

Numerical analysis of the influence of engine speed on the cylinder thermal stresses in supercharged diesel engine

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Abstract. The paper presents the numerical analysis of the influence of rotational speed of supercharged diesel engine with direct fuel injection to combustion chamber in the initial phase of its working on course of thermal stresses in the cylinder sleeve. Numerical calculations were based on the achieved data concerning the material and physical properties of the material which was used to prepare the cylinder as well as the experimental tests of the engine conducted earlier. The calculations were conducted with the use of original (two-zoned) model of combustion process, boundary conditions type III and finite element method (FEM) with the use of Cosmos/M program. The analysis was conducted on the characteristic surfaces of the cylinder sleeve. The results of the numeric calculations confirm the possibility of application of the assumed modelling method in the combustion process and the earlier made assumptions for the analysis of the values of distributions of the occurring thermal stresses on different surfaces of the cylinder and for different operational conditions of the engine.

1. Introduction

The development of the piston combustion engines is characterised with the increase of the unit power and, what is more, the rotational speed and effective pressure enhances due to the increase of their charging pressure. In the diesel engines the aim is to decrease the air excess ratio. The main aim of modernising engines is to increase their power while maintaining the same of slightly changed construction solutions. However, it is connected with the increase of mechanical and thermal load of the parts which surround the engine combustion chamber [7,10]. Thermal loads of the parts surrounding the combustion chamber of piston engine depend on the exploitation conditions. Most traction engines work in conditions which change in wide ranges. Other engines work close to their maximum loads. Heat loads can be influenced by the mean effective pressure, supercharging pressure, air excess ratio, rotational speed, advance angle of injection or ignition, temperature and flow intensity of the coolants. Those factors influence the heating and cooling conditions of the analysed parts. If the construction shapes do not change, the temperature of the parts surrounding the combustion chamber depends on: the average temperature of working medium, average heat transfer coefficient on the side of working medium, the temperature of the cooling medium and the heat transfer coefficient on the side of cooling medium. The temperature of the parts surrounding the combustion chamber grows together with the average temperature increase of the working medium and the average heat transfer



coefficient from the working medium. Those values grow together with the increase of average effective pressure, supercharge pressure, temperature of drawn air and decrease of air excess ratio. Together with increase of rotational speed the heat transfer coefficient increases [11]. Thermal stresses occur in construction elements as a result of temperature changes of a given part with simultaneous limitation of possibility to change its dimensions by other elements of the system. Those stresses exist without any external load of given part but only as a result of temperature change which caused the change in dimensions of the part - the phenomenon of thermal expansion. There are not many publications on the topic of the influence of exploitation factors, including rotational speed on forming the thermal loads on the combustion chamber parts. In literature there is a lot of information on the temperature values distributions in the elements of combustion chamber which allow for direct assessment of the heat load of chosen surfaces of engine parts. However, the information connected with distribution of thermal stresses, which are consequences of the above, are seldom to be found. Therefore, tests and numerical calculations were conducted on the influence of engine rotational speed with the same load on the value and distribution of thermal stresses in dry cylinder sleeve of supercharged diesel engine in the initial phase of its working.

2. Modelling of the thermal stresses in engine cylinder

The analysis of the rotational speed influence on the thermal stresses distribution in cylinder sleeve required modelling of the thermal loads of the cylinder [1,5,8,9]. Calculations were conducted with the use of variables and mean values of boundary conditions of III kind Fourier's. Those conditions are described with temperature of working medium and total heat transfer coefficient marked among others on the basis of Woschni dependency. In order to mark this coefficient it was also necessary to determine the coefficient which takes into account both the convection and the radiation of the flame. Temperature course of working medium for the whole cycle of engine operation was marked with the use of two-zoned model of combustion process on the basis of measured indication pressure course for two rotational speeds (fig.1 and 2) and the rest of the thermodynamic changes occurring in the engine combustion chamber [4].

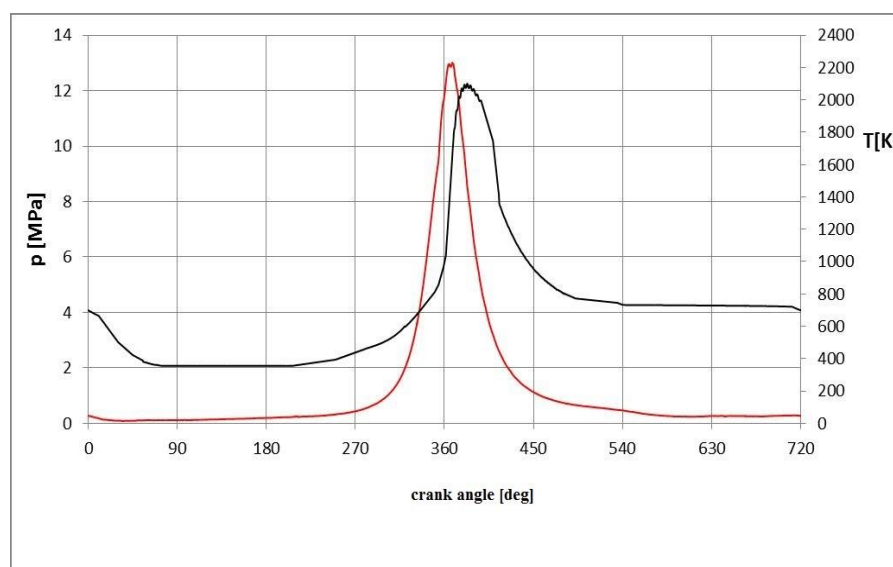


Figure 1. Course of measured pressure and calculated temperature in supercharged diesel engine with nominal power of $N = 85$ [kW] for rotational speed $n = 2000$ [min^{-1}]

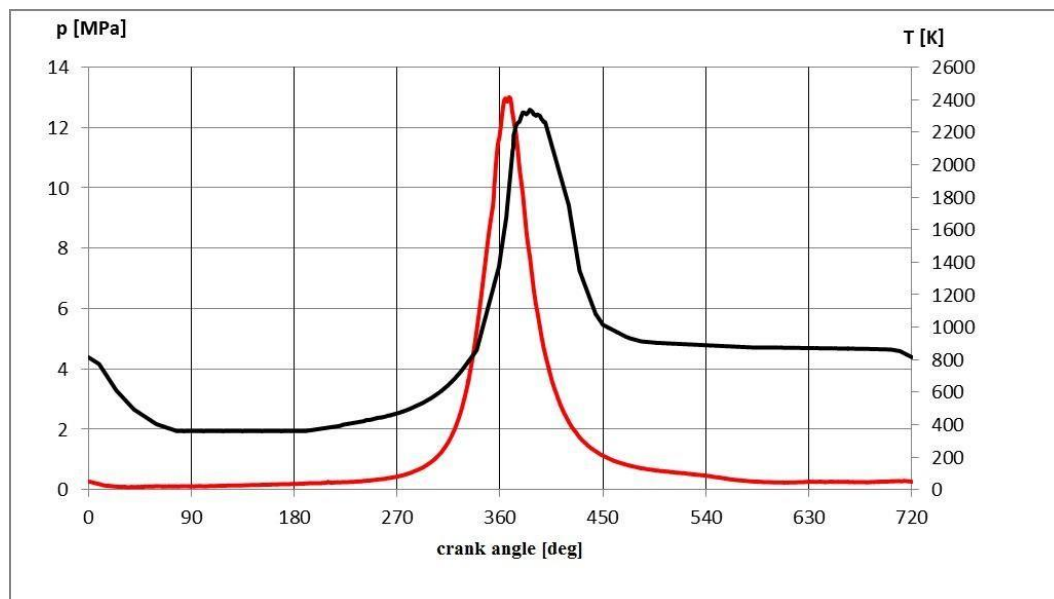


Figure 2. Course of measured pressure and calculated temperature in supercharged diesel engine with nominal power of $N = 85$ [kW] for rotational speed $n = 4250$ [min^{-1}]

The analysis of the influence of rotational speed on the value and distribution of thermal stresses was conducted in the initial phase of engine work to the moment when the temperature of the sleeve was equal to surrounding temperature till time when thermal loads in the cylinder changed only slightly. Modelling of the heat transfer process in diesel engine required making a division of the cylinder sleeve into four characteristic surfaces [6] which are: side face of the cylinder, cylinder bearing surface, cylinder embedment and below the cylinder lock. Next, the surfaces were sub-divided into certain areas. From the side face the heat flows towards the cooling liquid jacket in the head and as a consequence the conditions of heat transfer are reduced to the water jacket of engine head. On the surface of cylinder bearing surface, however, the conditions of heat transfer are variable in cycles. In the upper area the surface has contact with combustion gases in combustion chamber and in the lower area there is a heat transfer with piston rings, also through convection with combustion gases which flow through sealing devices.

On the outer surface of the cylinder embedment, which is cooled, the heat flow is dependent on the mean length of heat flow path from the sleeve embedment surface to water jacket and the thermal conductivity of the engine block material. In the area of surface below the cylinder lock the boundary conditions of heat transfer are reduced to the water jacket of engine block. The thickness of engine block between the sleeve and the cooling liquid has influence on the heat flow.

3. Results of numeric calculations of the influence of rotational speed on the value and distribution of heat stresses on the surface of the cylinder

The target of research on which the marking of thermal stresses distribution was conducted was the dry cylinder bearing surface of the five-cylinder, in-line, supercharged diesel engine with capacity of 2390 cm^3 with direct fuel injection to combustion chamber about nominal power 85 kW. The analysis was conducted for two rotational speeds $n = 2000 \text{ min}^{-1}$ and 4250 min^{-1} and for constant engine load, that is for the air excess ratio λ which equalled 1.69. In the initial stage of calculations the temperature values on the surface of cylinder sleeve were modelled in order to use them as the basis to mark its thermal stresses. Figure 3 shows the cylinder sleeve with its characteristic surfaces, and figure 4 shows the value and distribution of temperature on its surface after 60s of engine operation to the moment of its start-up.

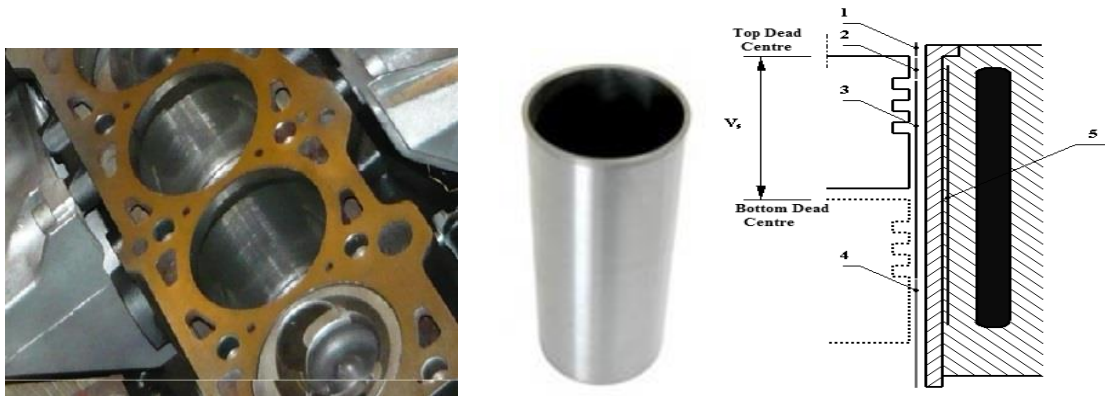


Figure 3. View of engine cylinder with its characteristic surfaces: 1- cylinder bearing surface from the side of engine combustion chamber, 2- cylinder bearing surface from the side of piston head in TDC to first ring, 3- cylinder bearing surface from the first ring of piston in TDC to the third ring in BDC of piston, 4- cylinder bearing surface below the third ring in BDC of piston, 5- cylinder sleeve from the side of coolant

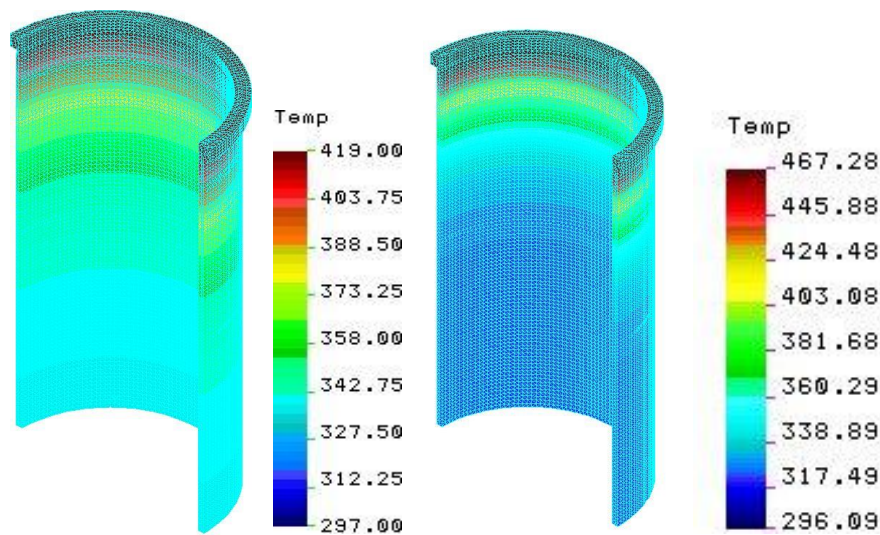


Figure 4. Temperature distribution on the surface of engine cylinder after 60 seconds for two speeds $n=2000 \text{ min}^{-1}$ and $n=4250 \text{ min}^{-1}$

The thermal stresses in the cylinder are caused by thermal loads of engine. In the analyzed cylinder it was assumed that its temperature at the moment of engine start up equals to the ambient temperature $T_0 = 273 \text{ K}$. Average temperature of cylinder after 60 seconds was about 400 K and the maximum was around almost 470 K for engine rotational speed of $n=4250 \text{ min}^{-1}$ and 420 K for engine rotational speed $n=2000 \text{ min}^{-1}$ [2,3]. The highest values of temperature occurred in the area near the upper edging ring of the cylinder and were decreasing up to its lower margin.

Finite element method with the use of program Cosmos/M was used to calculate the thermal stresses. In the conducted calculation, besides to the boundary conditions that have been accepted in the form of heat transfer coefficients and temperature for each characteristic surface of the cylinder (fig.3), there were many material data of the cylinder taken into account, such as Young's modulus, Poisson ratio and thermal expansion coefficient. In order to solve the task there was an equation (1) used, which enables to determine the fixed or non-fixed heat flow, both for linear and non-linear problem, taking into account the material properties depending on heat flow, convection or radiation in temperature and time function.

$$c_p \rho \frac{\partial T}{\partial t} = \frac{\partial}{\partial x} \left(\lambda_m(T) \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left(\lambda_m(T) \frac{\partial T}{\partial y} \right) + \frac{\partial}{\partial z} \left(\lambda_m(T) \frac{\partial T}{\partial z} \right) \quad (1)$$

where:

$T = T(x, y, z, t)$ - temperature,

t - time,

c_p - specific heat capacity at constant pressure,

ρ - density of material,

$\lambda_m(T)$ - thermal conductivity of the material

Results of the conducted calculations for two rotational speeds in time of 5, 20, 40 and 60 seconds of engine working are presented in figures 5, 6, 7 and 8.

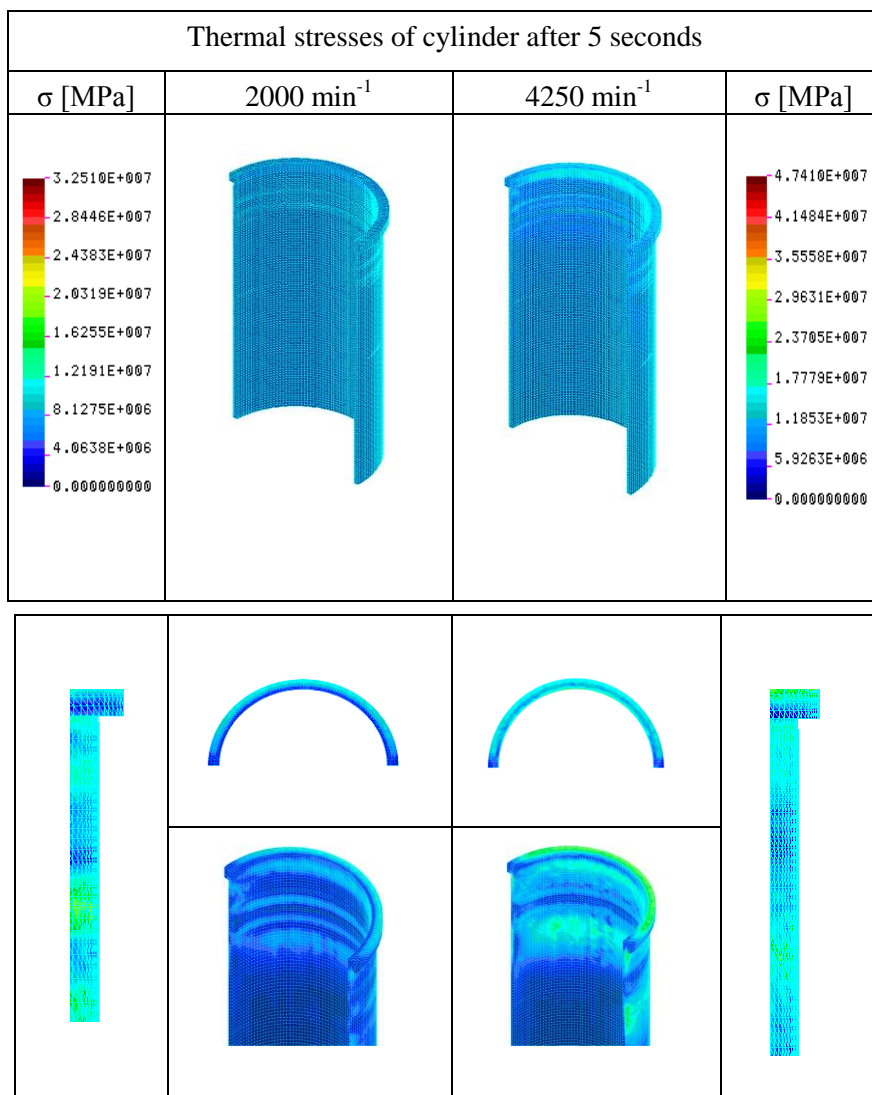


Figure 5. Distribution of thermal stresses on the surface of cylinder for engine heating time $t=5s$

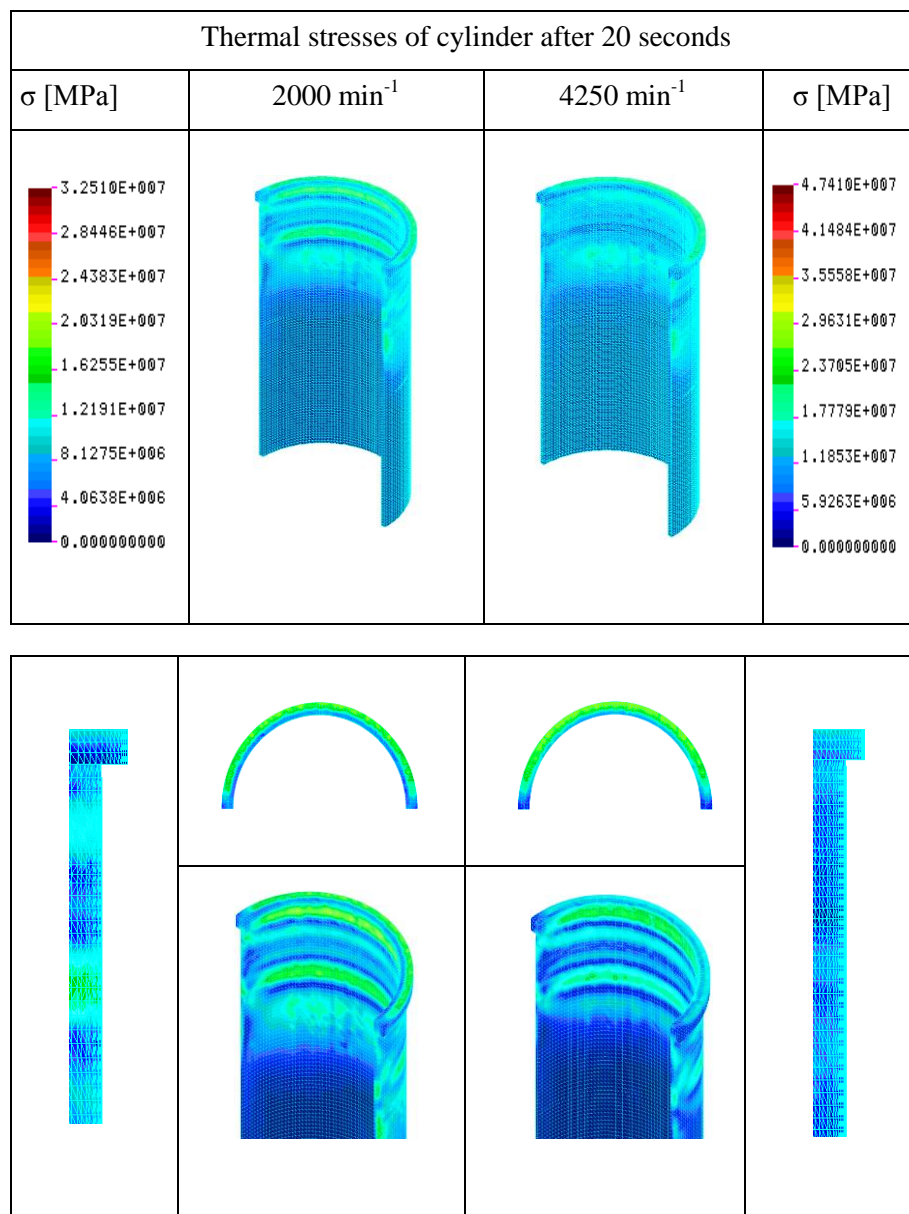


Figure 6. Distribution of thermal stresses on the surface of cylinder for engine heating time $t=20s$

Achieved values of the maximum stresses are on the level of about 25 MPa for the speed $n=4250 \text{ min}^{-1}$ and 15 MPa for the speed $n=2000 \text{ min}^{-1}$ after 20 seconds engine working. Moreover it can be observed a noticeable faster increase in thermal stresses for the higher engine speed on the upper surface of the cylinder.

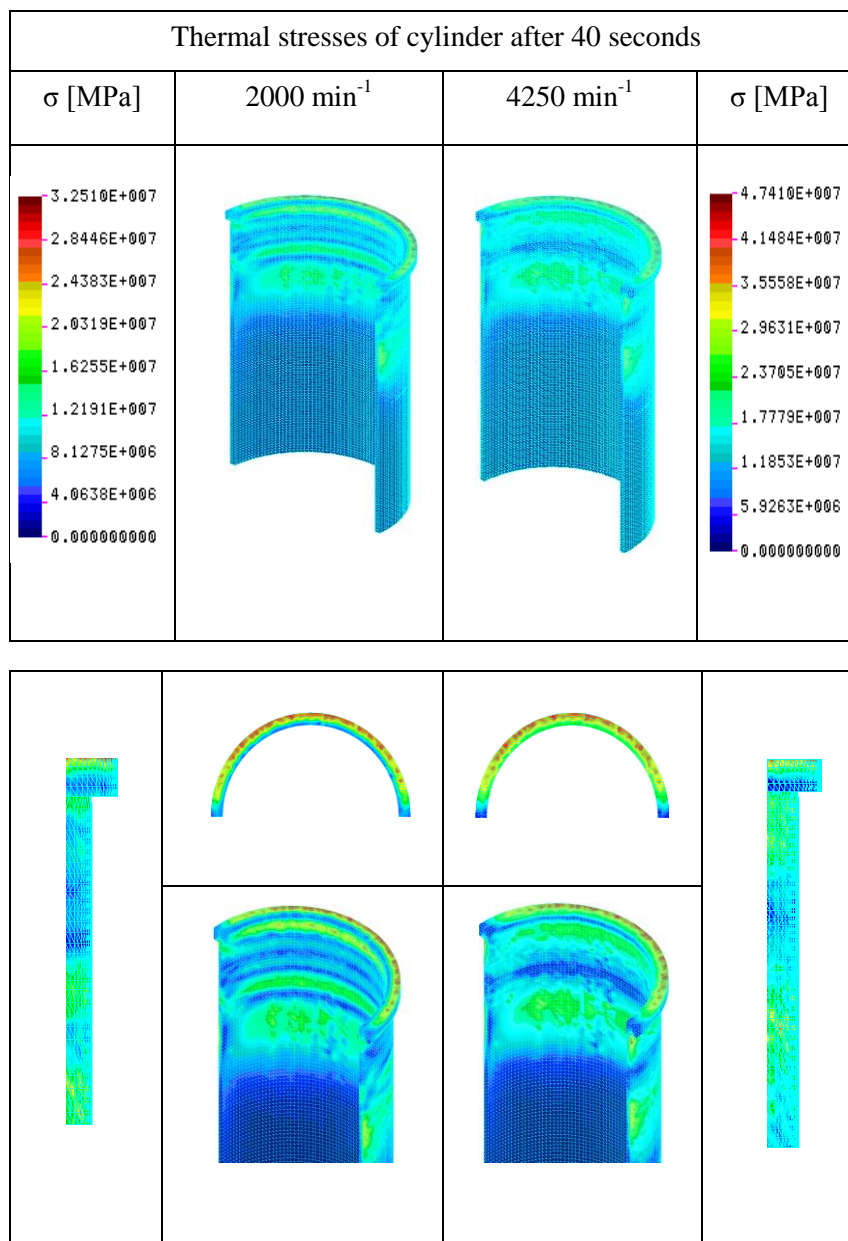


Figure 7. Distribution of thermal stresses on the surface of cylinder for engine heating time $t=40s$

As it was to be expected even more thermal stresses appeared on the upper surface of the cylinder after the next 20 seconds of warming up the engine. The maximum stresses values were about 40 MPa for engine speed $n=4250 \text{ min}^{-1}$ and 25 MPa for $n=2000 \text{ min}^{-1}$ after 40 seconds of engine working.

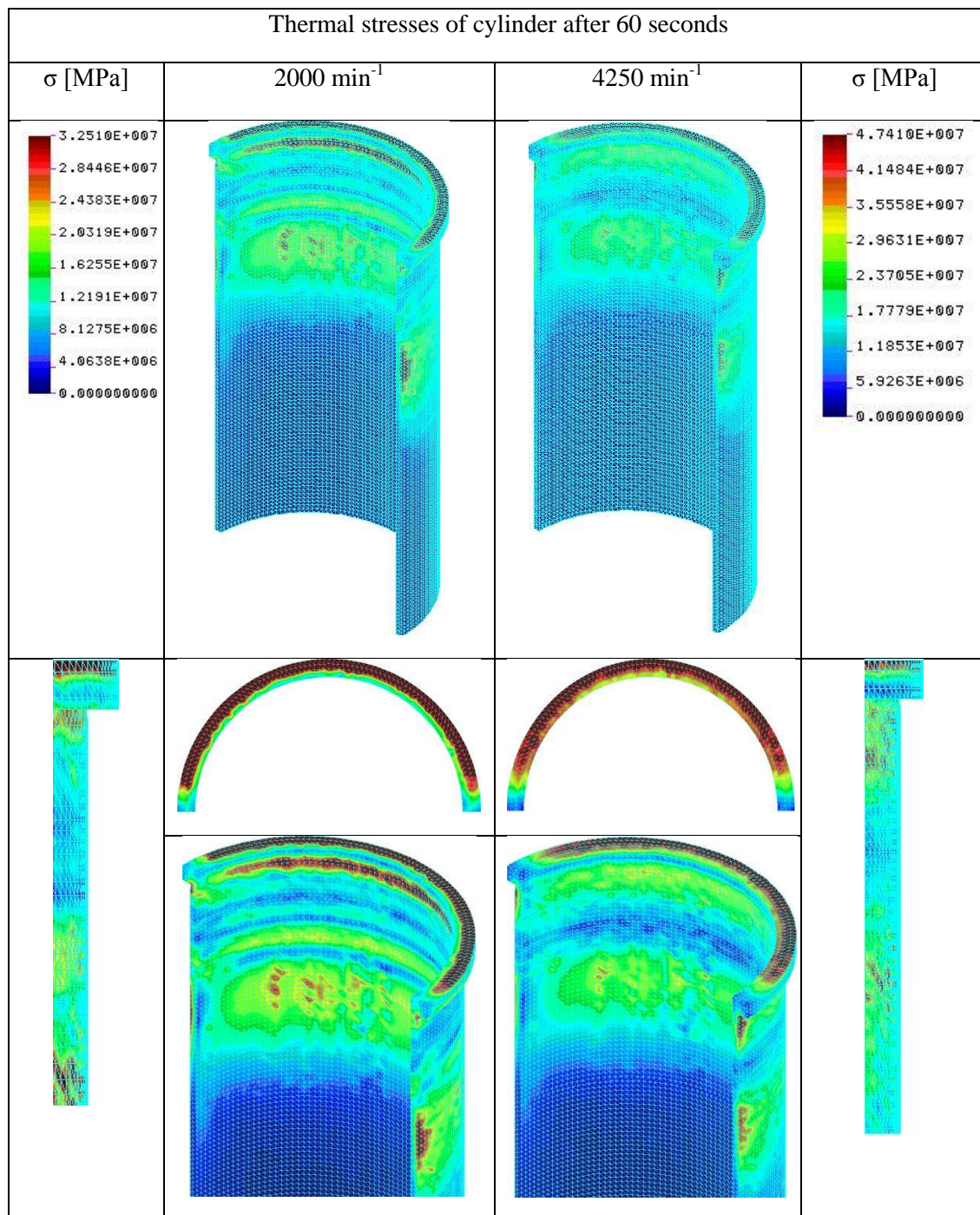


Figure 8. Distribution of thermal stresses on the surface of cylinder for engine heating time $t=60s$

After a next 20 seconds of engine working it can noticed a further increase of thermal stresses of the cylinder which cover the more larger areas. They can be observed particularly strongly on the upper surface from side of the combustion chamber and the cylinder surface from the side of the piston head at its Top Dead Centre (TDC).

On the basis of achieved results there were graphs (fig.9 and 10) prepared which show the courses of maximum stresses and changes of increments of maximum stresses occurring on the surfaces of modelled cylinder sleeve of engine.

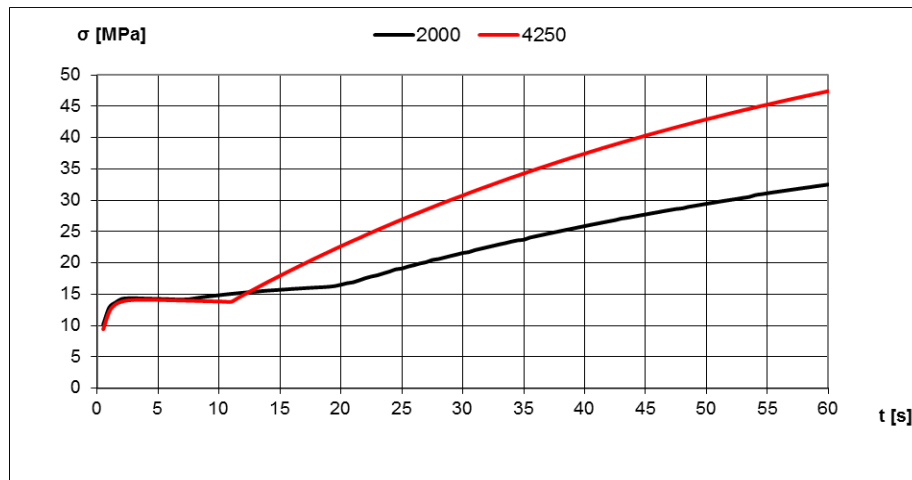


Figure 9. Course of maximum stresses values occurring on the surface of engine cylinder for two speeds $n=2000 \text{ min}^{-1}$ and $n=4250 \text{ min}^{-1}$

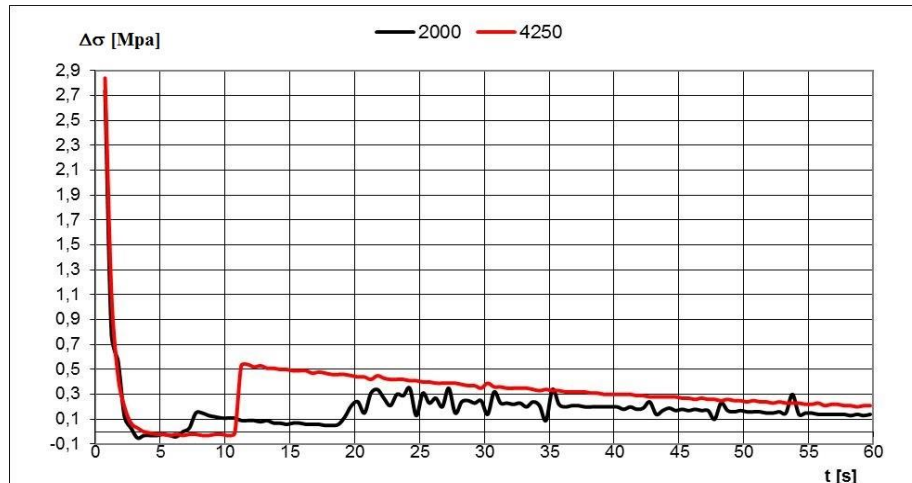


Figure 10. Course of changes of increments of maximum thermal stresses on the surface of engine cylinder for two speeds $n=2000 \text{ min}^{-1}$ and $n=4250 \text{ min}^{-1}$

It was stated after conducted calculations and analysis of the achieved results that there almost a doubled increase in rotational speed of engine, with the same load, causes an increase in thermal stresses of cylinder as a result of increased thermal loads on the engine. Achieved values of the maximum stresses are on the level of about 50 MPa for the speed $n=4250 \text{ min}^{-1}$ and 35 MPa for the speed $n=2000 \text{ min}^{-1}$. The minimum values of stresses for both rotational speeds change very rapidly in the first 30 seconds of engine work. Immediately after starting the engine due to the temperature shock that the cylinder experiences the changes of maximum thermal stresses are greatest at the beginning and for the speed $n = 4250 \text{ min}^{-1}$ $\Delta\sigma = 2,84 \text{ MPa}$, while for $n = 2000 \text{ min}^{-1}$ equal about 2,74 MPa. Later they are stabilizing.

Moreover average values of speed increase of thermal stresses are also bigger for the speed $n=4250 \text{ min}^{-1}$ and equal around 0.65 MPa/s whereas for the speed of $n=2000 \text{ min}^{-1}$ they equal almost 0.4 MPa/s.

4. Conclusions

It can be concluded, on the basis of conducted calculations that the rotational speed has influence on heat stresses distribution. Average thermal stresses from the whole surface of the engine cylinder for the speed $n=4250 \text{ min}^{-1}$ reach higher values than for the speed $n=2000 \text{ min}^{-1}$. For higher rotational speed they reach values of about 24 MPa and for slower speed the values on the level of around 16 MPa. It can also be noticed that the thermal loads are unevenly distributed on the surface of cylinder bearing. Those stresses are distributed the fastest and in biggest amounts in the upper and middle areas and in the slowest way and in the smallest amounts on the surface located below the third ring in Bottom Dead Centre (BDC) of the piston. Thermal stresses may be helpful during the assessment of the thermal load of the combustion chamber, although they do not serve as direct assessment of thermal load, which is temperature. The values of the highest stresses are observed in the area of the edging ring and in the ring areas in cylinder sleeve. The fastest changes in maximum thermal stresses occur in initial 30 seconds of engine working from the moment of its start-up.

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