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THE INFLUENCE OF ENGINE SPEED ON THERMAL STRESSES OF THE PISTON

Summary. In the paper, numeric calculations relating to the influence of engine speed on thermal stresses of the piston in a turbocharged diesel engine in the initial phase of its work were carried out. The calculations were based on experimental studies and the data resulting from them. They were made using a geometrical model of the piston in a turbocharged diesel engine with a capacity of 2,300 cm^3, with a direct fuel injection to the combustion chamber and a power rating of 85 kW. Modelling of the thermal stresses of the piston was carried out for the engine speed $n=2{,}000\ min^{-1}$ and $n=4{,}250\ min^{-1}$.
Keywords: diesel engine, thermal stresses, piston

1. INTRODUCTION

Along with an increase in the mechanical loads, increasing engine power is also accompanied by an increase in thermal loads. These loads have a significant influence on

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features of the engine, such as the exhaust blowing through to the crankcase, the engine oil wear or the level of pollutants emitted by the engine into the atmosphere. In particular, a piston experiencing thermal stresses, which are variable over time, is exposed to these effects. Already at the stage of preliminary design work, knowledge of the thermal loads of the piston will be required. Such information can be obtained by suitable modelling of the temperature distribution in the studied cross sections of the piston's characteristic surfaces. Design works and model tests are very expensive and prolonged. However, the application of mathematical models and suitable computer techniques allows for determining the temperature distribution for different materials, sizes and shapes of the piston [1, 8]. Subsequent analysis of this information helps to formulate initial design assumptions, as well as modernize existing solutions for operating the engine at various speeds and loads. Very good results in studies on thermal stresses of the piston are provided by the application of the finite element method. However, in order to carry out any numerical calculations, some assumptions and use of empirical methods of data gathering for each of the analysed operation conditions of the engine are needed.

2. ANALYSES OF THE INFLUENCE OF SELECTED PARAMETERS ON THE THERMAL LOADS OF THE PISTON

The conditions of the engine operation include a change in the effective pressure. Assuming that mechanical efficiency is constant, an increase in the average effective pressure is equivalent to a higher heat emission, which leads to an increase in the piston temperature. The influence of the increase in the average effective pressure on unit heat flux for the parameter characterizing the heat load of the cylinder results from the following dependence:

$$K_c = bc_m^{0,56} \frac{p_e g_e}{D^{0,5}(\eta_v p_d)^{0,435}} \frac{T_d}{T_0} \tag{1}$$

where:
b = coefficient of the amount of strokes (for four strokes, b=2)
$\eta_{\square}$ = fill coefficient
c_m = average velocity of the piston [m/s]
D = diameter of the cylinder [dm]
p_d = pressure at the inlet valve [MPa]
T_d = temperature at the inlet valve [K]
p_e = average effective pressure [MPa]
g_e = actual fuel consumption [g/kWh]
T_0 = ambient temperature (T_0=293 K)

The increase in the average effective pressure of a diesel engine is achieved by injection of a higher dose of fuel per working cycle into a cylinder. Thus, a higher amount of heat is transferred to the piston while reducing the excess air ratio. The lower the excess air ratio λ, the larger the relative amount of heat that may be released from the fuel in the cylinder. The temperature changes are analogous to the changes in engine power. Both the mixture enrichment and impoverishment cause a drop in the temperature of the piston. With a too-rich mixture, a large part of the fuel is not burned. A lean mixture burns slowly, reducing the combustion temperature, despite the fact that, as a result of chronic combustion, the temperature of the exhaust gas increases. In a diesel engine, an increase in the engine load leads to a decrease in the excess air ratio λ, resulting in the supply of more fuel. It leads to an increase in the amount of heat released in the engine's combustion chamber and in the temperature of the elements surrounding it.

Another parameter affecting the thermal load on the piston is the engine speed. The influence of this parameter is quite complicated. On the one hand, an increase in the engine speed is equivalent to an increase in the frequency of combustion in the cylinder, increasing the amount of heat in the combustion chamber. On the other hand, it affects the change in the engine-filling efficiency and thus the course of the combustion process itself. In a diesel engine, the amount of fuel being provided into the cylinder does not depend on the engine-filling efficiency with air, given that, for all rotational speeds, the engine sucks in a different, albeit maximum, value of the air mass. The amount of the injected fuel depends on the curve of the dosing characteristic of the injection pump and on the excess air ratio, which in turn depends on both the amount of intake air and injected fuel. Figure 5 shows the course of the calculated maximum values of the piston head surface temperature during a 60-second operation of a turbocharged diesel engine, calculated by counting from the engine start its two rotational speeds n=2,000 min^{-1} and n=4,250 min^{-1}.

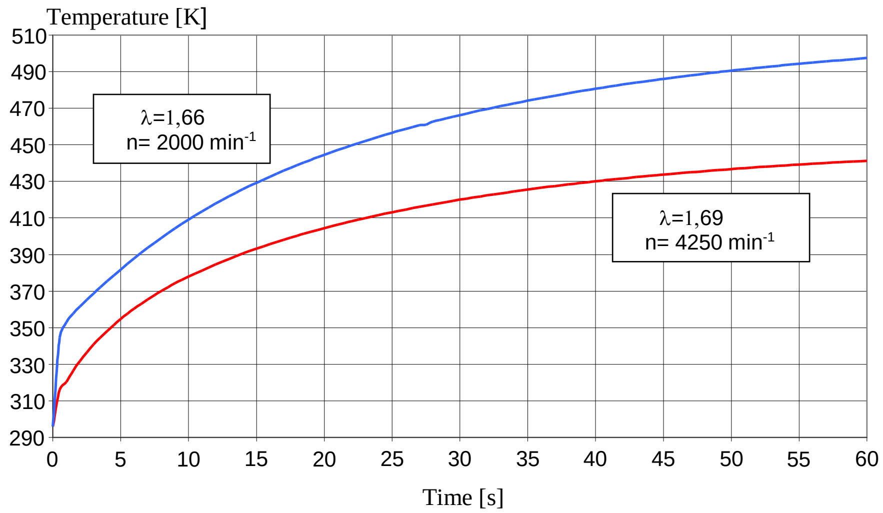


Fig. 1. The course of maximum temperature on the surface of the piston head for two engine speeds

Based on the calculations, it was found that an almost twofold increase in the rotational speed of a turbocharged diesel engine for the same load causes lower thermal loads of the piston head [6]. This is due to a higher speed of heat exchange between the piston and its environment, in comparison with the amount of heat generated in the combustion chamber of the engine.

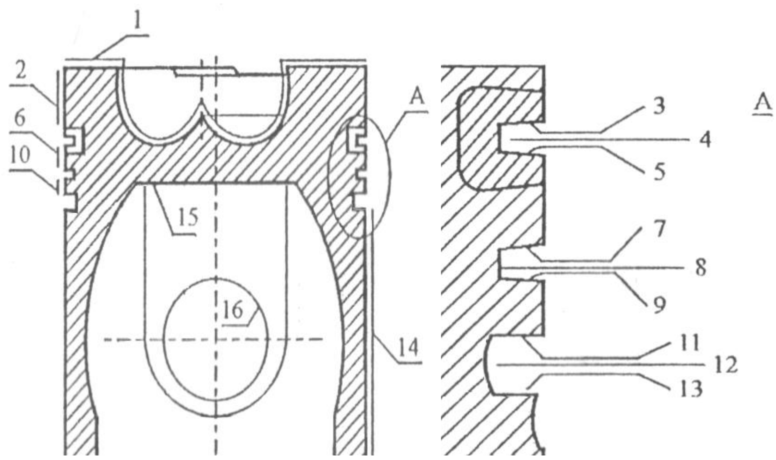
3. MODELLING OF THERMAL STRESSES OF AN ENGINE PISTON

After starting the engine, the piston heats up until it reaches a state of equilibrium, which results from the balance between the heat taken from hot gases in the combustion chamber and transformed into useful work, and the heat transferred to the environment by, among others, the coolant and the combustion gases. Determination of thermal stresses of the piston by means of modelling requires the assumption of equations and mathematical expressions for the calculations, describing the process of heat exchange in such a way that the model is able to reflect the actual processes occurring on the characteristic surfaces. This model was created for the piston on the basis of the differential equation of the heat flow in solids.

$$\frac{\partial T}{\partial t} = a\nabla^2 T + \frac{1\partial\lambda}{c_p\rho\partial T}\left[\left(\frac{\partial T}{\partial x}\right)^2 + \left(\frac{\partial T}{\partial y}\right)^2 + \left(\frac{\partial T}{\partial z}\right)^2\right] + \frac{q_v}{\rho c_p} \tag{2}$$

where:
a = coefficient of temperature compensation,
c_p = specific heat capacity at constant pressure [J/kgK],
ρ = density [kg/m^3],
T = temperature [K],
q_v = volumetric efficiency of the internal heat source [W/m^3],
λ = thermal conductivity [W/mK].

The numerical calculations of the stresses were performed by means of the COSMOS/M program based on the knowledge of the temperature distribution for assumed operating conditions of the studied engine. In the program, an actual three-dimensional discrete geometric model of the piston was created based on the real component. In the model, 16 characteristic surfaces of the piston were distinguished, for which the temperature distributions and specific values of type III boundary conditions (Fourier conditions) were determined. These conditions determine the temperature of the medium surrounding the piston and the heat transfer coefficients of the characteristic surfaces. These surfaces are shown in Figure 7 [4].



Surface of:
1 – piston head
2 – side of the piston over ring I
3 – top surface of ring groove I
4 – groove bottom of ring I
5 – lower surface of ring groove I
6 – between rings I and II
7 – top surface of ring groove II
8 – groove bottom of the ring II
9 – lower surface of ring groove II
10 – between rings II and III
11 – top surface of ring groove III
12 – groove bottom of ring III

Fig. 2. Characteristic surfaces of the piston

For individual piston surfaces, the conditions of heat exchange equivalent to those in the combustion chamber for each cycle of the engine were assumed in the calculations. Based on the recorded indicator diagrams and the calculated total heat transfer coefficient, the temperature of the working medium surrounding the combustion chamber and the values of the heat transfer coefficient for the engine speed of n=2,000 min-1 and speed of n=4,250 min-1 were determined [2-5]. Figures 3, 4, 5 and 6 show the exemplary values of thermal stresses of the piston during a non-stationary heat flow, corresponding to 10 and 20 seconds of engine operation measured from its start-up.

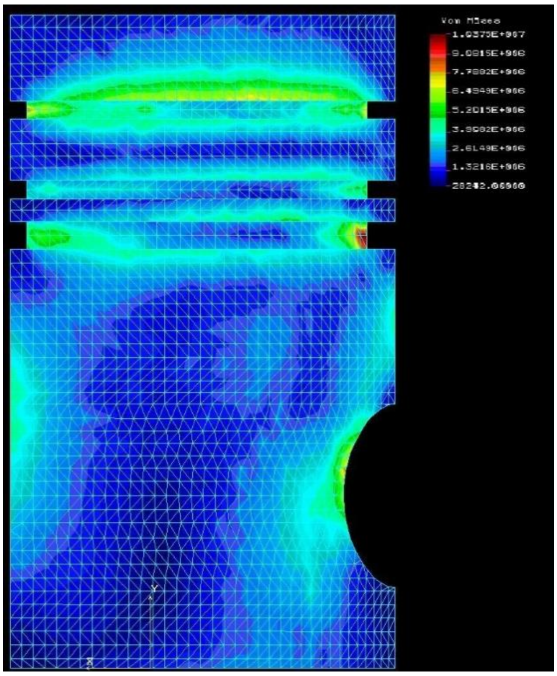


Fig. 3. Thermal stresses of the piston after 10 seconds for n=2,000 min^{-1}, λ=1.66

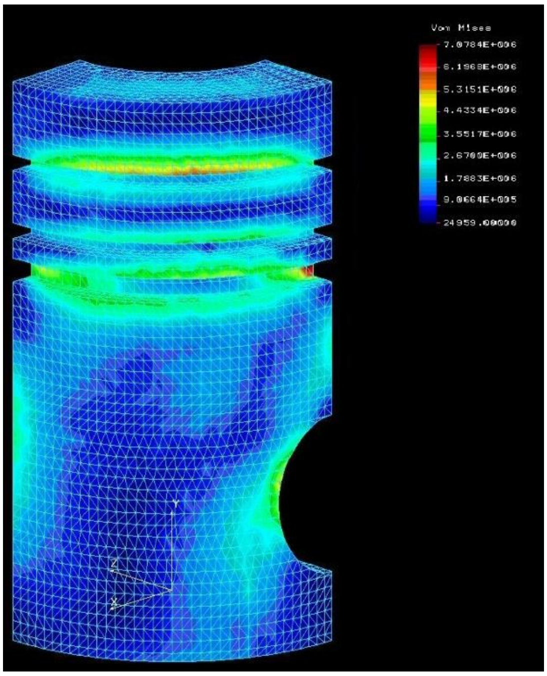


Fig. 4. Thermal stresses of the piston after 10 seconds for n=4,250 min^{-1}, λ=1.69

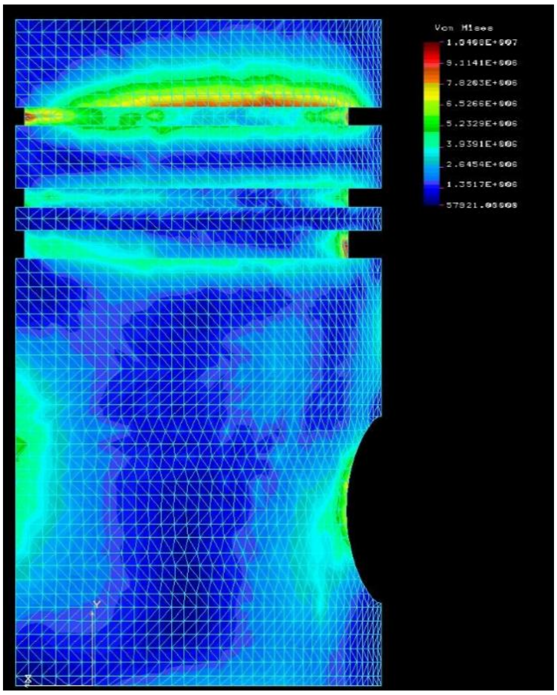


Fig. 5. Thermal stresses of the piston after 20 seconds for n=2,000 min^{-1}, λ=1.66

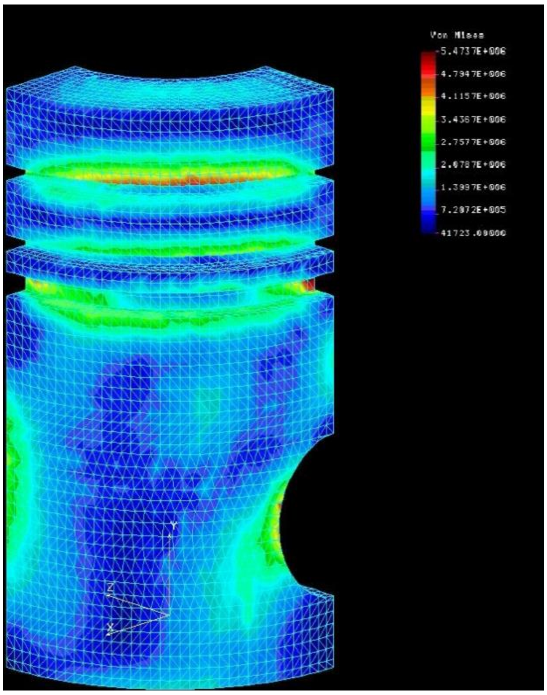


Fig. 6. Thermal stresses of the piston after 20 seconds for n=4,250 min^{-1}, λ=1.69

4. CONCLUSION

Based on the preliminary results of the calculations, it can be concluded that maximum values of thermal stresses of the piston are found mainly in the ring portion and on the surface of the piston head. On the other hand, the lowest values are found in the guide part. The obtained maximum values of thermal stresses for the engine speed of n=2,000 min-1, where λ=1.66, are bigger than thermal stresses for the engine speed of n=4,250 min-1, where λ=1.69. According to the authors, the thermal stresses represent an important factor, together with mechanical stresses, in the design and subsequent operation of the piston for a specified model and type of engine. However, the calculations should be verified experimentally in order to obtain the results of numerical calculations, which ought to correspond with real thermal stresses in the engine during the warming-up stage in the future [7].

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