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MECHANICAL AND THERMAL STRESSES ISSUES RELATED TO A SIZE OF A FOUR-STROKE PISTON BASED ON A RENAULT PREMIUM DXI11 430 460 EEV ENGINE

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Abstract

The size of an engine is one of the factors affecting its thermal efficiency. It is known that with an increase of the size of the engine, the cubic capacity and heat generation grows in the third power, whereas thermal losses are proportional only to the second power of the size (due to heat exchange surface). However, the increase in the size of the engine generates some problems related to its mass, rotational speed and heat load, the last of which is a subject of these considerations. In the article, the influence of the piston size on its thermal and mechanical stresses is considered. Similar boundary conditions for both cases were assumed. Simulation of the steady-state heat transfer and mechanical simulation were carried out using the Finite Element Method. In each analysis, both the original version of the piston and its scaled version were considered. The boundary conditions were adopted on the basis of engine catalogue data and available literature. The results of analyses were discussed.

Keywords: *heat transfer, temperature distribution, four-stroke engine piston, finite element method, size related issues*

1. Introduction

Renault Premium DXi11 460 EEV (Fig. 1) is an engine of power 460 hp at rotational speed of 1,800 rpm and torque of 2,200 Nm at 950-1,400 rpm (Fig. 2). Displacement volume of its 6 cylinders is 10.836 dm^3 and compression ratio is 18.3:1. It is well-tested and proven construction widely used in long distance trucks [4].

Renault Premium piston was 3D scanned and described in publication ”Analysis of Thermal and Mechanical Stresses of Renault Premium DXi11 460 EEV Four-stroke Piston” [3]. Geometry of piston and assumed material remain the same as briefly presented in Tab. 1 [1] and Fig. 3.

Fig. 1. Engine view

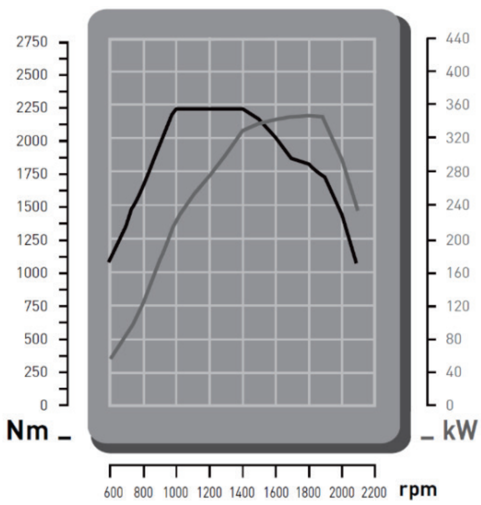

Fig. 2. Characteristic chart of Renault Premium DXi11 460 EEV engine

Tab. 1. Properties of 40 HM steel

T [ºC]	E [GPa]	ν [–]	λ [W/m^{2}K]	CTE [μm/m]	$Re_{0.2}$ [MPa]
20	220	0.3	33.5	12	415
200	195	0.3	33.9	12.7	370
400	175	0.3	34.1	1.36	340
600	155	0.3	34.5	1.44	180

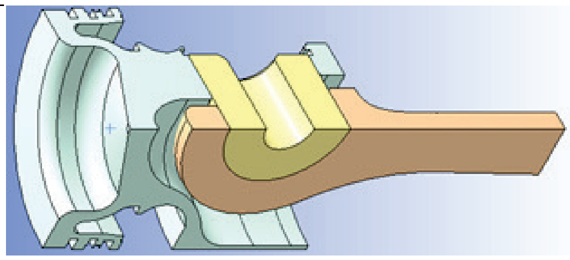

Fig. 3. Engine view DXi11 460 EEV piston

2. Boundary conditions

Thermal and mechanical boundary conditions were widely described in [3] as well. They are presented shortly in Fig. 4 as well as in Tab. 2-4. Symbols α_1 and T_1 stand for mean convection heat transfer and temperature inside a cylinder. They were calculated via AVL Boost simulation and Hohenberg formula [2]. Convection coefficients α_2, α_3 and α_4 were assumed basing on Wiśniewski publication [5]. Temperatures T_2, T_3, T_4 (which are functions of distance measured along a cylinder axis from the highest piston point) and coefficient α_2 were assumed basing on authors' experience. Thermal conductance in a piston – wrist pin – connecting rod system is assumed to be 2500 W/m^{2}K. It is also assumed that friction of the rings during its movement along cylinder wall generates heat of 91200 W/m^2, half of which is dispersed to piston rings. Assumed mechanical boundary conditions are presented in Fig. 5.

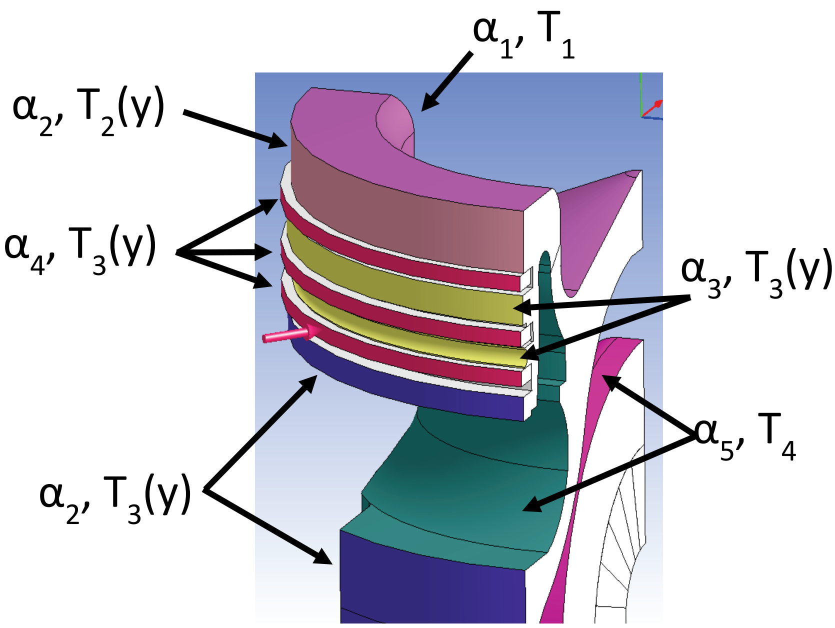

Fig. 4. Thermal boundary conditions

Tab. 2. Constant HTCs and temperatures

α_1	720.9 W/m^{2}K
T_1	869.7ºC
α_2	500 W/m^{2}K
α_3	750 W/m^{2}K
α_4	24 000 W/m^{2}K
α_5	1 000 W/m^{2}K
T_4	80ºC

Tab. 3. Upper piston wall reference temperature

y [mm]	0	-10
T_2 [ºC]	188.5	178.5

Tab. 4. Piston wall and rings reference temperature

y [mm]	0	-10	-20	-30	-40	-50	-60	-70	-80	-100	-120	-140	-160	-180
T_3 [ºC]	188.5	178.5	169.2	160.6	152.6	145.4	138.9	133.1	128.0	119.9	114.5	112.0	112.3	115.4

3. Finite Element Analysis results of bore diameter 123 mm

Stationary thermal analysis results in a maximum of 486ºC placed in a convex blended surface of a piston head. Heat transferred by piston is listed in Tab. 5. As it is supposed piston is heated mainly by contact with gases inside a cylinder – only a small part of heat is transfer from cylinder wall to cooler part of a piston. Main cooling phenomenon is a lubricant spread from crankcase resulting in piston temperature drop. Only ~17% of heat is left by a contact between piston rings and cylinder wall surface. Heat transfer and temperature distribution are visualised in Fig. 6 and 7.

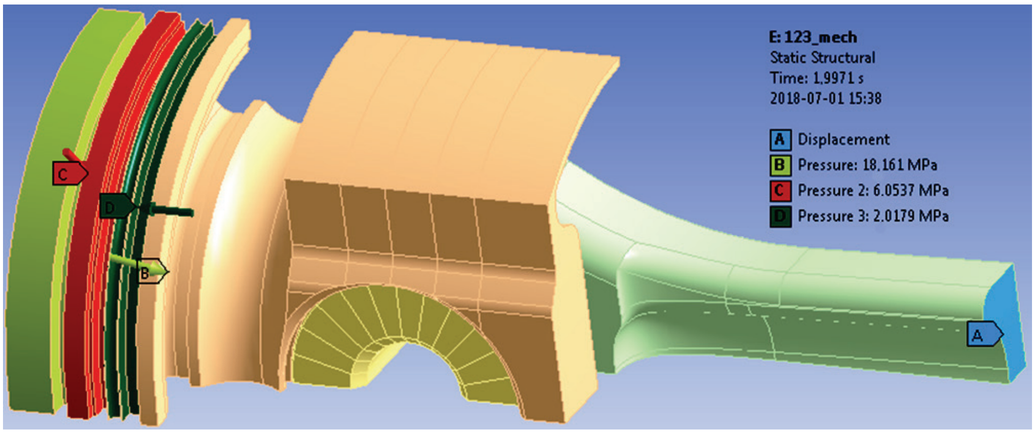

Fig. 5. Mechanical boundary conditions

Tab. 5. Heat transfer in piston of bore diameter 123 mm

Boundary condition		Heat transfer [W]	Relative heat transfer
α_1, T_1	Piston head	4,921.6	87.2%
α_2, T_2 (y)	Piston wall nearest to piston head	343.2	6.1%
α_2, T_3 (y)	Piston wall further to piston head	242.6	4.3%
α_3, T_3 (y)	Piston wall between rings	-54	-1%
α_4, T_3 (y)	Piston rings surface	-941.3	-16.7%
α_5, T_4	Convection by air and oil spread from crankcase	-4,646.4	-82.4%
Heat generated by friction of piston rings		134.1	2.4%

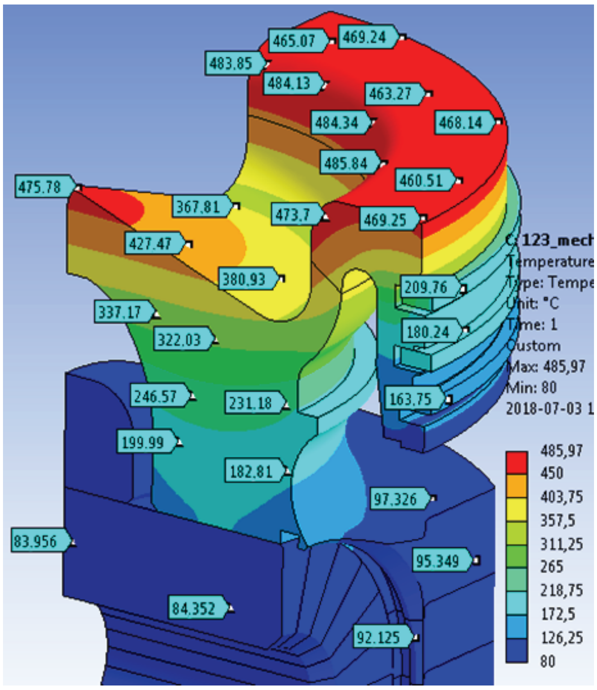

Fig. 6. Temperature distribution in a piston of diameter 123 mm

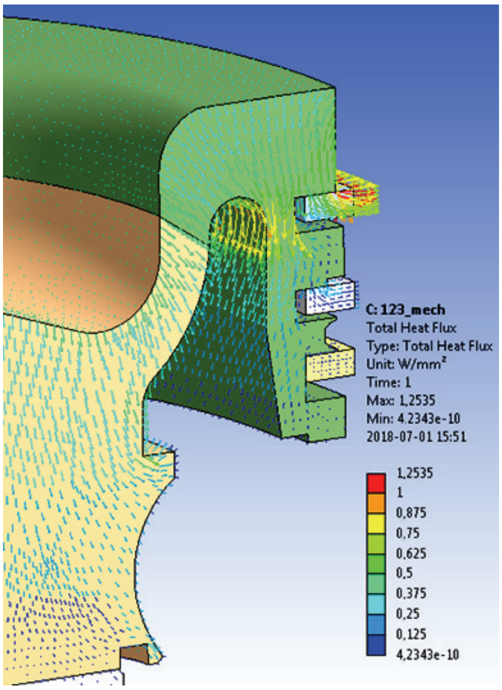

Fig. 7. Heat transfer in a piston of diameter 123 mm

The most mechanically loaded part is concave blend surface near to the fire ring groove. Equivalent stresses in these places vary from 230 to 580 MPa. The concave blend's in top piston surface equivalent stress varies from 250 to 330 MPa. Wrist pin is loaded to 389 MPa of equivalent stress during maximal pressure in cylinder. Thermal and mechanical stresses are presented in Fig. 8 and 9 [3].

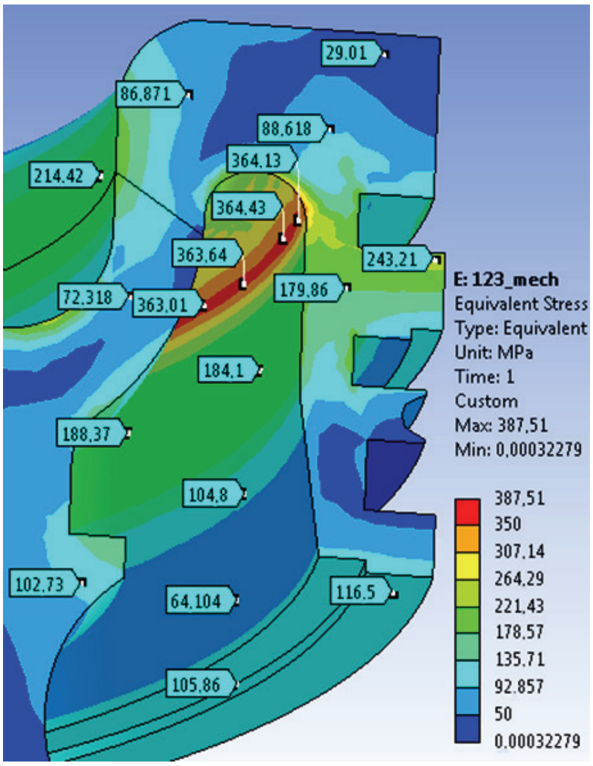

Fig. 8. Thermal stresses in a piston of diameter 123 mm

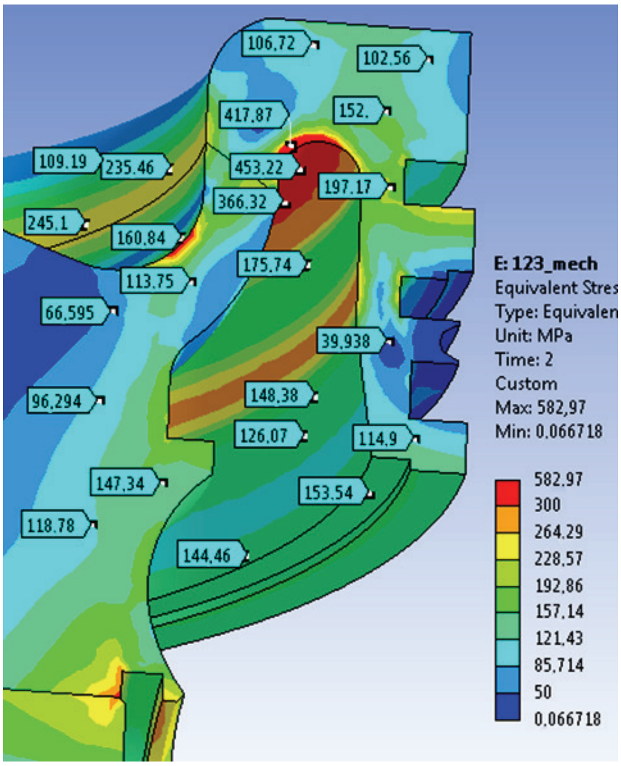

Fig. 9. Thermal and mechanical stresses in a piston of diameter 123 mm

4. Finite Element Analysis results of piston 200 mm

Thermal analysis of larger piston results in a maximum temperature of 544.6ºC placed in the same place as in previous case (Fig. 10). Heat transferred in piston is listed in Tab. 6 and graphically presented in Fig. 11. Relative values of heat transfer do not significantly differ from simulation of 123 mm piston.

Tab. 6. Heat transfer in piston of bore diameter 200 mm

Boundary condition		Heat transfer [W]	Relative heat transfer
α_1, T_1	Piston head	11,576.4	87.4%
α_2, T_2 (y)	Piston wall nearest to piston head	652.9	4.9%
α_2, T_3 (y)	Piston wall further to piston head	661.9	5.0%
α_3, T_3 (y)	Piston wall between rings	-96.5	-0.7%
α_4, T_3 (y)	Piston rings surface	-1,873.5	-14.1%
α_5, T_4	Convection by air and oil spread from crankcase	-11,276.4	-85.1%
Heat generated by friction of piston rings		335	2.7%

In case of bigger piston thermal equivalent stresses exceed significantly 300 MPa in two places, i.e. concave blend in the piston top and concave blend near to the fire ring groove. Moreover, area of high stresses is much larger than it was in case of 123 mm piston. Mechanical stresses combined with thermal stresses are as high as 638.9 MPa. In concave area at the piston, top surface stresses vary at 370-430 MPa during a cycle. In a concave area near to the fire ring stresses changes values in range 380-680 MPa. Wrist pin is still loaded to 389 MPa of equivalent stress. Fig. 12 and 13 presents thermal and thermal combined with mechanical stresses in a piston.

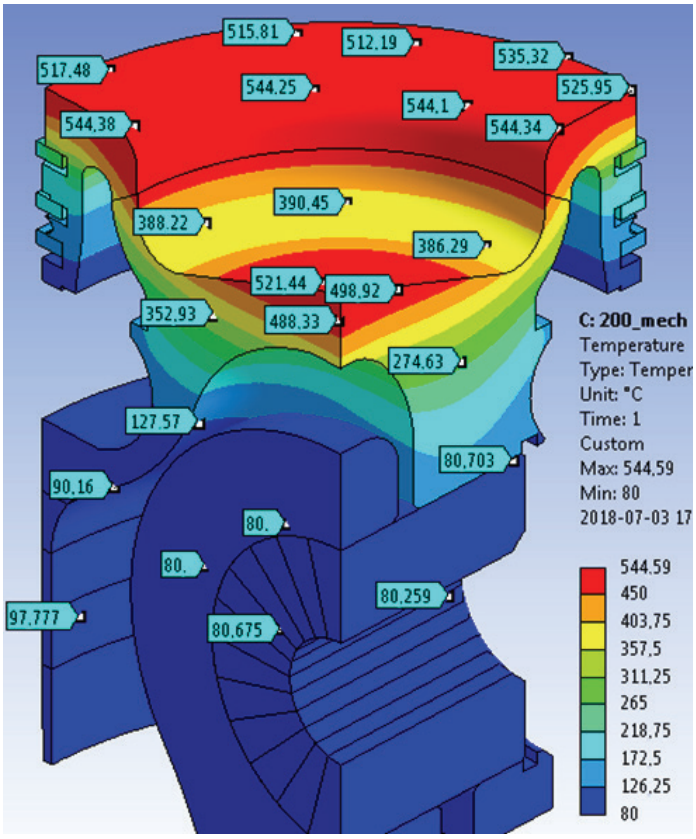

Fig. 10. Temperature distribution in a piston of diameter 200 mm

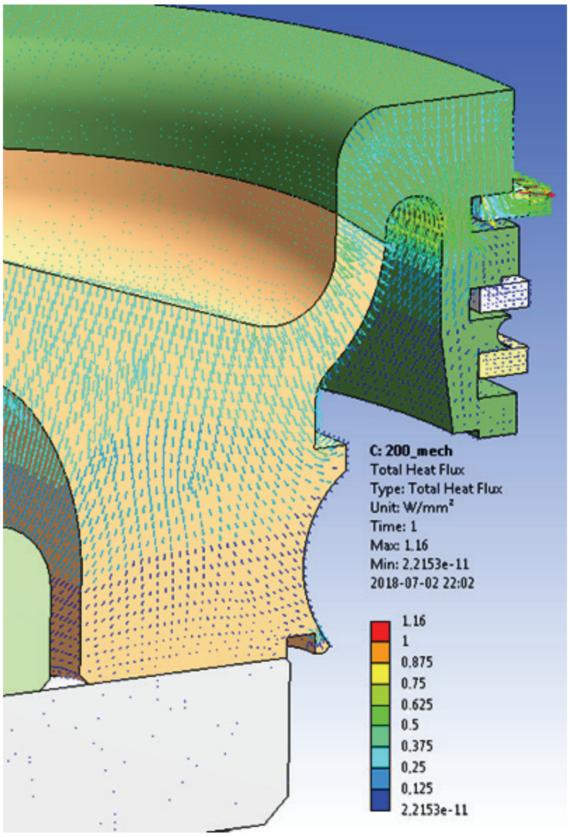

Fig. 11. Heat transfer in a piston of diameter 200 mm

5. Conclusions

Maximum temperature rises with resizing of piston from 123 mm to 200 mm. It is related to a simple fact that heat resistance of geometry rises with dimension. The simple resizing of a piston is not enough while redesigning it to larger engine.

Temperature of 545ºC is much too hot for assumed material. Its proof stress drops drastically in such a temperature. In fact even piston of diameter 123 mm is too much loaded for high-cycle fatigue while larger piston would have trouble to withstand only thermal stresses caused by its temperature.

Increase of piston size results also in small change of stresses distribution. While stresses in case of 123 mm piston was kind of regular, stress distribution in case of larger piston starts to differ along a piston circumference. It is directly related to non-rotational piston geometry.

Equivalent stresses in case of a wrist joint remain on the same level what could be explained by transverse shear stress at this place. Strength of a joint rises with second power of size while transverse force does as well.

Temperature distribution, thermal and mechanical stresses of 123 mm piston is compared to the same quantities in 200 mm piston are presented in Fig. 14, 15 and 16, respectively.

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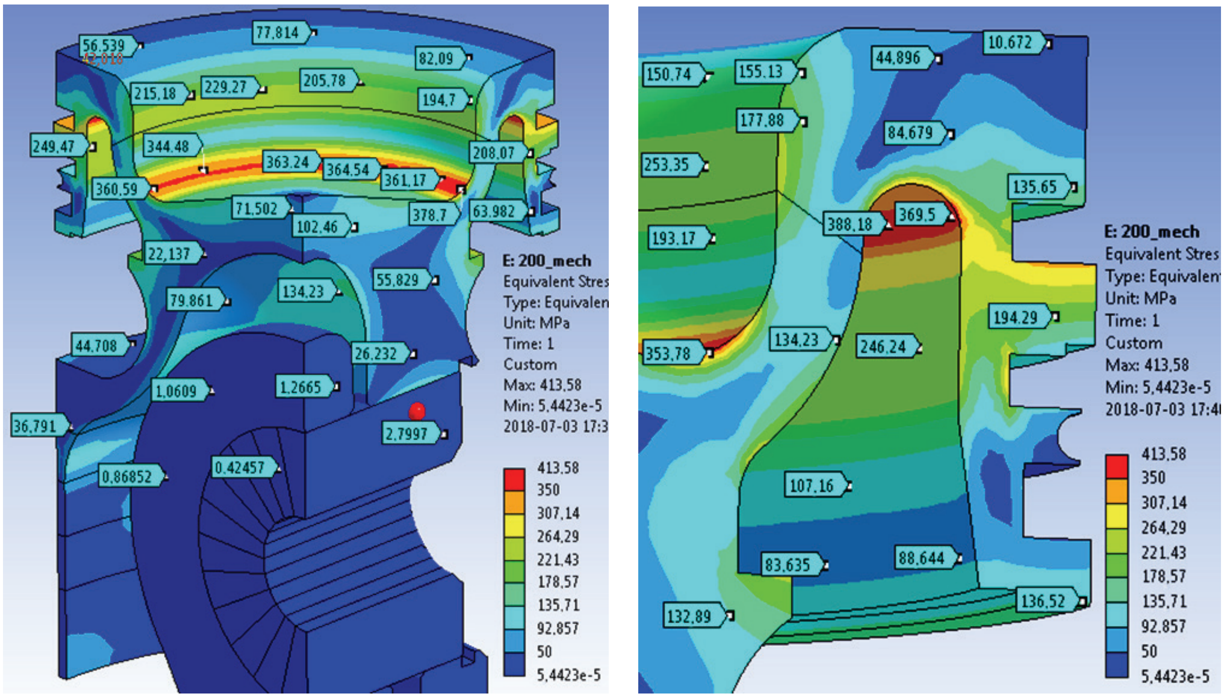

Fig. 12. Thermal stresses in a piston of diameter 200 mm

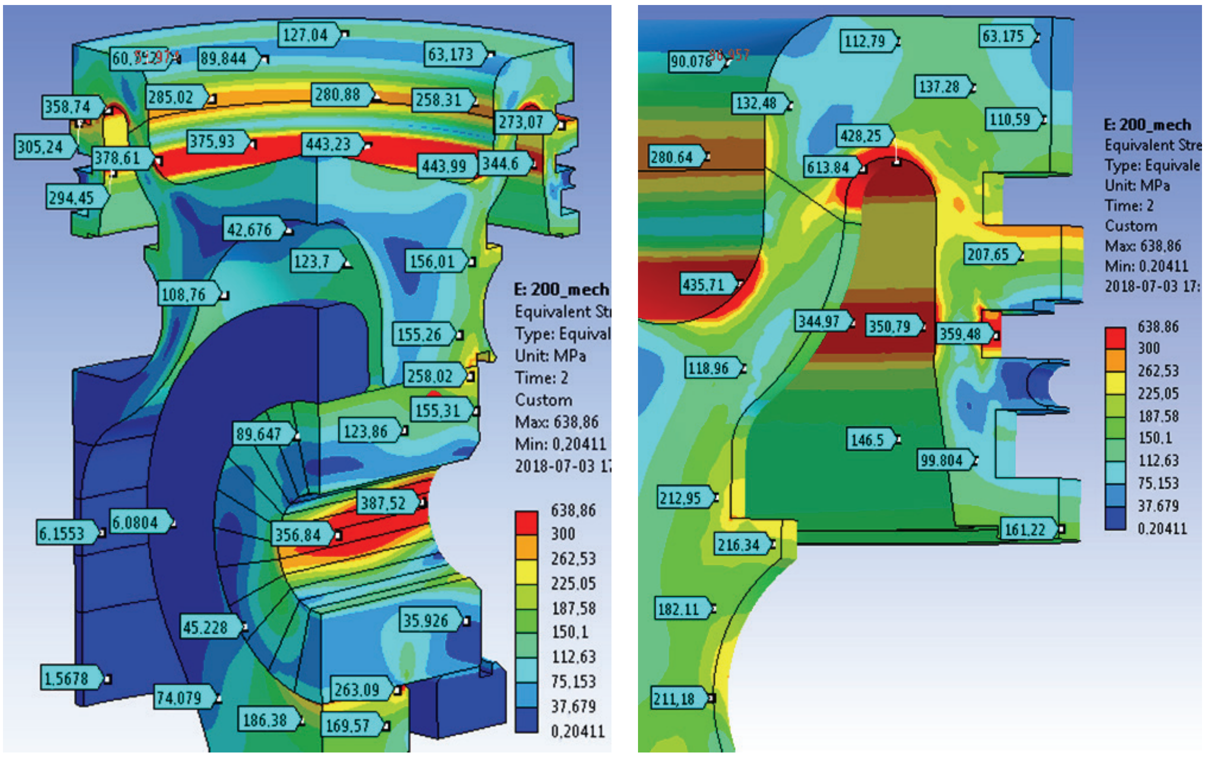

Fig. 13. Mechanical stresses in a piston of diameter 200 mm

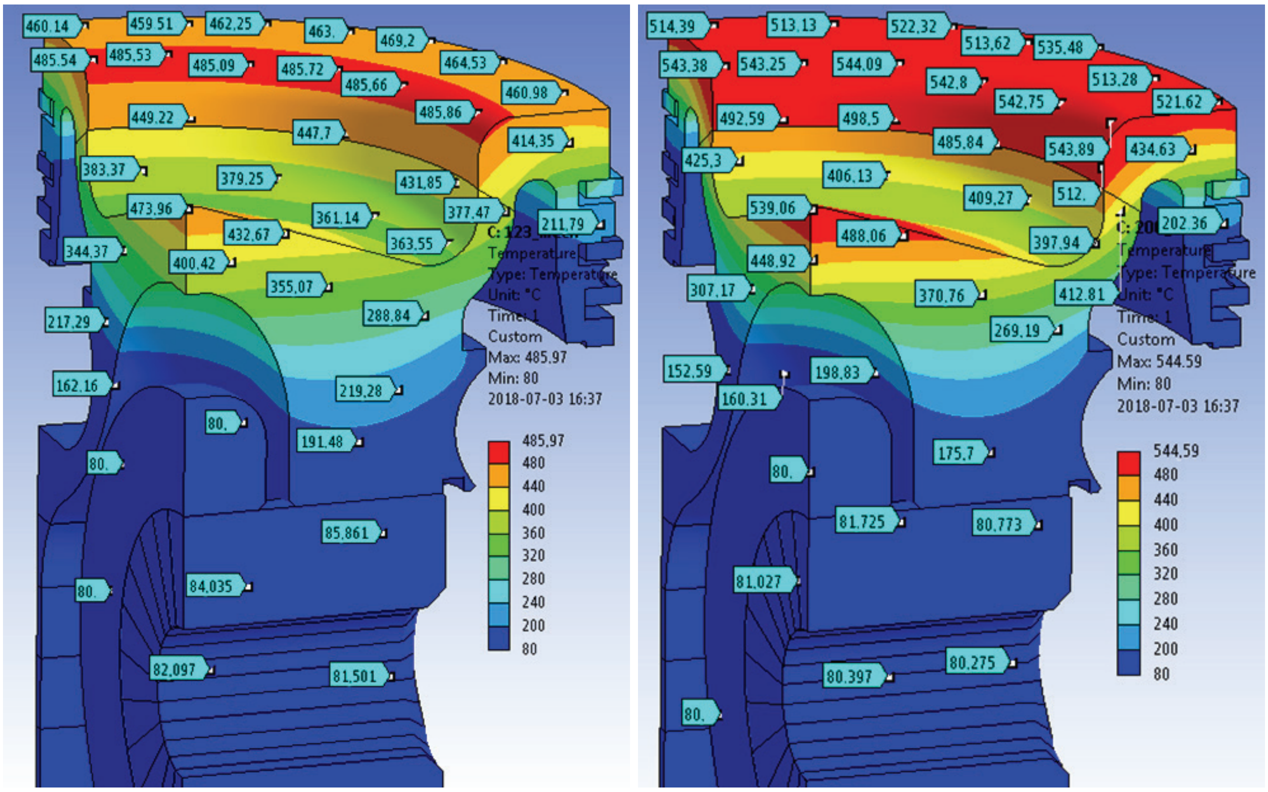

Fig. 14. Temperature distribution in a piston of diameter 123 mm (left) and 200 mm (right)

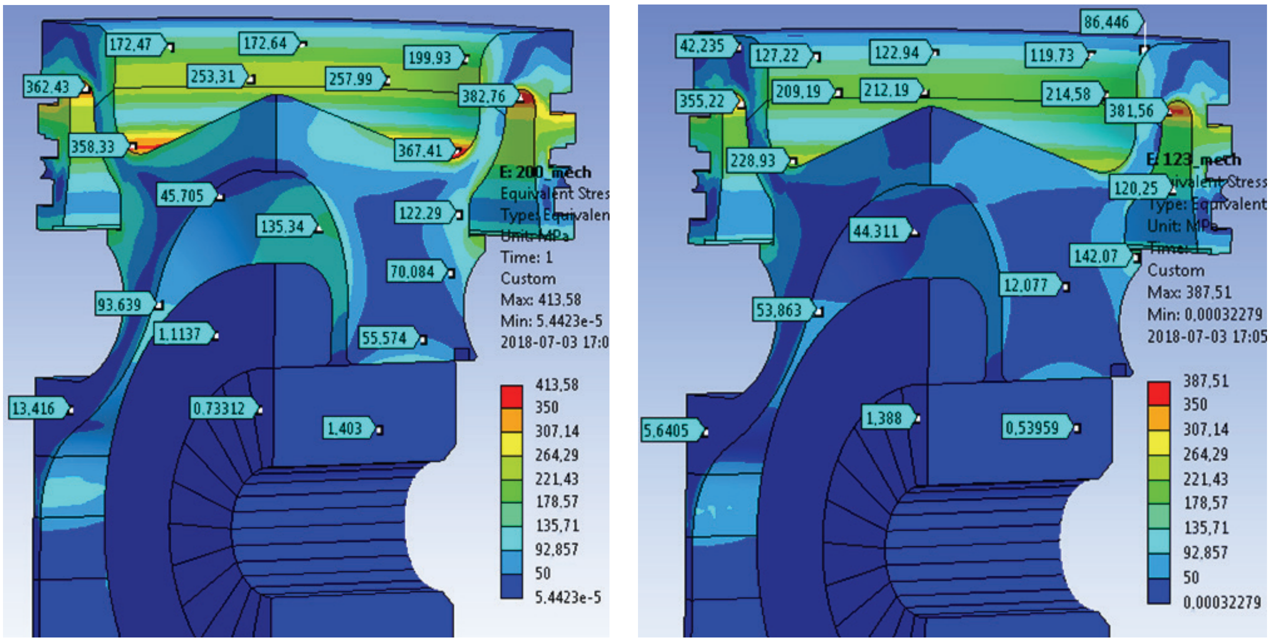

Fig. 15. Thermal and mechanical stresses in a piston of diameter 123 mm (left) and 200 mm (right)

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