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Mechanical and thermal stresses analysis in diesel engine exhaust valve with and without thermal coating layer on valve face

Maher A.R. Sadiq Al-Baghdadi, Sahib Shihab Ahmed, Nabeel Abdulhadi Ghayadh

Faculty of Engineering, University of Kufa, Najaf, Iraq.

Abstract
This paper investigates mechanical and thermal stresses that arise in the exhaust valve due to its operating with and without thermal coating layer (ceramic) on face exhaust valve. Three dimensional models of an exhaust valve four cylinders, four stroke, and direct injection diesel engine have been presented. The governing equations were discretized using a finite-volume method (FVM) and solved using multi-physics COMSOL® package Version 5. The engine's exhaust valve crown is coated with various materials in different thermal conductivity such as ($Gd_2Zr_2O_7$), over a 150μm thickness of bond coat. The maximum thickness of coating is about 300 μm. Results indicate that after creating a coating layer exhaust valve the temperature distribution, temperature gradients distribution, von-Mises stress distribution and displacement distribution are decreased.

Keywords: Exhaust valve; Thermal stresses; Thermal coating; Diesel engine; Finite volume method.

1. Introduction

The lifestyle within the modern society has become highly dependent on different means of transportation, enabling vast movement through a variety of different transportation means. However, the environmental cost of such transportation is beginning to take its toll on a global level because of the associated greenhouse emission. As a consequence, political forces and regulations have been put in place to ensure that future research strives for more efficient fuel consumption [1]. As of today, the road transportation sector is dominated by two different types of internal combustion engines, namely the Spark-Ignition Engine (SI-engine) and the Compression-Ignition Engine (CI-engine). The engine of choice depends on the required specifications, such as emissions, cost, power ratios and efficiency, just to name a few. The different characteristics are inherited in the design and working principle of the respective engine concept [1]. Researches for decreasing costs and consumed fuel in internal combustion engines and technological innovation studies have been continuing. Engine efficiency improvement efforts via constructional modifications are increased today; one of the enhancements for instance using the alternative fuel as (hydrogen, naturel gas, etc....). To improve engine performance, fuel energy must be converted to mechanical energy at the most possible rate. This operation leads to increase the temperature and pressure in internal combustion engine cylinders. Hence, an increase in engine efficiency should be observed. But the increasing in temperature and pressure in cylinders leads to increase wear and thermal stresses. Ceramics have a higher thermal durability and lower thermal conductivity that controls the temperature distribution and heat flow in the structure. Lower heat rejection from the combustion chamber through thermally insulated components causes an increase in available energy that would increase the in cylinder work and the amount of energy carried by the exhaust gases, which could also be utilized [2]. Internal combustion four-stroke engine consists of two valves known as inlet and exhaust valve. The inlet valve allows the air or air-fuel mixture into the chamber. The exhaust valve forces out the exhaust gases. Many things can make a valve fail. The usual causes are thermal and mechanical over stresses, longitudinal cyclic stress, and creep conditions, forging defects etc. These lead to many troubles [3]. Because of exposure to hot exhaust gases; the exhaust valve of an internal combustion engine is one of the most critical parts. The design of valves depends on many parameters, such as fluid dynamics of the exhaust gas, fatigue strength of the valve material, oxidation characteristics of the valve material, exhaust gas behaviour of the material at high temperature [4]. To obtain an optimum condition by coating exhaust valve by ceramic layer, thermal and mechanical analysis guide use to design and optimize the exhaust valve accurately and consequently to prevents failure of the parts due to excessive stresses, fatigue, corrosion, etc.

Much of the latest researches in the field of coating ceramic have been done about structural refinement to improve the mechanical properties of the coating and perhaps lower thermal conductivity. Chan and Khor [5] reported that (4 to 7%) improvement in fuel consumption in single cylinder DI diesel engine is achieved by using constant air flow rate with boosting pressure with 1 mm thick PSZ coating to the cylinder head face and the valve heads by placing a short solid PSZ cylinder liner in the area above the piston rings and heat insulated steel piston. Lavanya and Ahmed [6] studied the surface of a piston in an engine when coated with multi-layer coating powder by the plasma spray technique, and analysed its surface behaviour. The purpose of this study is to analyse the mechanical and thermal effects of surface coating for a piston in frictional mechanism. In this related, with and without coated specimens were prepared, then the microstructure, hardness, corrosion test were carried out. From the obtained test and finite element analysis results, they are found that the coated specimen having better properties in the diesel engine performance. The results show less deformation and fewer scratches due to wear on the multi-layer coated piston as compared to uncoated one. Kubert and Kumar [7] carried out a finite element method (FEM) simulation of the piston ring in a multi-body single cylinder internal combustion engine. The model deals with an assembly of piston top compression ring, liner, connecting rod and the crank shaft. The results of such simulation show that the engine performance was influenced by the ring geometry, coating, method of coating and the mechanical and thermal properties. Through this research, the ring deformation and stresses developed in the ring-liner interface were evaluated using FEM. Krishnan et al. [8] investigated the effect of AlSi graphite particle coating on piston in a diesel engine and observed significant improvement in the thermal efficiency using diesel as fuel. Balkrishna et al. [9] investigated the performance and combustion characteristics on a single cylinder low heat rejection engine using diesel and multi-blend biodiesel. They reported that Al_2O_3 coated engine gave better performance than conventional diesel engine in terms of brake power, engine efficiency and specific fuel consumption.

Santhanakrishnan et al. [10] carried out an experimental study for a diesel engine fuelled with diesel and 50% mahua oil biodiesel blend. The ceramic coating was done on the piston surface, cylinder head and valves of the engine to convert the conventional engine into low heat rejection engine. It was observed that the heat transferred to the coolant and surrounding was reduced well due to the thermal barrier coating. The specific energy consumption of LHR engine with biodiesel was higher than LHR engine fuelled with diesel fuel, but lower than the conventional engine operations.

Ciniviz et al. [11] investigated the engine performance of a four strokes, direct injection, four cylinders, and turbocharged diesel engine after coated with ceramic thermal barrier using plasma spray coating method. They are found better engine performance after the coating process.

Kanna et al. [12] have been studied the valve performance by coating Al-Si alloy on the surface of mating zone of engine valve. Al-Si alloy coated valve had tested and the comparative results approved that the mechanical characteristics increased without affecting the functionality. The Al-Si coating was done on the engine valve by physical vapour deposition method in a controlled environment. As the analysis results are satisfactory, the same coating can be extended to other parts of the engines to improve the overall effectiveness of the engine.

Sharma1 et al. [13] have been studied the operating temperatures, heat fluxes and radial thermal stresses in the valves of a modern diesel engine with and without air-cavity. Temperatures, heat fluxes and radial thermal stresses were measured theoretically for both cases under four thermal loading conditions. By creating an air cavity inside the valves stem, it acts as an insulating medium and prevents the heat flow;

hence the need of providing insulation coating on valves was minimized. The main motive of this was to reduce the weight of engine and cost associated with thermal coating. Results observed in the engine valves revealed that after creating an optimized air cavity in the valve, thermal stresses and temperatures at all nodal point's decreases slightly. The weight of the valve decreased up to 11% without losing its strength. In addition to heat transferred by convection and radiation from combustion gases, the temperature and heat flux distributions were considerably affected by heat conduction from valve seat. The temperature field, heat transfer rate and thermal stresses were investigated with numerical simulation models using FORTRAN FE (finite element) software. Imdat [14] studied the effect of insulated surfaces (piston, cylinder head and valves) on diesel engine energy balance system by plasma spray. The results indicate a reduction in fuel consumption and heat losses to engine cooling system of the ceramic coated engine. Pawar and Jajoo [15] made a model (Annand's model for heat transfer), and it has been developed for comprehensive predictions and assessments of varying temperature and heat transfer through cylinder head and valves of diesel engine. Thermal insulation materials like (PSZ) and (SN) were used. In case of without insulated valves the heat transfer rate was higher by about 54.62% and 37.57% than the 1 mm and 0.5 mm PSZ thermal insulated valves, respectively and 12.62% higher than 1 mm SN thermal insulated valves.
The aim of this work is to study the effect of ceramic coating on the mechanical and thermal stresses induced in exhaust valve of diesel engine.

2. Numerical model

Three dimensional finite volume method (FVM) models of an exhaust valve of a diesel engine have been presented. The model analyses the mechanical and thermal loads that arise in the valve due to its operating. The geometry of the exhaust valve is shown in Figure 1. The exhaust valve sits on the cylinder head of a combustion chamber. The engine coolant liquid passes around the cylinder liner and the water passages in the cylinder head. The valve pops up and down to let the exhaust gases leave the combustion chamber. The up-and-down motion of the valve takes place with the help of a rocker lever which is connected to the push rod. The push rod rests over cams on the camshaft. The valve is spring loaded. The spring keeps the valve connected to the camshaft during its motion. After the expansion process, the exhaust gases, at high temperature, are purged through the exhaust valve and as a result the temperature of the exhaust valve increases. In order to avoid any damage to the exhaust valve due to this high temperature, heat must be continuously taken away from the valve. This is achieved when the valve is in contact with its seat. As the exhaust valves touch its seat, a significant drop in exhaust valve temperature occurs.

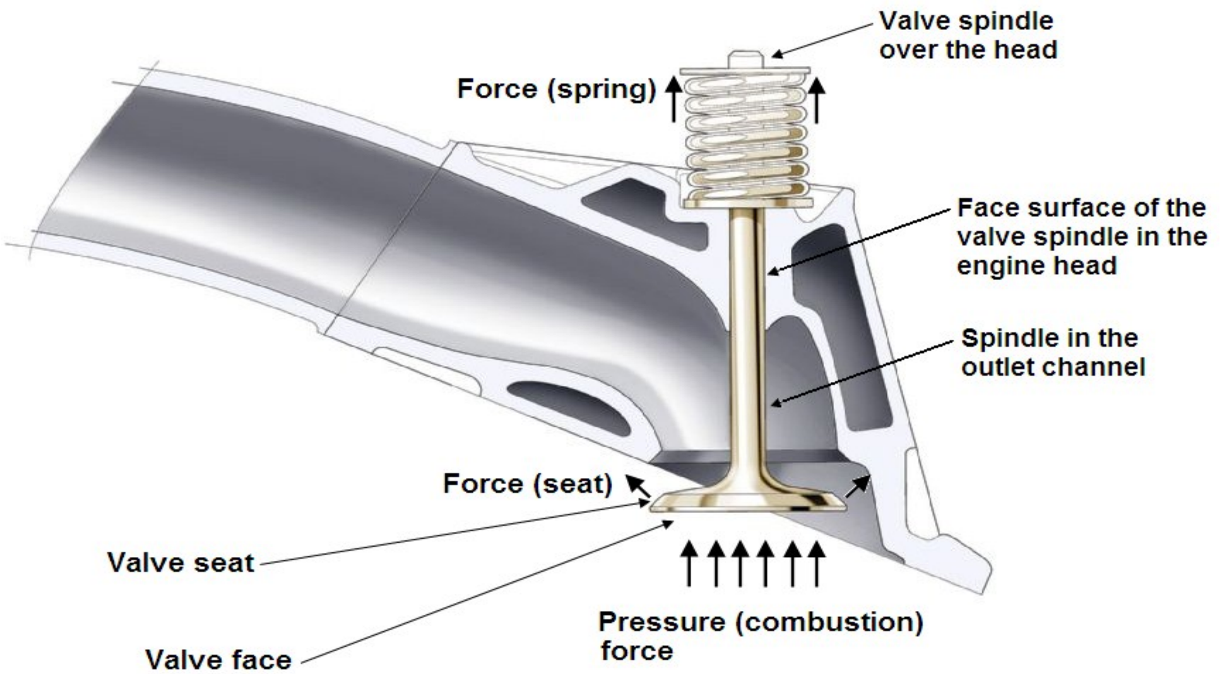

Figure 1. Geometry of the exhaust valve in the engine head.

2.1 Computational domain

AutoCAD is used to create the full scale 3D domain of the real exhaust diesel engine valve with high degree of accuracy. The physical geometry and the three dimensional computational domains of the exhaust valve used in the diesel engine are shown in Figure 2.

Figure 2. Real and three dimensional computational domains of the exhaust valve.

2.2 Modelling equations

The prediction of the temperature distribution in the exhaust valves, involves the solution of the heat transfer equation; heat conduction, heat transfer to the contact surface and heat convection with the appropriate boundary conditions.

The heat transfer in the exhaust valve is governed by [16];

$$\rho c_p \frac{\partial T}{\partial t} + \rho c_p \mathbf{u}.\nabla T = \nabla.(k\nabla T) + Q \tag{1}$$

where ρ is the density [kg/m^3], c_p is the heat capacity [kJ/kg.K], k is the thermal conductivity [W/m.K], **u** is the velocity vector [m/s], and Q is the heat source [W].

The exhaust valve head is subjected to the pressure force of the hot gases as shown in Figures 3 and 4. The heat transfer coefficient at the exhaust valve head is calculated using the following equation [17];

$$h_g(\theta) = 3.26\big(P_g(\theta)\big)^{0.8}\big(6.18 \times V_p\big)^{0.8}\big(b^{-0.2}\big)\big(T_g(\theta)\big)^{-0.55} \tag{2}$$

where h_g is the heat transfer coefficient [W/m^2.K], P_g is the gas pressure [Pa], T_g is the gas temperature [K], V_p is the mean piston speed [m/s], b is the piston bore [mm], and θ is the crank shaft angle [degree].

Because of high variation of the temperature and pressure inside the combustion chamber during the engine cycle, the resulting gas temperature (T_{gr}) and mean heat transfer coefficient (h_{gm}) can be calculated as [17];

$$T_{gr} = \frac{(h_g T_g)_m}{h_{gm}} \tag{3}$$

$$h_{gm} = \frac{1}{720}\int_0^{720} h_g(\theta)d\,\theta \tag{4}$$

$$\big(h_g T_g\big)_m = \frac{1}{720}\int_0^{720} h_g(\theta)T_g(\theta)d\theta \tag{5}$$

The temperature of the valve seat is assumed to be 300 ^{o}C with the heat transfer contact coefficients between the valve and valve seat of 5000 W/m^2.K. The temperature of the valve guide near the cylinder head is assumed to be 90 ^{o}C with the heat transfer coefficient of 170 W/m^2.K. When the valve is in contact with the valve seat, there is natural heat transfer from the valve stem to the gases (air and the residual exhaust gas) in the exhaust port. The values of the gas temperature and the heat transfer coefficient are estimated at 200 ^{o}C and 12W/m^2.K, respectively. Similarly, there is a natural heat transfer at the top of the valve stem (exposed to enclosed air). The values of the temperature and heat transfer coefficient at this end are estimated at 30 ^{o}C and 12W/m^2.K, respectively. These values are provided by the engine manufacturer using computational and experimental results [17].
When the exhaust valve opens, the exhaust gases leave the combustion chamber through the exhaust valve. In this case, the necessary boundary condition for numerical analysis is the exhaust gas heat transfer coefficient, and is calculated using the following equations [17];

$$Nu = \frac{hD}{k} = 0.18(Re)^{0.62} \tag{6}$$

$$Re = \frac{\rho V D}{\mu} \tag{7}$$

where D is the valve stem diameter [m], k is the thermal conductivity coefficient of the exhaust valve [W/m.K], V is the exhaust gas speed [m/s], ρ is the density of the exhaust gas [kg/m^3], and μ is the viscosity of the exhaust gas [kg/s.m].

Mechanical and thermal stresses will be analysed with the following equations [16];

$$-\nabla.\sigma = \mathbf{F}\mathrm{v} \tag{8}$$

The thermal strains resulting from a change in temperature of an unconstrained isotropic volume are given by [16];

$$\epsilon_{th} = \alpha\left(T - T_{ref}\right) \tag{9}$$

where α is the thermal expansion [1/K], and T_{ref} is the valve reference temperature.

The analysis was performed under the worst thermal loading condition of rated power. The engine specification and operating condition are summarized in Table 1.

Table 1. Engine specifications and operating conditions [17].

Component	Value
Piston bore [mm]	87.3
Connecting rod [mm]	130
Cylinder number	4
Int. valve number.	4
Exh. valve number	4
Compression ratio	8.6
Valve lift [mm]	9.5
Engine speed [rpm]	4700
Air fuel ratio	12
Power [hp]	66
Piston stroke [mm]	66.7
Mean piston speed [m/s]	10.4

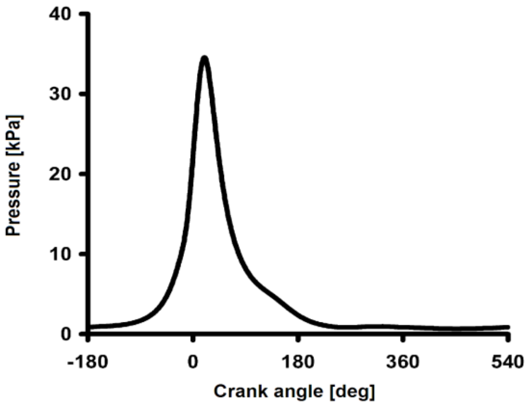

Figure 3. Diagram of measured gas pressure in the cylinder.

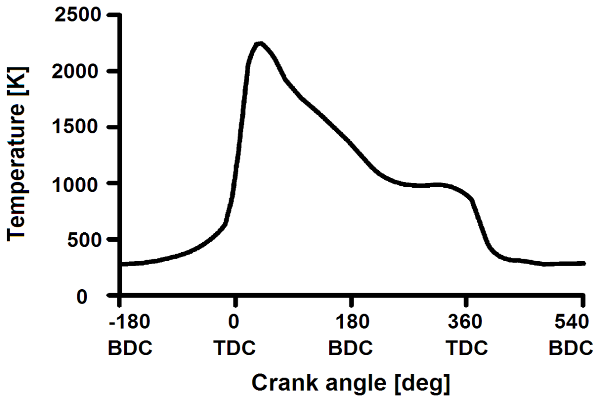

Figure 4. Diagram of measured gas temperature in the cylinder.

2.3 Computational procedure
The governing equations were discretized using a finite-volume method and solved using multi-physics COMSOL® package Version 5. Stringent numerical tests were performed to ensure that the solutions were independent of the grid size. A computational quadratic mesh consisting of a total of 9884 domain elements, 3706 boundary elements, and 612 edge elements was found to provide sufficient spatial resolution (Figure 5). In addition to the heat transfer boundary conditions (section 2.2); the mechanical boundary conditions were applied. The mechanical boundary conditions are noted in Figure 1. As well to the combustion pressure force on the valve face, a constant pressure force is applied on the key groove located in the valve spindle over the head corresponding to a case where the valve spring keeper retention to control the spring force. The coupled set of equations was solved iteratively, and the solution was considered to be convergent when the relative error was less than 1.0×10^{-6} in each field between two consecutive iterations.

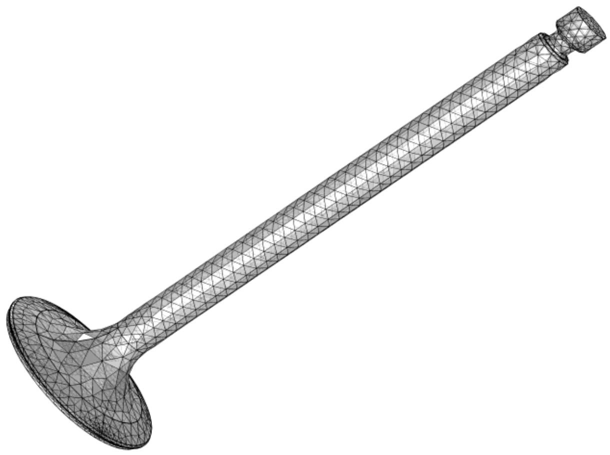

Figure 5. Computational mesh of the computational domain.

2.4 Comparing with experimental data
The results for base case operating conditions (without coating layer on the valve face) were verified with experimental results provided by Shojaefard et al. [17]. The temperature distribution of the numerical model during steady-state engine operation shown in Figure 6 is in very good agreement with the experimental temperature curve. The results of the numerical model are also showing the temperature gradients in the exhaust valve. The maximum values of the temperature gradients appear around the exhaust valve seat and also occur in the spindle in the outlet channel near the conical. This leads to develop and increase of the maximum thermal stress at the valve seat contact zone of the valve in the hoop direction, and as a result, it contributes to the formation of microcracks. At the worst conditions for the cooling of the valve such as distortion of the seat, this stress causes radial cracks at the edge of the valve. In addition, microcracks lead to loss in material of the exhaust valve and consequently to its defects. Examples of damage of the exhaust valve shows in Figure 7 with good similarity to the numerical model.

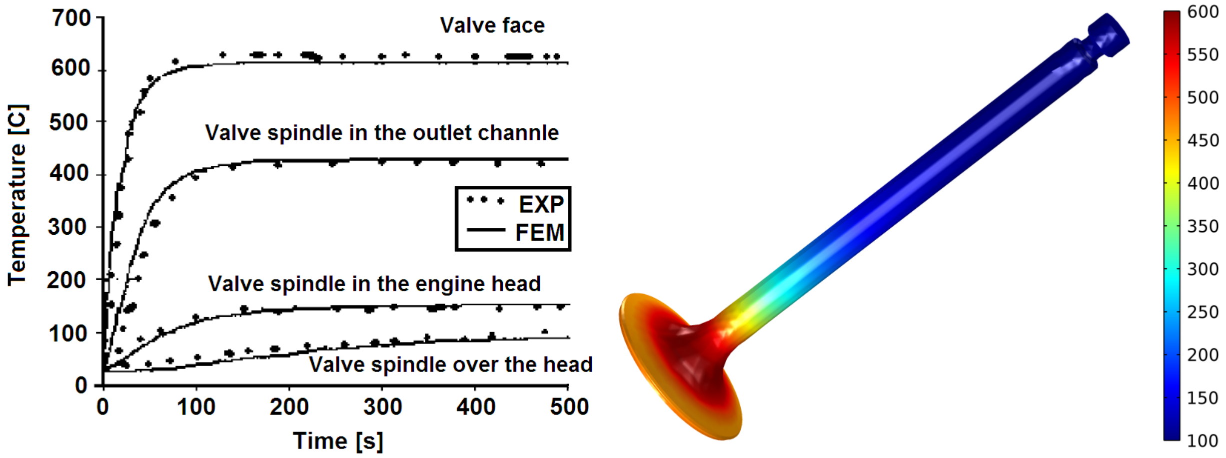

Figure 6. Comparison between the numerical and experimental results.

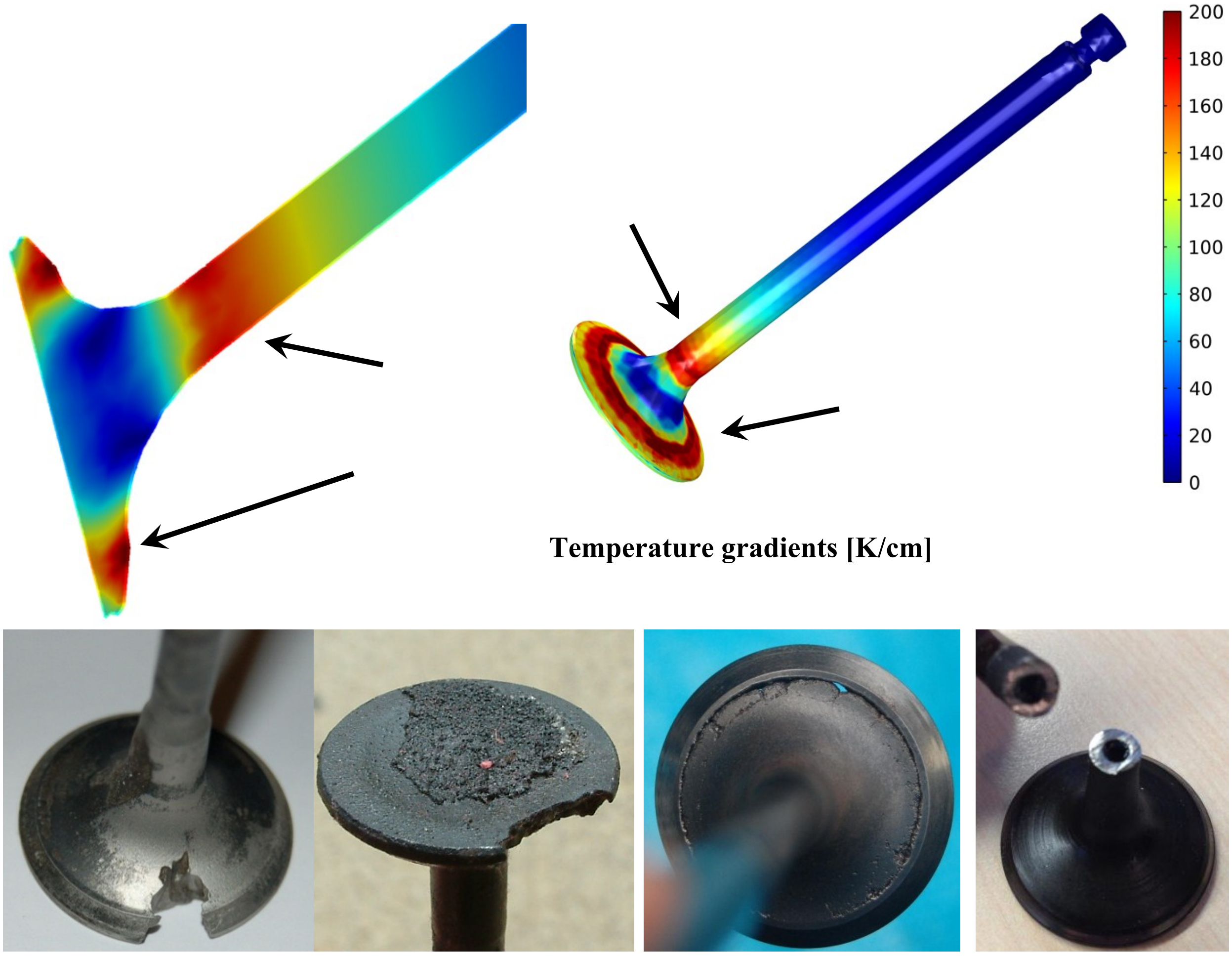

Figure 7. Visual comparison between the results of the numerical model and examples of the real damage valves.

3. Effect of the coated layer on the valve performance

In addition to revealing the detail of mechanical and thermal phenomena inside the valve, the comprehensive three-dimensional model can also be used to investigate the sensitivity of certain parameters on valve performance. The validated model is now ready for studying the effects of coating the valve face with different types of thermal barrier coatings material on the valve performance. The performance characteristics of the valve based on a certain parameter can be obtained by varying that parameter (material properties of the coated layer) while keeping all other parameters constant at base case conditions. Results obtained from these parametric studies will allow the identification of the critical parameters for valve performance as well as the sensitivity of the model to these parameters. Material properties of each coated layer are shown in Table 2

Table 2. Material properties of the coated layer on the exhaust valve face.

Case no.	Material	Density [g/cm^3]	Thermal conductivity [W/m.K]	Thermal expansion coeff. [1/K]
1	$Gd_2Zr_2O_7$	7.0	1.6	11.6e^{-6}
2	MgO-ZrO_2	3.0	1.57	09.9e^{-6}
3	$La_2Zr_2O_7$	6.0	1.5	09.7e^{-6}
4	$Sm_2Zr_2O_7$	6.7	1.5	10.8e^{-6}

4. Results and discussion

As mentioned earlier the aim of this study is to develop thermal and mechanical properties by coating for exhaust valve in diesel engine. A comparison of the Temperature distribution of the exhaust valve without and with coating layer on the valve face is shown in Figure 8. The maximum temperature in the valves occurs at the bottom surface (valve face) because those nodal points are directly exposed to the combustion gasses. By using the coating layer the temperature distribution is decreased on the valve face, as it well known that ceramic has a low thermal conductivity material. Figure 9 shows Von-Mises stress distribution of the valve without and with coating layer on the valve face. It can be observed that the maximum Von-Mises stress appears near the valve seat. The analysis of the valve with coating layer shows that the Von-Mises stress is less as compared to valve without coating layer. This phenomenon can be explained with the load type. In other words, the combustion pressure applied at the bottom of the valve makes the large stresses at the valve seat. When the valve is closing, the inertia force is applied upward to the whole valve. It can be shown that the stresses of the valve seat were low due to the coating layer. A comparison of the temperature gradients distribution of the exhaust valve without and with coating layer on the valve face is shown in Figure 10. The maximum values of the temperature gradients appear around the exhaust valve seat and also occur in the spindle in the outlet channel near the conical. This leads to develop and increase of the maximum thermal stress at the valve seat contact zone of the valve in the hoop direction, and as a result, it contributes to the formation of micro cracks by using coating layer on the valve face decreasing temperature gradients distribution of the exhaust valve because of the ceramic has a low thermal conductivity material.its results due to reduced failure in exhaust valve. The results of calculation is carried out and have been presented in Figure 11 showing the displacement field (Displacement distribution) through the valves for valve without and with coating layer on the valve face.

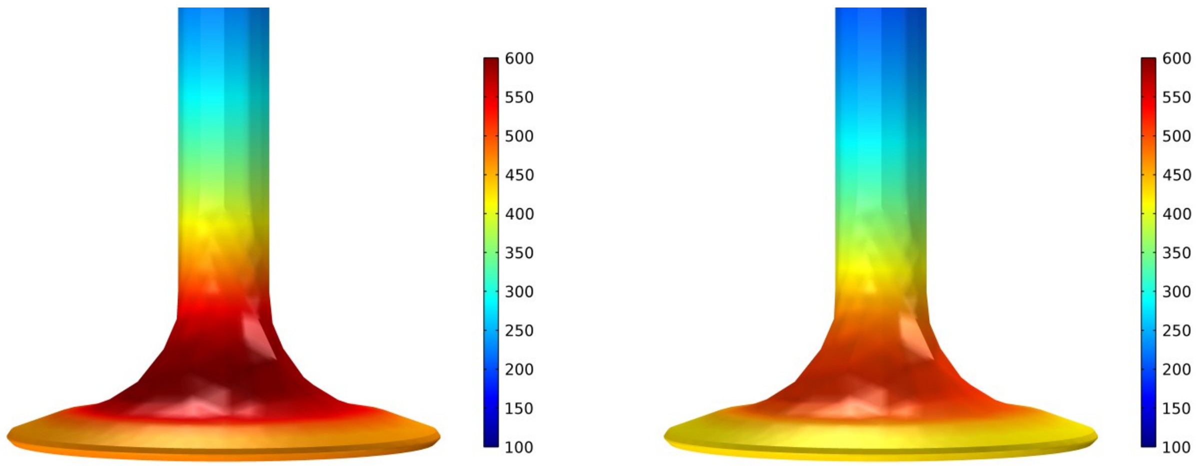

Figure 8. Temperature distribution of the valve [^{o}C] without (left) and with (right) coating layer on the valve face.

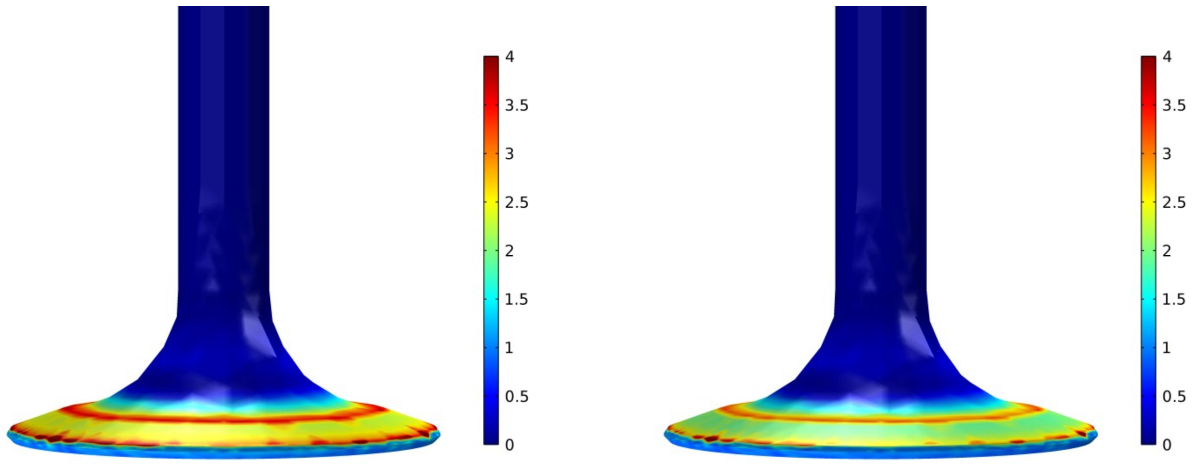

Figure 9. Von-Mises stress distribution of the valve [GPa] without (left) and with (right) coating layer on the valve face.

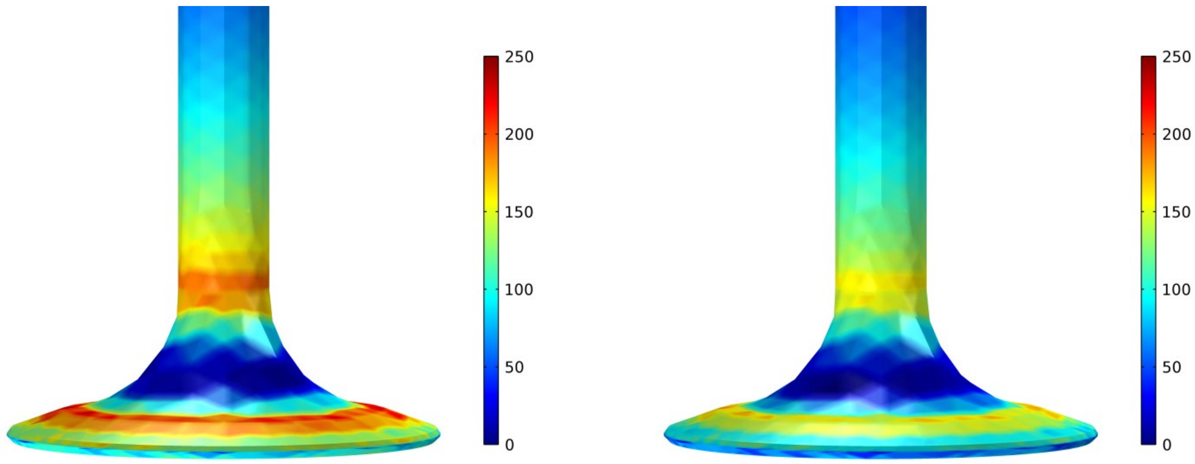

Figure 10. Temperature gradients distribution of the valve [K/cm] without (left) and with (right) coating layer on the valve face.

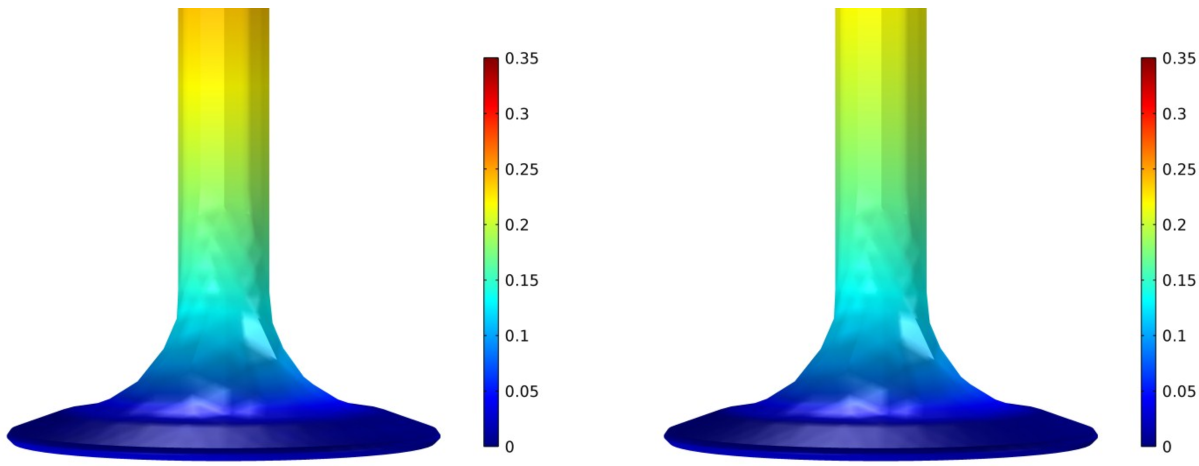

Figure 11. Displacement distribution of the valve [mm] without (left) and with (right) coating layer on the valve face.

The result shows that there is a tendency to decrease the displacement field in the valves coating by ceramic and the maximum Displacement occurs in spindle of the out channel. The basic material made the exhaust valve expands with varying high heat transmitted from the exhaust gases through the exhaust valve face, so the coating of the face of the exhaust valve by ceramic reduces heat transfer and thus reduces the expansion, Because of the ceramic has a low thermal conductivity material.

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5. Conclusion

The degradation of material strength due to high temperature and the dynamic load when the exhaust valve closes is very important. The model expected position exactly agrees with the failure position in the engine test. The purpose was to compare behaviour of the exhaust valve without and with coating layer on the valve face under thermal load and mechanical load. The obtained results show that the thermal stresses and mechanical stresses induced in exhaust valve with coating layer are less as compared to the exhaust valve without coating layer. Through the analysis, it is concluded that the main factor influencing the exhaust valve is the temperature, thus providing basis for the optimization method to improve of the exhaust valve. The deformation and the stress of the exhaust valve are mainly determined by the temperature, so it is necessary to decrease the exhaust valve temperature through coating layer on the valve face.

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