesel engine: improving the cooling of the cylinder head is accompanied by a deterioration of the thermal state of the crankcase and the cylinder liner until boiling coolant in the crankcase of the cooling jacket.

Boiling coolant in the cooling cavity crankcase is accompanied by the emergence of pronounced unevenness of the cylinder liner, resulting in take place a significant increasing (up to 4.5 times) of the distortion cylindricality inner surface of the cylinder liner with respect to the case of lack of boiling coolant.

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