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Unsteady state heat flow in the exhaust valve in turbocharged Diesel engine covered by the layer of the carbon deposit

A. Hornik*, D. Jędrusik , K. Wilk
Department of Automotive Vehicle Service, Faculty of Transport,
Silesian University of Technology, ul. Krasińskiego 8, 40-019 Katowice, Poland
* Corresponding e-mail address: aleksander.hornik@polsl.pl

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ABSTRACT

Purpose: The determination of the temperature distribution, temperature gradients and thermal stresses in the exhaust valve with using the layer of the carbon deposit in initial phase of the work of turbocharged Diesel engine.

Design/methodology/approach: The results of calculations of the temperature distribution, temperature gradients and thermal stresses in the exhaust valve of turbocharged Diesel engine with using the layer of the carbon deposit on the different surfaces of the valve were received by means of the two – zone combustion model and the finite element method.

Findings: The computations presented the possibility of use of the geometrical models of the layer of carbon deposit on the different surfaces of the exhaust valve and heat transfer on individual surfaces of the exhaust valve used by the variable values of the boundary conditions and temperature of working medium in initial time of the working engine.

Research limitations/implications: The modelling of thermal loads were carried out by analysing the temperature distribution, temperature gradients and thermal stresses in the exhaust valve in initial phase of the work of turbocharged Diesel engine.

Originality/value: The layer of the carbon deposit was used for modelling of thermal loads in the exhaust valve as the geometric model with the use of material properties. The results obtained allow to analyse distribution of temperature, temperature gradients and thermal stresses in the exhaust valve.

Keywords: Numerical Techniques; Heat loads; Carbon deposit; FEM

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METHODOLOGY OF RESEARCH, ANALYSIS AND MODELLING

1. Introduction

Modern internal combustion engines have to meet high requirements: parameters of technical exploitation, profitabilities of production and economics of the use and protection of the environment. One of the basic parameters of the technical service shall maintain adequate stability of power unit, which determines among others the size of the thermal load of the surrounding the combustion chamber. Exceeding of limit values for the thermal load of the combustion chamber in the engine: worsening work conditions, reduces work conditions, reduces the viability of the engine, in extreme cases can lead to the immobilisation of the engine.

One of the main factors negatively affecting the change in operating conditions for the exchange of heat in the combustion chamber is the carbon deposit. To one of the most loaded heat elements of the engine belong exhaust valves [1]. The modelling of the heat loads outlet valves were carried out on the basis of periodically changing boundary conditions of type III, which describe the surface film conductance α as well as the temperature *T* of the working medium (Fig. 1). The temperature of the working medium was marked on basis of measured course of the indicated pressure (Fig. 2) by means of the two-zone of combustion process in the turbocharged Diesel engine [2]. Analysis of thermal load in the exhaust valve was conducted based on the possibility of appearing of the layer of the carbon deposit on different surfaces of the valve by finite element method. The analysis of the heat loads in the valve for the engine speed n = 4250 rpm and the excess air number λ = 1.69 was carried out. Further information about the carbon deposit and the heat loads of the of the other engine components can be found in ref. [3-12].

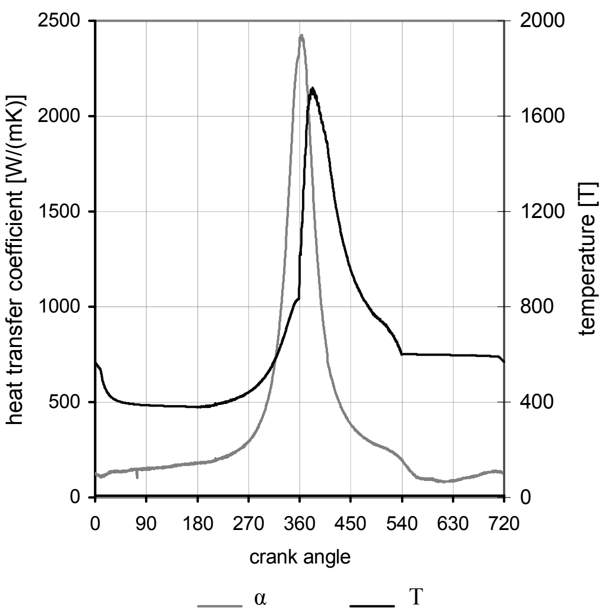


Fig. 1. The diagrams of average temperature of the working medium for engine speed n = 4250 [rpm] and λ = 1.69 [2]

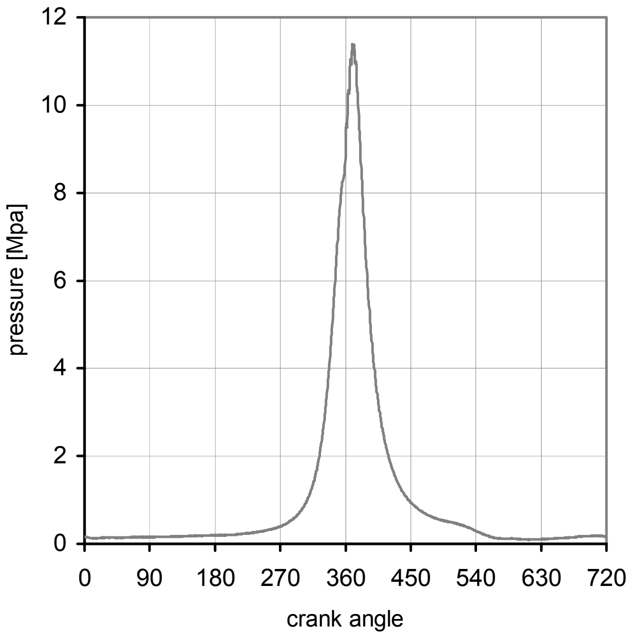


Fig. 2. The diagrams of the indicated pressure for turbocharged Diesel engine with power rating N=85 [kW] and engine speed n = 4250 [rpm] for λ = 1.69 [2]

2. Explicitness conditions

2.1. The physical conditions

The material properties of the exhaust valve are selected for X53CrMnNi21-9 austenitic steel. Because the calculations of the heat flow in the exhaust valve concerned unsteady state, six basic physical properties of the used material were necessary [13-14]:

- density ρ,
- Poisson ratio ν,
- thermal conductivity k,
- specific heat capacity c_P,
- Young's modulus E,
- thermal expansion coefficient α.

The calculation assumes the variables values k, c_P, E, α as a function of temperature (Figs. 3-6).

For the layers of the carbon deposit the following values were assumed [15]:

- thermal conductivity k=0.11 W/mK,
- density ρ=1530 kg/m^3,
- specific heat capacity c_P=1.34 kJ/kgK .

2.2. Initial conditions

While the calculations assume that at the beginning the distribution of temperature in the valve is constant and equal to the ambient temperature (at the moment τ = 0 s).

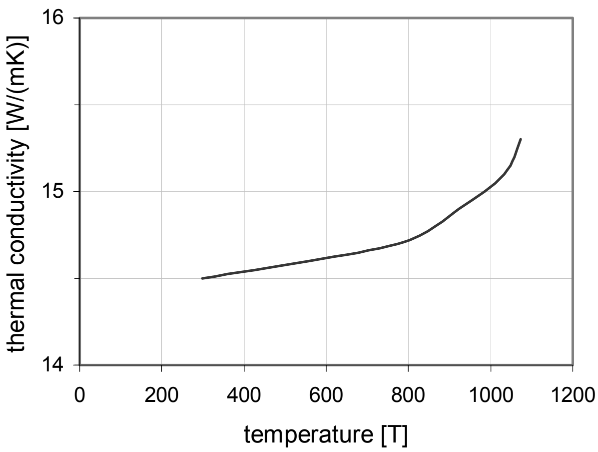


Fig. 3. The diagram of the thermal conductivity k as a function of temperature T [13]

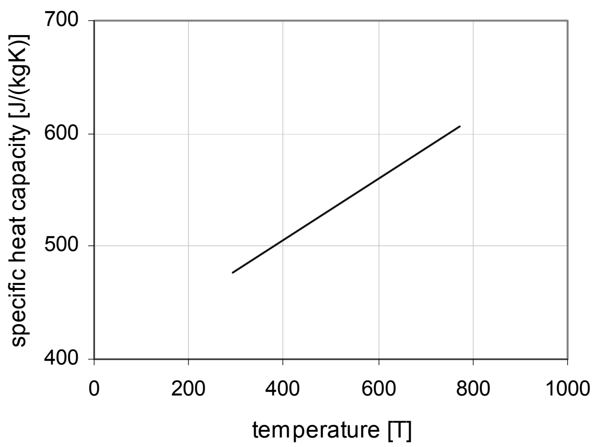


Fig. 4. The diagram of the specific heat capacity c_P as a function of temperature T [13]

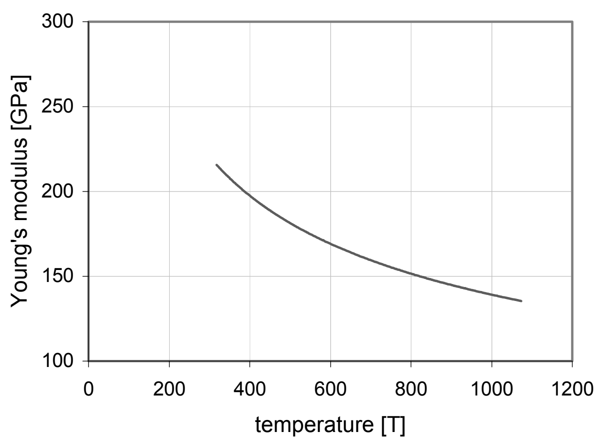


Fig. 5. The diagram of the Young's modulus E as a function of temperature T [13]

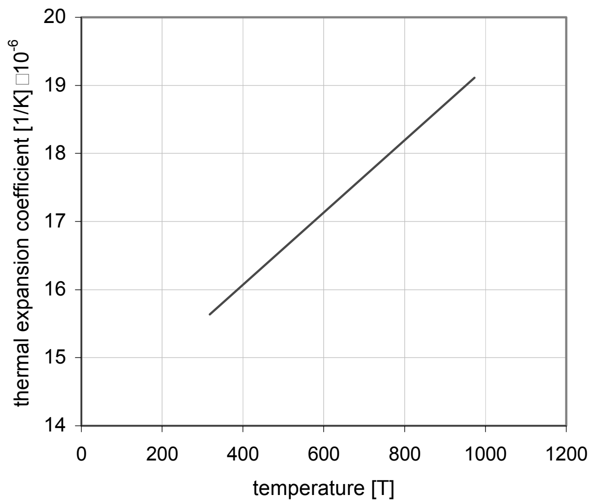


Fig. 6. The diagram of thermal expansion coefficient α as a function of temperature T [13]

2.3. Geometrical conditions

Geometrical conditions describe shape and size of the considered body. To create the geometric model of the valve, an isoparametric three–dimensional solid element with 8 nodes dimension of 1 mm was used [16].

To create the geometric models of the valve (Fig. 7) and the layers of the carbon deposit (Figs. 8-9) the following stages were used:

- definition of element type (SOLID),
- creation of a two-dimensional half-section using points and curves, definition of the outline and region of the model,
- generation of a two-dimensional grid using an element of type QUAD,
- creation of a three-dimensional model by rotating the two-dimensional model,
- the polyhedron function, which removes the two-dimensional grid and generates a three-dimensional grid.

a) b)

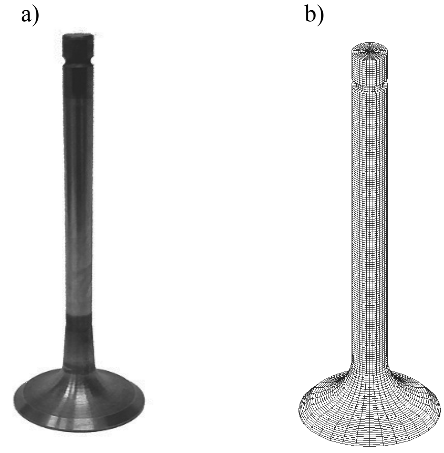


Fig. 7. The exhaust valve: a) real model, b) discrete model

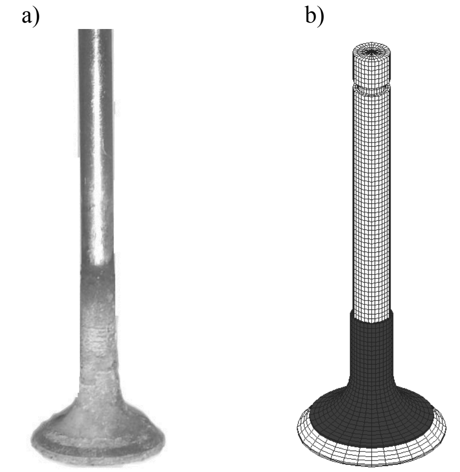


Fig. 8. The layer of the carbon deposit (the first case): a) real model , b) discrete model

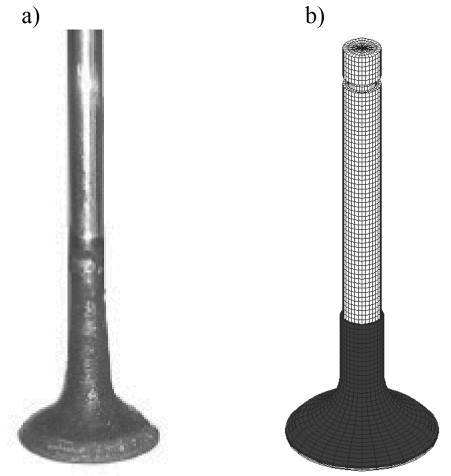


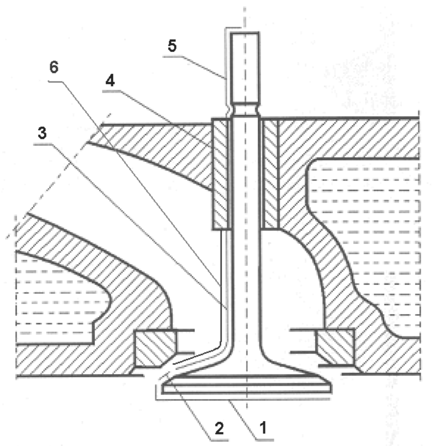
Fig. 9. The layer of the carbon deposit (the second case): a) real model , b) discrete model

Two models of the layer of carbon deposit were created. In the first case the layer of the carbon deposit covering the lower part of the stem valve (Fig. 8).

In the second case the layer of the carbon deposit covering the lower part of the stem valve and valve seat (Fig. 9).

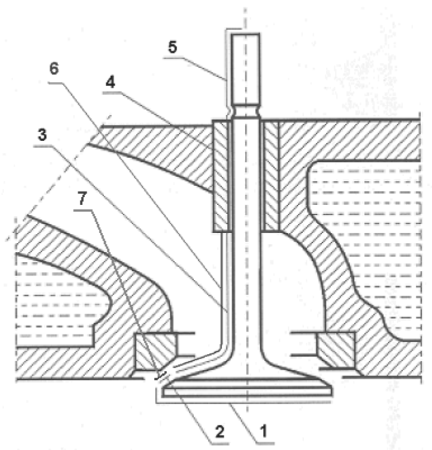
3. Boundary conditions

Depending on considered cases of covering valves with the layer of the carbon deposit in the valve, the following areas were distinguished (Figs. 10-11).



1 – the valve face,
2 – the valve seat,
3 – spindle in the outlet channel,
4 – face surface of the valve spindle in the engine head,
5 – valve spindle over the head,
6 – the layer of the carbon deposit.

Fig. 10. Surfaces of the outlet valve in the engine head (the first case)



1 – the valve face,
2 – the valve seat,
3 – spindle in the outlet channel,
4 – face surface of the valve spindle in the engine head,
5 – valve spindle over the head,
6, 7 – the layer of the carbon deposit.

Fig. 11. Surfaces of the outlet valve in the engine head (the second case)

3.1. The boundary conditions for surfaces uncovered the layers of carbon deposit

For surfaces (1), (2), (3), (6) and (7) applied conditional variable boundaries of the third type, because these surfaces have direct contact with the working medium (Figs. 10-11). For the remaining surfaces were used the average conditions of heat exchange. Further information about the boundary conditions of heat exchange of the exhaust valve can be found in ref. [3-6].

3.2. The boundary conditions for the layers of carbon deposit

Modelling of thermal loads between the valve surfaces and the carbon deposit were made by direct contact (Fig. 12).

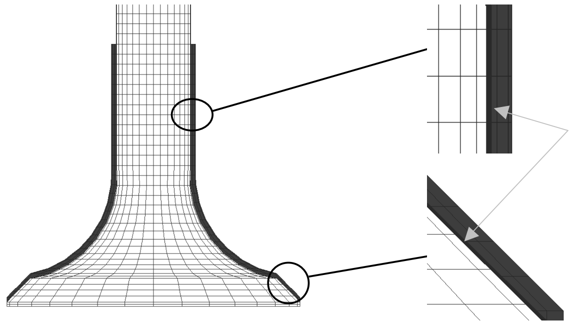


Fig. 12. Boundary conditions for heat flow between two surfaces (carbon deposit and valve)

The modelling conditions of heat exchange at the close of the valve for the surface (7) covered of the layer of carbon deposit includes the phenomenon of leaks between the valve face and valve seat. Assume the following values of heat-transfer coefficient $\alpha_{7Z}(\varphi_i)$ and the temperature $T_{7Z}(\varphi_i)$ of medium surrounding [1].

$$\alpha_{7Z}(\varphi_i) = Nu(\varphi_i)\frac{\lambda(\varphi_i)}{d_h} \quad \left[\frac{W}{m^2 K}\right] \tag{1}$$

$$T_{7Z}(\varphi_i) = T(\varphi_i) \quad [K] \tag{2}$$

$$Nu(\varphi_i) = A \cdot \mathrm{Re}(\phi_i)^{0.58} \tag{3}$$

where:
$Nu(\varphi_i)$ – Nusselt number,
$\lambda(\varphi_i)$ – heat conductivity of medium working,
$T(\varphi_i)$ – temperature of engine working medium,
d_h – internal diameter of the valve,
A – constant Annand (Fig. 13),
$\mathrm{Re}(\varphi_i)$ – Reynolds number.

$$\mathrm{Re}(\varphi_i) = \frac{\overline{w} \cdot d_h \cdot \rho(\varphi_i)}{\eta(\varphi_i)} \tag{4}$$

$$\overline{w} = \frac{F_{tl} \cdot \overline{w}_{tl}}{f} \quad \left[\frac{m}{s}\right] \tag{5}$$

$$F_{tl} = \frac{\pi D^2}{4} \tag{6}$$

$$\overline{w}_{tl} = \frac{S \cdot n}{30} \tag{7}$$

$$f = \pi h_z \cos\alpha (d_g + h_z \sin\alpha \cos\alpha) \quad [m^2] \tag{8}$$

where:
$\overline{w}$ – average speed of the flow of the working medium through the valve seat,
$\rho(\varphi_i)$ – density of the working medium,
$\eta(\varphi_i)$ – coefficient of the absolute viscosity of the working medium,
F_{tl} – the area of the active piston head,
$\overline{w}_{tl}$ – the average speed of the piston,
f – surface area of the flow between valve face and valve seat (Fig. 14),
D – diameter of the piston,
S – lift of the piston,
n – speed engine,
α – angle between valve face and valve head.

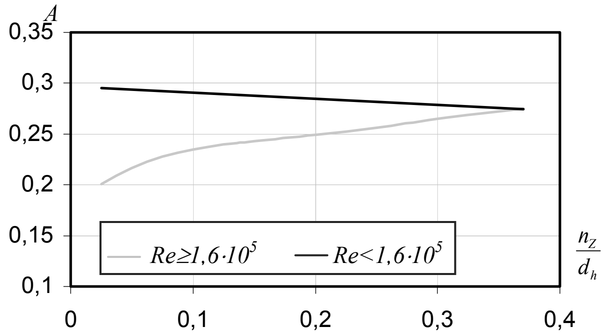


Fig. 13. Graph of changes of the coefficient Annand [1]

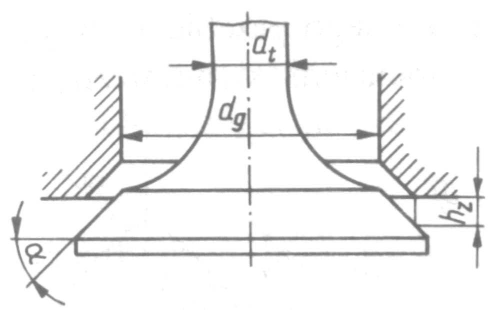


Fig. 14. Basic dimensions of valve needed for calculations [17]

4. Calculations results

This work has introduced the heat loads in the exhaust valve with using the layer of the carbon deposit in turbocharged Diesel engine with direct injection to the combustion chamber with the capacity of about 2390 cm^3 and power rating of 85 kW at the speed of 4250 rpm. The two cases were considered.

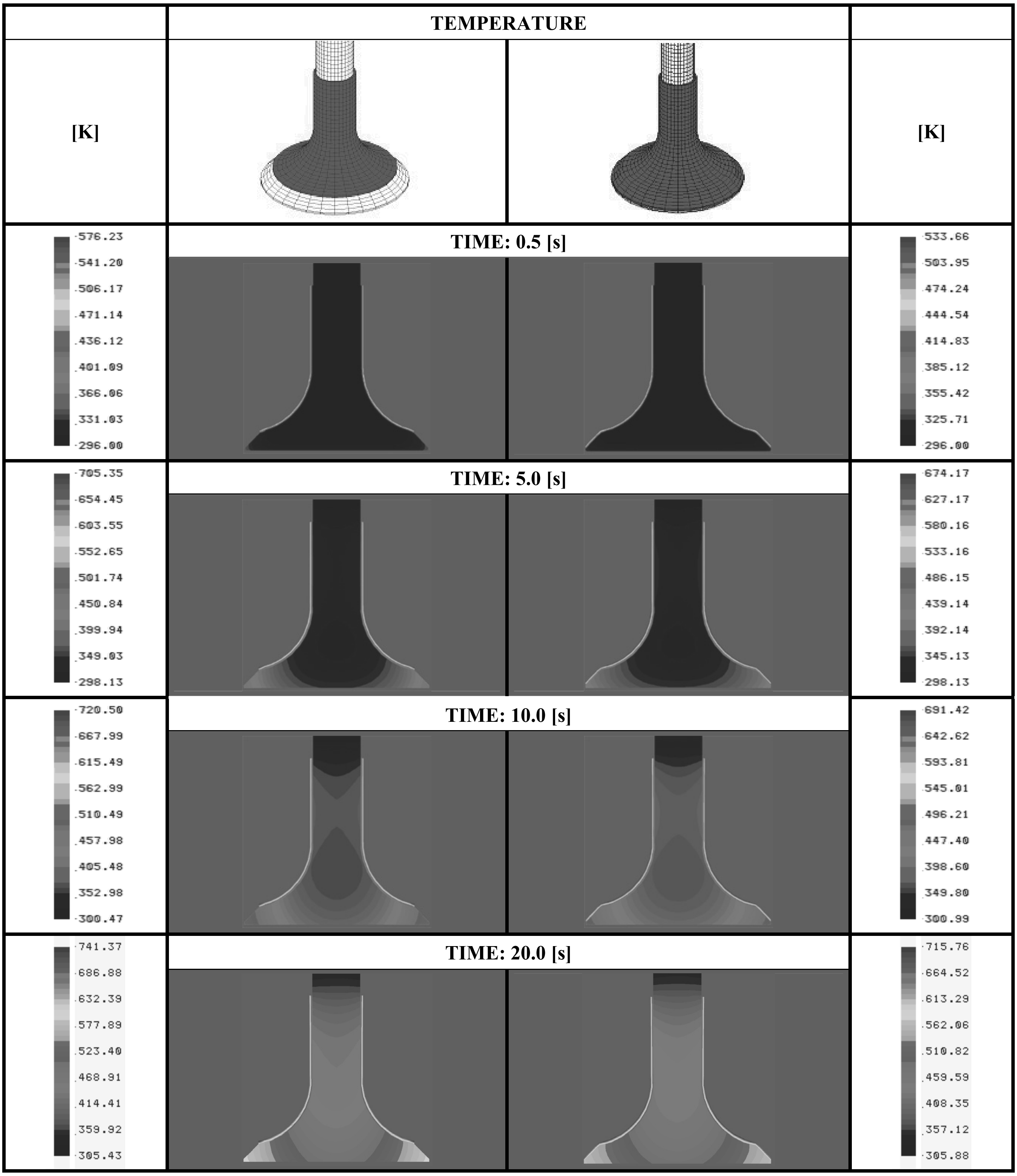


Fig. 15. The following phases of warming up of the valve

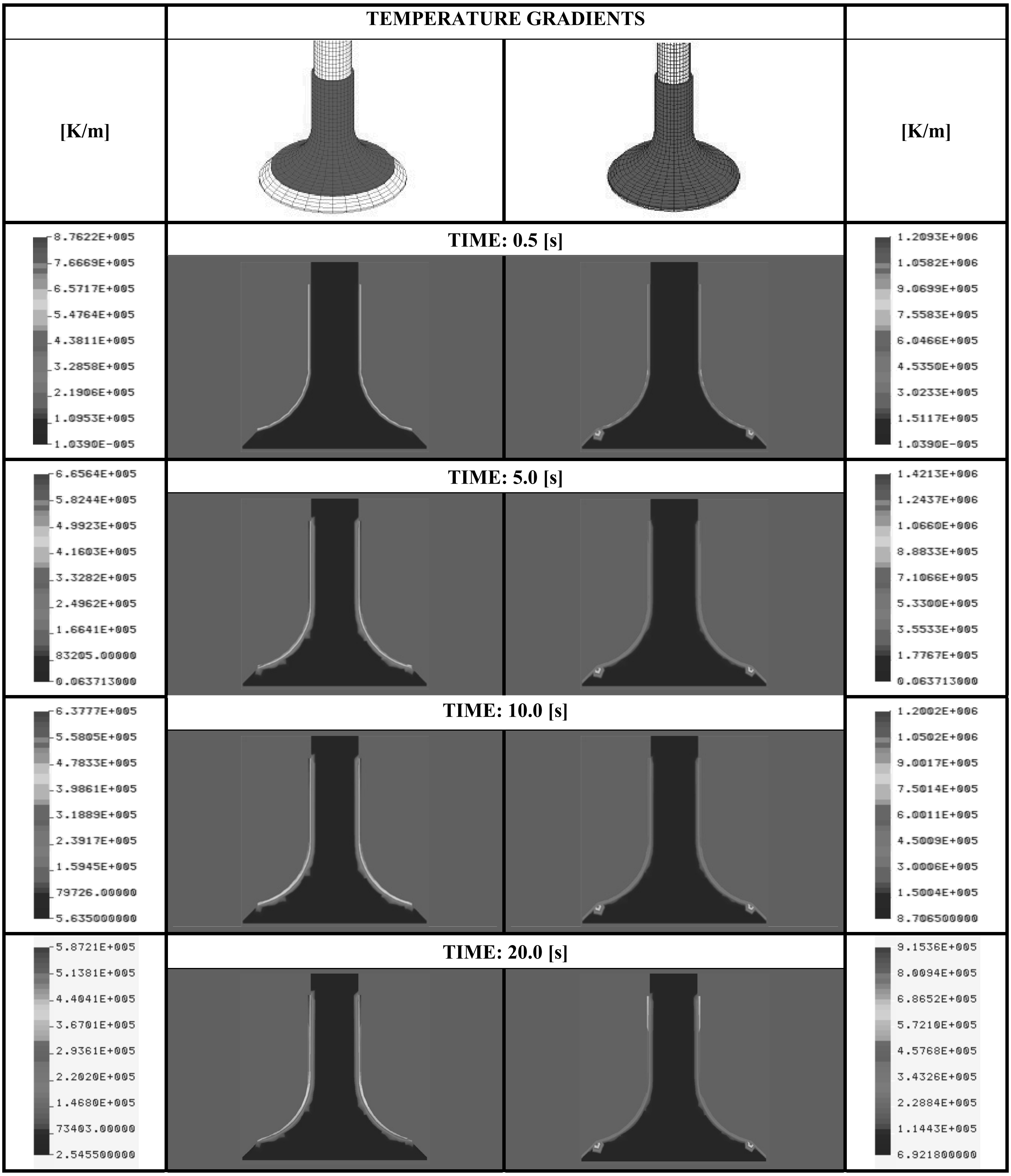


Fig. 16. The following phases of warming up of the valve

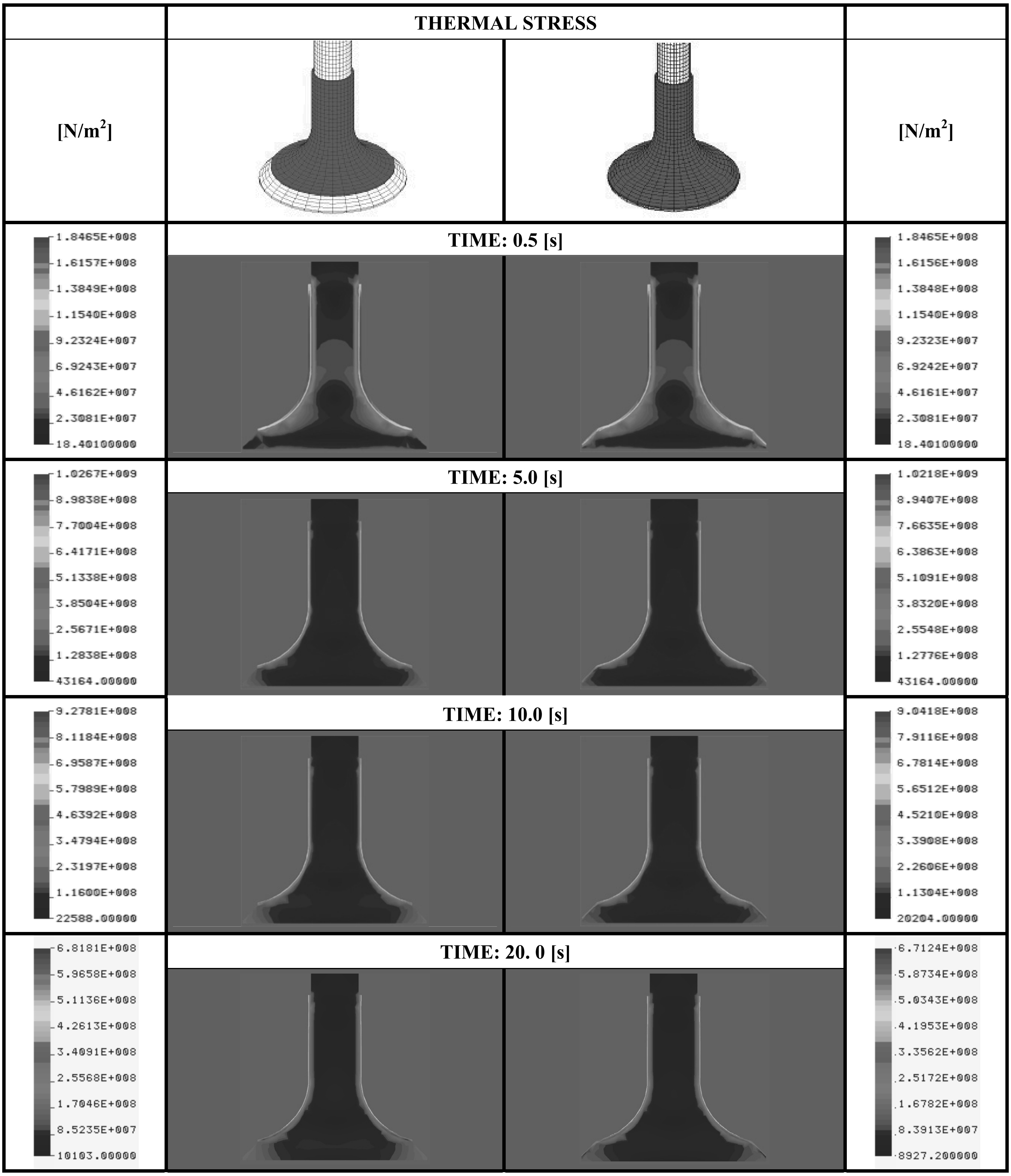
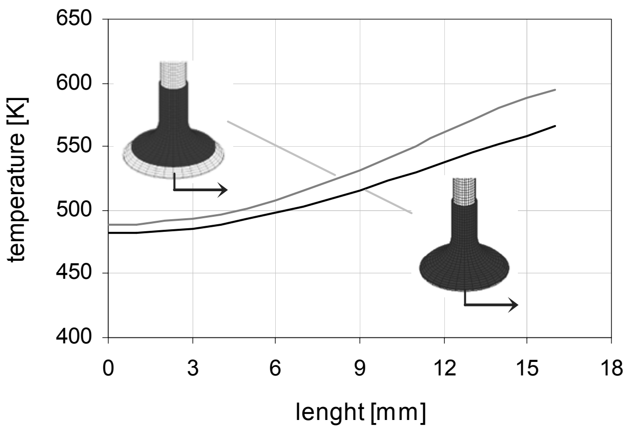
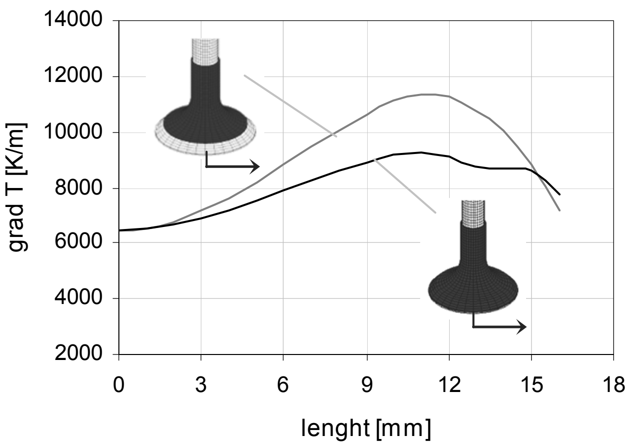


Fig. 17. The following phases of warming up of the valve

a)



b)



c)

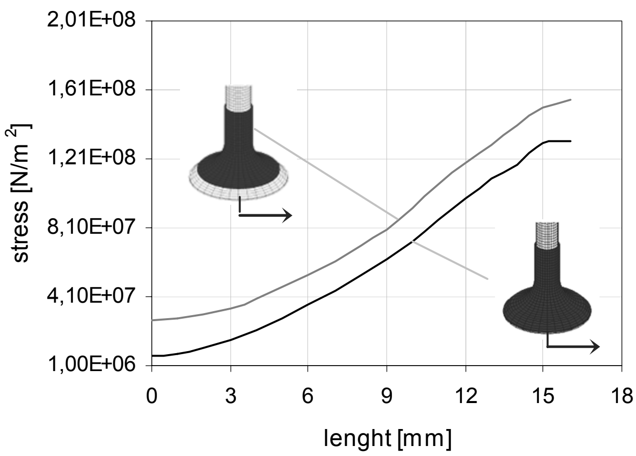


Fig. 18. Distribution of: a) temperature, b) temperature gradient, c) thermal stress on the length from centre of the valve in radial direction for the time of 20 s (both cases)

In the first case, the layer of the carbon deposit covering the lower part of the valve stem. In the second case, the layer of the carbon deposit covering the lower part of the valve stem and valve seat. Figures 15, 16 and 17 present the following phases of the warm up of the valve after 0.5, 5, 10, 20 s of the work of turbocharged Diesel engine. In these figures it can be observed, that temperature gradients and thermal stresses are growing. In the initial phase of the working engine the maximum values of temperature gradients and thermal stresses are appearing directly under the layer of the carbon deposit. For the time of 0.5 s in the first case the maximum value of temperature gradient is about 8.76e+005 K/m and in the second case is about 1.21e+006 K/m. For both cases the maximum value of thermal stresses are similar and is about 1.16e+008 N/m^2. With the increase of time heating it can be noted that the maximum stress is beginning to occur near the surface of the valve seat. For the time of 20 s in the first case the maximum value of thermal stress is about 1.56e+008 N/m^2, and in the second case is about 1.32e+008 N/m^2. Figure 18 present distribution of temperature, temperature gradient and thermal stresses on the length from centre of the valve in radial direction for the time of 20 s. In the Figures 18b, 18c it can be observed that location of the layer of carbon deposit is affecting changes of the value of temperature gradients and thermal stresses.

5. Summary

The results of the calculations show that the layer of carbon deposit affects the increase in value of the temperature gradients and thermal stresses in the exhaust valve. In the initial phase of the work of the engine, the maximum values of temperature gradients and thermal stress occur directly under the layer of carbon deposit. In the next cycles of the working engine, maximum stress values are beginning to appear around the valve seat. The increase in thermal stress is undesirable because it contributes to the formation of microcracks. Microcracks lead to loss in material of the valve and consequently to its defects. Examples of damage of the valves show Figure 19. The preparatory analysis also showed that arranging the layer of carbon deposit on different surfaces of the valve was affecting the value of thermal stresses (Fig. 18c). The difference in values of thermal stress between the first and the second case is about 0.25e+008 N/m^2. Finally, it cannot be concluded that which case of covering with the layer of carbon deposit is more dangerous for the valve, because the calculations inclusive the initial phase of the working engine and temperatures of valves is not yet stabilized. This will be done in the future works.

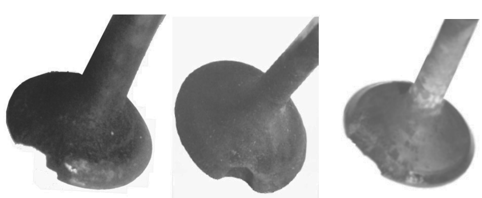


Fig. 19. Examples of damage valves

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