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# Analysis of the co-operation of bimetallic valves and a valve guide – thermal problems

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The paper presents results of research and thermal analysis of valves made of various materials. Monolithic (of valve steel) and bimetallic valves produced with the same technology have been compared, the external layer of bimetallic valves being of the valve steel and the internal of steel 45. Results of valve heating research and measured temperatures on the surface of a valve and a guide have been presented. Model computations have been carried out using the finite elements method, temperatures distribution in a valve placed on the measuring position and during operation of an engine. Also, the impact of a crevice between a guide and a valve on the carrying away of heat have been analyzed (width of the crevice and its lubrication). For the purpose of the analysis a model of a guide together with a guide has been built. On the basis of analysis of heat emitted in the combustion chamber and the outlet channel, the conditions of heat transfer have been determined. The results of the analyses have been presented and compared with the research results. It has been stated that in case of using the bimetallic valves the amount of heat taken from the walls of the combustion chamber and from the outlet channel is higher, which enables their application in engines more loaded in terms of heat loading. Application of this type of valves enables also to reduce the production costs.

## 1. Introduction

Valves applied in the internal combustion engines control the delivery of the fresh load to the cylinder and the exhaust of gases. Since they control the supply of the load to the chamber and carrying away of exhaust gas, they are subject to rapidly-changing, mechanical and thermal loading. A valve is to fulfil its role in all the possible operating conditions of the engine. It should also remain relatively light, fulfil demands in terms of heat abstraction, and be inexpensive in the course of production. The mentioned above, expectations seem to be contradictory; in practice, however, a compromise may be obtained. The bimetallic valves fulfil the expectations. The analysis of the thermal loading presented below enables the improvement of the valve design.

## 2. Thermal loading of a valve

Valves are subject to gas forces, resulting from the pressure of the exhaust gases in the combustion chamber, and to mechanical forces that have an impact on the collet and the stem at the point of co-operation with the cam or the intermediate elements. The thermal loading, resulting from the increase of temperature of a valve, were as important as the mechanical ones. The temperature of a valve increases as a result of "washing" of the valve head by agents of various temperatures on the side of the combustion chamber and the exhaust channel. Valves belong to the most loaded, in terms of the thermal loading, elements of the engine. Significant amount of heat is provided to the valve head not only from the side of the combustion chamber but from the side of the exhaust channel as well. The heat is given up to the valve seat, guide and timing. A valve and a co-operating with it guide, has been used for the purpose of the analysis. A valve applied in the air-cooled engine, being $\phi = 28$ mm in the head diameter and $l = 116$ mm in length, has been used for the analysis (because of its significantly higher operating temperature). A monolithic valve made of the 50H21G9N4 steel and a bimetallic valve, whose external layer is made of this steel and the internal is made of the steel 45, have been examined. Steel 45 is better at heat conduction than the austenitic steel. Applying of the bimetallic valves enables also to reduce production costs (by about 30%), maintaining at the same time comparable mechanical and heat-resisting characteristics.

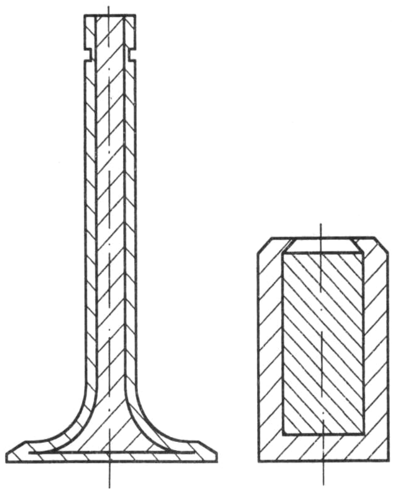

Fig. 1. A bimetallic valve and a semi-finished product needed for its production
Rys. 1. Zawór bimetalowy i półfabrykat do jego wykonania

Figure 1 shows an intersection of a bimetallic valve and a semi-finished product needed for its production. Monolithic and bimetallic valves were produced by the use of the same technology, namely by hot extrusion.

Average operating conditions of a valve for the whole cycle have been determined for the analyses (operating conditions corresponding to the rotational speed of 3500 rpm and the stabilised full loading of the engine). Average values of the heat transfer coefficients and the temperature of the surrounding agent have been estimated for these conditions, by the use of dependencies presented below. They have been determined for the particular parts of a valve co-operating with: the combustion chamber, valve seat, exhaust channel, valve guide and collet surroundings.

The dependency worked out by Woschni [9] has been used for establishing the coefficient and the temperature in the combustion chamber. The run of pressures and temperatures has been determined on the basis of the program of engine cycle simulation [6], employing the Wibe dependency:

$$\alpha = 127{,}9 \cdot D^{-0{,}2} \cdot p^{0{,}8} \cdot T^{-0{,}53} \cdot [C_1 \cdot c_m + C_2 \cdot \frac{V_H}{p_1}\frac{T_1}{V_1} \cdot (p - p_0)]^{0{,}8},$$

where: $\alpha$ – heat transfer coefficient [W/m$^2$K],
$D$ – cylinder diameter [m],
$T$ – temperature of gases in the cylinder [K],
$p$ – pressure of gases in the cylinder [Pa],
$c_m$ – average piston speed [m/s],
$V_H$ – volume over the piston [m$^3$],
$C_1$ – coefficient dependent on the phase of the cycle,
$C_2$ – coefficient dependent on combustion process,
$C_1 = 6{,}18+0{,}417\ C_u/c_m$ – at the gas exchange,
$C_1 = 2{,}28+0{,}308\ C_u/c_m$ – at the compression and expansion of gases,
$C_2 = 3{,}24 \cdot 10^{-3}$ [m/sK]– at the direct injection and the type M chamber,
$C_u/c_m$ - swirl ratio,
$C_u$ – average speed of the Pischinger's wheel,
$p - p_o$ – difference of pressures between the operating and non-operating engine [Pa],
$p_1, V_1, T_1$ – pressure, volume and temperature at the start of the compression stroke.

Radiation of gases in the combustion chamber has been omitted due to its little share in ignition combustion engines. Average values of the heat transfer coefficients and temperature of the surrounding agent for the valve seats have been determined from the dependency [2]:

$$\overline{\alpha} = \frac{\Delta\varphi_o \cdot \alpha' + \Delta\varphi_z \cdot \alpha''}{2\pi} \quad \text{and} \quad \overline{T} = \frac{\Delta\varphi_o \cdot \alpha' \cdot \overline{T}' + \Delta\varphi_z \cdot \alpha'' \cdot \overline{T}''}{2\pi \cdot \overline{\alpha}},$$

where:
α', α" – heat transfer coefficients in the gas exchange phase (') and operating phase ("),
T', T" – temperature of the surrounding medium in the gas exchange phase and in the operation phase.

Heat transfer coefficient in the exhaust channel has been established from the Nishiwaki, Shimamoto, Miyake dependency [5]:

$$\alpha_e = 91{,}99 \cdot D^{-0{,}422} (c_m \cdot p)^{0{,}578} \cdot T^{-0{,}199} .$$

Heat transfers between a valve and a valve seat, similarly as between a valve and a guide, cannot be analysed without taking into consideration of heat transfer between the seat and the cylinder wall and the cooling agent. In such circumstances the problem has been based upon the heat transfer model of a multilayer wall, contact resistance between walls has been omitted. Figure 2 presents the flow of heat through the multilayer flat wall.

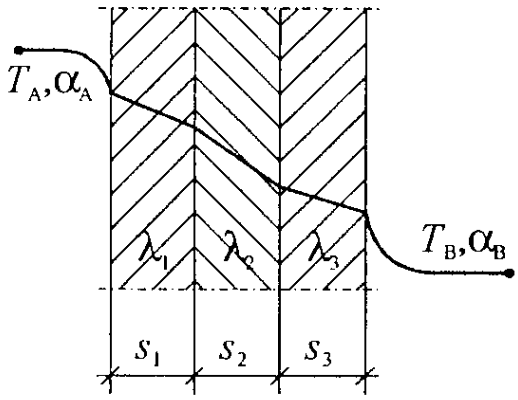


Fig. 2. The flow of heat through the multilayer flat wall
Rys. 2. Przepływ ciepła przez wielowarstwową ściankę płaską

Presented model of the heat transfer enables to determine the difference of temperatures between mediums separated by a wall, which is described in the dependency [7]:

$$T_A - T_B = \frac{Q}{A \cdot \tau}\left(\frac{1}{\alpha_A} + \sum \frac{s_i}{\lambda_i} + \frac{1}{\alpha_B}\right) = \frac{Q}{A \cdot \tau} \cdot \frac{1}{\alpha_{zast}} ,$$

where:

$T_A$ – temperature of the internal wall,
$T_B$ – temperature of the external wall,
$Q$ – amount of heat,
$\tau$ – time of heat penetration,
$\alpha_{A,B}$ – heat transfer coefficient of the walls of the barrier,
$s_i$ – thickness of the consecutive $i$ layer,
$\lambda_i$ – heat transfer coefficient of the consecutive $i$ layer,
$A$ – surface of the heat transfer,
$\alpha_{zast}$ – substitute coefficient of heat transfer.

In case of cylindrical walls, the surface of heat transfer differs for the internal and external layer, but the computation error does not exceed 1,4%.

Relying on the dependencies shown below, heat transfer conditions have been determined, which have been juxtaposed in the table 1.

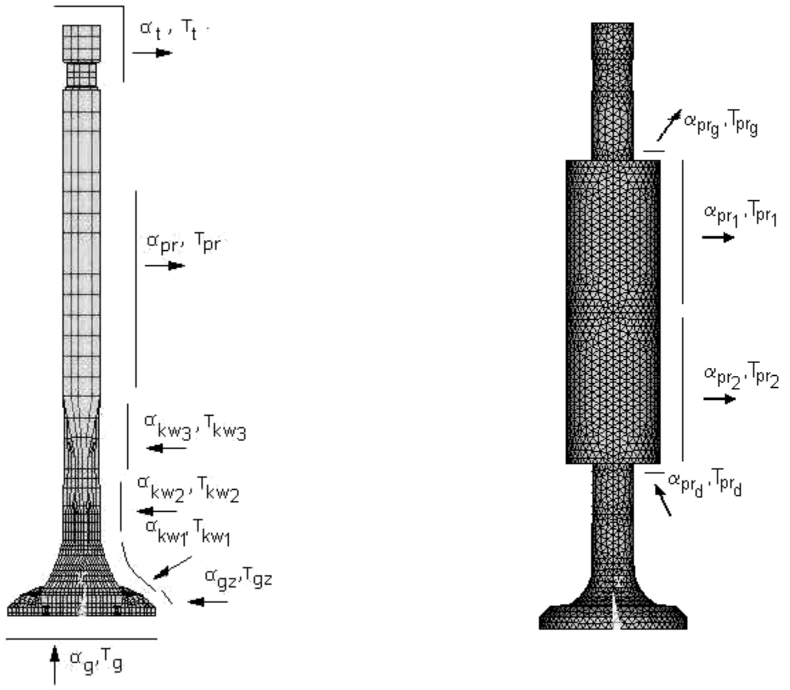


Fig. 3. Heat transfer scheme in an exhaust valve and a valve with a guide:
$\alpha$ – heat transfer coefficient, T – temperature of the surrounding medium, indices: pr – valve guide, kw – exhaust channel (divided on the 3 areas), gz – valve seat, t – valve stem, g – combustion gases
Rys. 3. Schemat wymiany ciepła w zaworze wylotowym i zaworze z prowadnicą:
$\alpha$ – współczynnik przejmowania ciepła, T – temperatura ośrodka otaczającego, indeksy: pr – prowadnica zaworu, kw – kanał wylotowy (podzielony na 3 obszary), gz – gniazdo zaworowe, t – trzonek zaworu, g - gazy spalinowe

Table 1. Heat transfer conditions in a valve
Tabela 1. Warunki wymiany ciepła w zaworze

| No. | Place of heat transfer | Symbol | Temperature | Heat transfer coefficient |
|---|---|---|---|---|
| | | | °C | $W/(m^2 \cdot deg)$ |
| 1 | Combustion chamber | g | 870 | 298 |
| 2 | Valve face | $gz_1$ | 430 | 915 |
| | | $gz_2$ | 410 | 915 |
| | | $gz_3$ | 390 | 915 |
| 3 | Curve part of a valve | $kw_1$ | 350 | 500 |
| 4 | Lower part of a valve stem | $kw_2$ | 350 | 450 |
| 5 | Middle part of a valve stem | $kw_3$ | 350 | 400 |
| 6 | Valve guide 1 | $pr_1$ | 145 | 1350 |
| | Valve guide 2 | $pr_2$ | 155 | 1350 |
| 7 | Valve guide (channel part) | $pr_d$ | 350 | 400 |
| 8 | Upper part of a valve stem | $pr_g$ | 100 | 80 |
| 9 | Valve rocker | dz | 100 | 2800 |

Table 2. Data of the materials of a valve and a guide
Tabela 2. Dane materiałowe zaworów i prowadnicy

| No. | Material/element | Heat transfer coefficient $\lambda$ [W/(m*deg)] |
|---|---|---|
| 1 | Valve – valve steel | 14,6 ÷ 17 |
| 2 | Valve – steel 45 [10] | 78 ÷ 30,2 |
| 3 | Crevice between a valve and a guide of 0,02 mm | 0,122÷0,04 |
| 4 | Valve guide | 53 |

Table 2 shows data for the analysis of the heat flow between a valve and a guide.

## 3. Analysis of the heat transfer between a valve and a guide

Relying on the characteristics of bimetallic valves, an attempt has been made to determine the impact of heat conduction on the capability of a valve to carry away heat from the combustion chamber. Measurements of heating of the monolithic and bimetallic valves by the determined temperature have been carried out for the purpose. Fig. 4 shows the measuring position and the results of measurements by the determined temperature of the valve head 400°C.

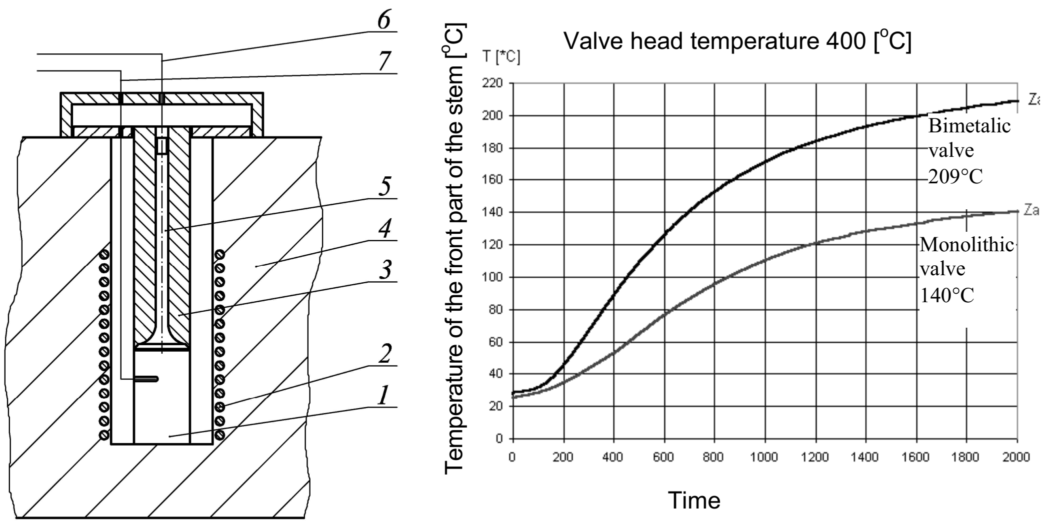


Fig. 4. Scheme of the measuring position for the measurement of the valve heating and the results of the measurement:
1- copper insert, 2 – heating element, 3 – valve insulation, 4 - oven insulation, 5 – valve examined, 6 – thermocouple, 7 – copper insert thermocouple
Rys. 4. Schemat stanowiska do pomiaru nagrzewania się zaworu i uzyskane wyniki:
1- wkładka miedziana, 2- element grzejny, 3- izolacja zaworu, 4- izolacja pieca, 5-zawór badany, 6- termopara czoła trzonka, 7- termopara wkładki miedzianej

Heating has been carried out in the oven and the temperature of the valve head was stabilised exact to 2 degrees. In the remaining part the valve was thermally isolated. Also the upper part of the stem was isolated. As inferred from the measurements, after about 2000 seconds (above 30 min) the temperature of the stem comes asymptotically close to the temperature of stabilisation for both of the valves. At first, after about 200 seconds, the temperatures of the ending of the stem begin clearly to vary. With time the measured temperature in the bimetallic valve becomes higher than the temperature of the monolithic valve by 20 do 60°C but temperature of the valve head remains the same. It means that the time of temperature levelling in the bimetallic valve is significantly shorter. For the purpose of confirming the thesis, a measurement of heating of a valve with fixed guide has been carried out. In the guide, the temperatures within the distance of 33, 49, 65 and 81 mm from the surface of valve head have been measured. The measurements have been made on the measuring position shown on the fig. 5. The Position was also used for the analysis of the impact of the change of the clearance between a valve and a guide and of the impact of the intensity of lubrication of this connection.

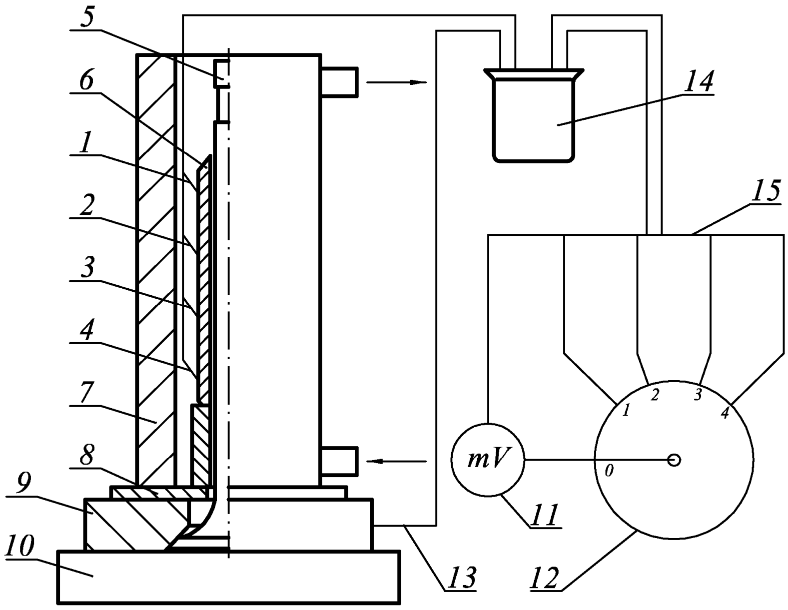


Fig. 5. Scheme of the measuring position:
1, 2, 3,4 – guide thermocouple, 5 – valve, 6 – guide, 7 – isolation mantle, 8 – isolating separator, 9 – pressure plate, 10 – heating element, 11 – milivoltmeters, 12 – rotary switch, 13 – plate thermocouple, 14 – thermos flask, 15 – union piece

Rys. 5. Schemat stanowiska pomiarowego:
1, 2, 3, 4-termopary prowadnicy, 5 – zawór, 6 – prowadnica, 7- płaszcz izolacyjny, 8 – przekładka izolacyjna, 9 – płytka dociskowa, 10 – element grzewczy, 11-miliwoltomierze, 12 – przełącznik obrotowy, 13 – termopara płytki, 14 – termos, 15 – złączka

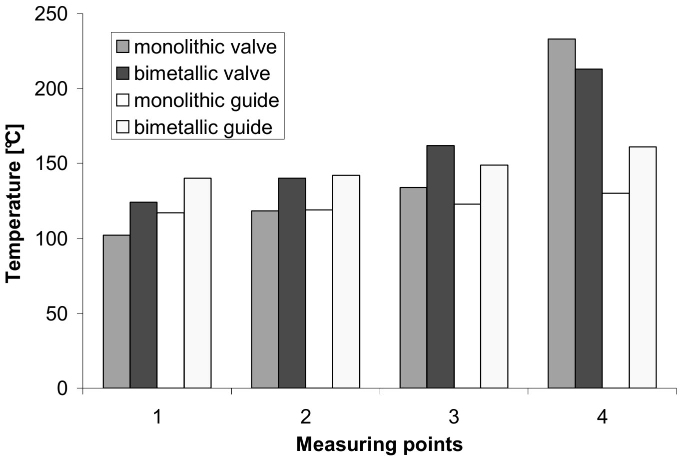


Fig. 6. Temperature distribution in the valve stem and the valve guide
Rys. 6. Rozkład temperatur w trzonku zaworowym oraz prowadnicy

The measuring position enables establishing of the external temperature by the use of the isolation mantle cooled with a liquid, and at the same time establishing the temperature of the heating element. There are thermocouples connected to the guide fixed to the valve. In this same way where measured temperatures on the wall of valve, using copper rings instead of valve guide.

The measured temperatures have been shown on the figure 6. On the basis of the measurement is may be stated that the measured temperatures in the thermocouples marked on the figure as 1 and 2 are higher by about 20 degrees in the guide of the bimetallic valve than in the monolithic valve.

For the purpose of the analysis of the heat transfer between a valve and a guide, the finite elements method has been employed. The computations have been made in the ANSYS system. A three-dimensional model of an exhaust valve containing 31424 knots and 19725 elements has been prepared for the purpose. For the description of the valve's geometry the SOLID87 elements have been used. Similarly, the model of a guide and a clearance between the guide and the valve. The size of the model of the valve together with the guide is determined by the total number of knots 45425 and elements 67868. Simplifications have been made by the construction of the model, assuming that the temperature of the agent in the cylinder is average for the whole cycle, similarly to the temperature of the agent in the channel and on the guide. It has been also assumed that the sealing of the valve is correct and the clearance in the crevice between the valve and the guide is uniform.

Computations of the temperature distribution and the thermal stress have been carried out for the assumed conditions of heat transfer. Fig. 7 presents the results of the computations of temperature distribution in a valve.

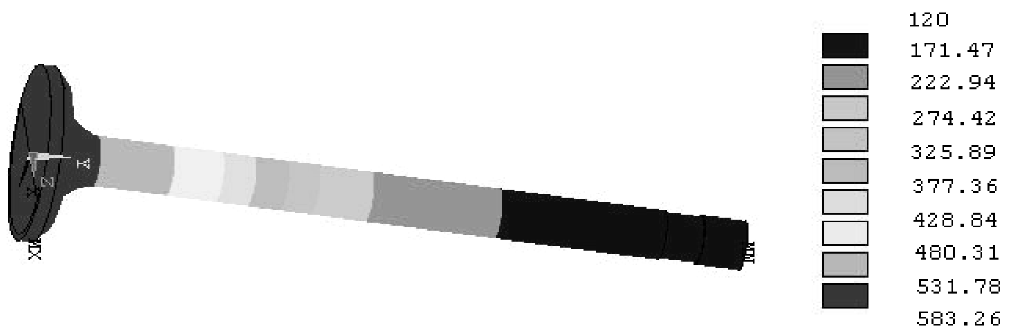


Fig. 7. Temperature distribution in a bimetallic valve [°C]
Rys. 7. Rozkład temperatur w zaworze bimetalowym [°C]

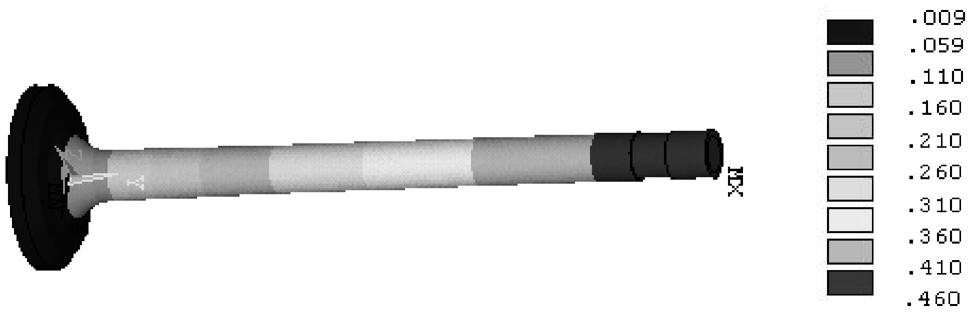


Fig. 8. Alteration of size of a bimetallic valve under the influence of temperature [mm]
Rys. 8. Zmiana wymiarów zaworu bimetalowego pod wpływem temperatury [mm]

On the basis of the computations the results of the measurement have been confirmed. Application of bimetallic valves, having better characteristics in terms of heat conduction, leads to increase of temperature in the valve guide and stem.

It enables to increase the amount of heat carried away from the combustion chamber walls and the exhaust channel by about 23%. It also has an effect on diminishing of the temperature gradient in the valve head by about 22 %.

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The diagram (fig.9) presents the percentages of heat received by a guide and appliances (camshaft, spring, oil mist) from parts of a stem in a monolythic and a bimetallic valve.

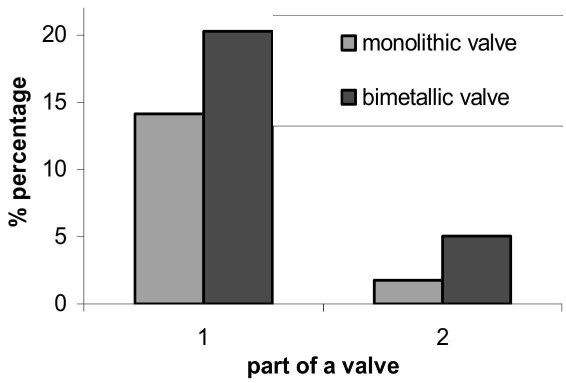


Fig 9. Percentage of heat conducted to a valve guide (1) and to the environment (2) by the middle and the upper patr of a stem
Rys. 9. Procentowy udział ciepła przekazywany do prowadnicy zaworowej (1) i do otoczenia (2) przez środkową i górną część trzonka zaworu

## 4. Impact of the valve-guide connection wear on the operating conditions of a valve

In the course of a regular exploitation of an engine, the wear processes of the elements of the valve-guide connection take place. As a result of the processes, the crevice betweet a valve and a guide is enlarged. It has been assumed for the analyses that the wear of the connection is uniform and, in effect, only the volume of the crevice is increased. The change of the difference between the diameters of a valve and a guide in the range between 0,02 mm and 0,10 mm has been a subject of analysis.

The purpose of the analysis was to determin the impact of the clearance on the temperature distribution in a valve. Figure 10 shows the impact of the crevice on the maximal temperature of a valve.

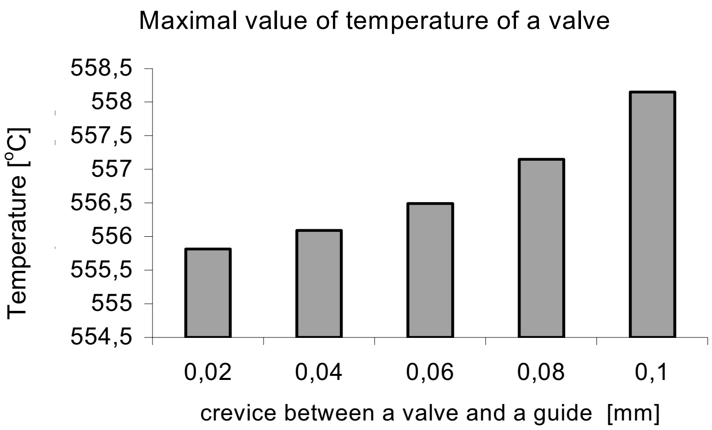


Fig. 10. The impact of the crevice between a valve and a guide on the maximal temperature of a valve
Rys. 10. Wpływ wielkości szczeliny między zaworem a prowadnicą na maksymalną temperaturę zaworu

As comes from the presented diagrams, the alteration of temperature exceeds 2,5 degrees. The increase of the crevice between a valve and a guide results in the growth of the maximal temperature of a valve. The computated value of the temperature change confirm the results obtained form the measurements.

## 5. Impact of the valve-guide connection lubrication on the operating conditions of a valve

During the analysis of the change of the operating conditions of a valve-guide connections the impact of intensity of lubrication on the change in the temperature distribution in a valve has been examined. It has been assumed for the puropse of the analysis that there is an air-crevice partly filled with oil between a valve and a guide. Cases have been examined, where a specified percent of the crevice was filled with the mixture of air and oil. The impact of the lubrication of the valve-guide connection on the temperature distribution in a valve has been analysed. Figure 11 shows the impact.

In may be inferred from the presented diagrams that the alteration of termerature does not exceed 2,5 degree. Increase of intensity of lubrication results in the diminishing of the maximal temperature of a valve. The computaded values of the change of temperatures confirm the results obtained from the measurements.

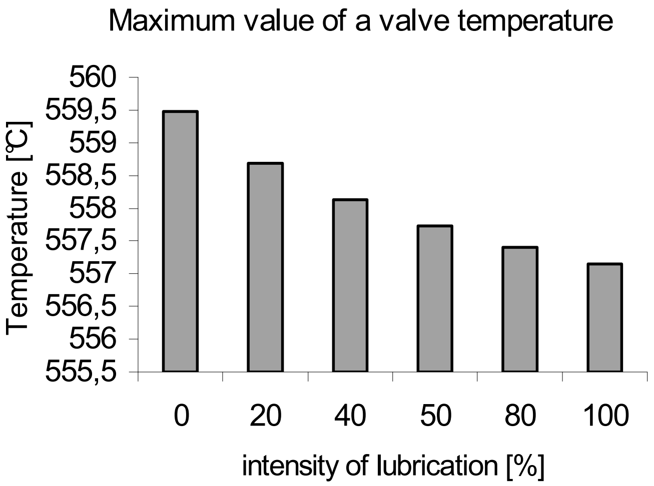


Fig. 11. Impact of the intensity of lubrication of the valve-guide connection on the maximal temperatures in a valve
Rys. 11. Wpływ intensywności smarowania połączenia zawór-prowadnica na maksymalne temperatury w zaworze

The temperatures in the measuring points of a guide have been measured (fig.5). The difference of temperatures obtained for the forth measiring point, located near the bottom edge of the guide, is 3,7 degree, with and without lubrication of the crevice.

The change of temperature by different intensity of lubrication, determined on the basis of the computations, is higher and exceeds 4 degrees.

## 6. Comparison of the computation results and measurements

The measurement of temperature was made in the measuring points 1,2,3,4 (fig.5) on a valve. Also, the model computations of temperatures in particular points of a valved have been made (for the assumed conditions of heat transfer appearing during the measurement on the measuring position). The comparison of the results of measurements and computations is presented in the figure 12. It can be inferred from the diagram that a bimetallic valve has lower temperature in its lower part (near the bottom edge of a guide) and higher temperature in the part cooporating with the upper edge of a guide. The computations are confirmed by the results of measurements.

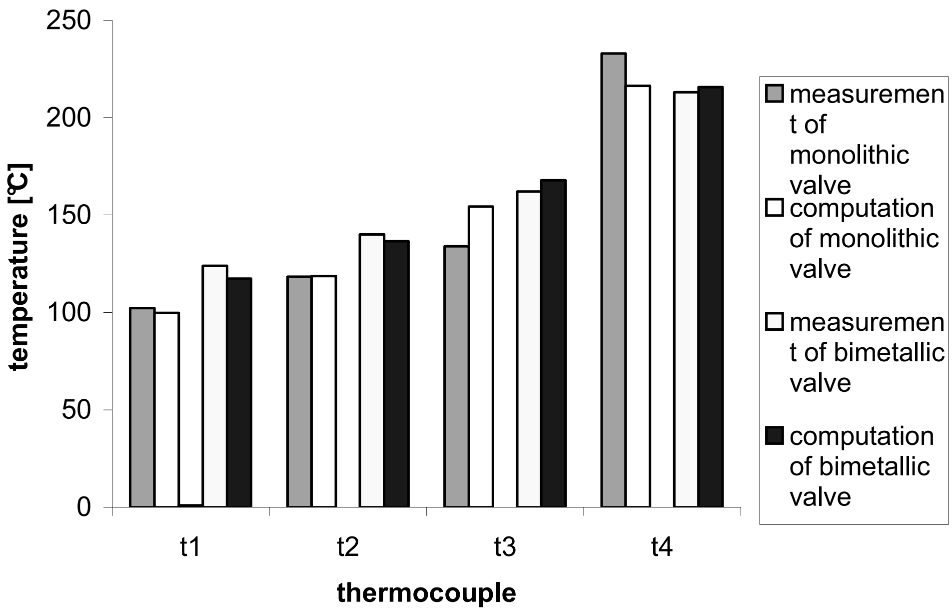


Fig. 12. Comparison of temperatures in the measuring points of a valve and the computations
Rys. 12. Porównanie temperatur w punktach pomiarowych zaworu z obliczeniami

## 7. Conclusion

Numerical analyses of the thermal and mechanical loadings of exhaust valves and experimental verification enable one to state that:

1. The bimetallic valves are better at carrying away heat, which results in diminishing of the temperature of a valve head by almost 40 degrees.
2. Due to application of bimetallic valves the amount of heat carried away from the combustion chamber is increased by about 23 %.

3. Application of bimetallic valves does not, in principle, result in the change og the value of the maximal stresses. They are the consequence of the difference in thermal expansion of materials used for the production of valves. The difference of the core elongations and the external layer is compensated by the transition zone between metals consisting of almost pure ferrite.
4. In the course of analysis of the impact of the volume of clearance in the valve-guide connection it has been found that:
   – increase of the clearance volume causes the decrease of the amount of heat carried away by a valve to a guide, which results in the growth of temperature of a valve by about 2,5 degrees,
   – lubrication of the connection has an impact on a better carrying away of heat and on the diminishing of the temperature of a valve by about 2,5 degrees,
   – lubrication causes also the increase of temperature in the bottom part of a guide (on the side of the valve head) by about 5 degrees, as a result of better heat transfer with a guide.
5. Impact of the changes in intensity of lubrication and the clearance between a guide and a valve on the maximal temperatures of a valve is small and has an insignificant influence on the amount of heat carried away from the combustion chamber. It enables to maintain similar thermal conditions of an engine during the whole period of its exploitation.
6. The measurements of temperatures in the specified points of a valve made on the measuring position are consistent with the results of measurements.
7. Thermal analysis enables to determine the thermal balance of a valve and to determine actual heat transfer coefficients between a valve and a guide.

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## Analiza współpracy zaworów bimetalowych z prowadnicą – zagadnienia cieplne

Streszczenie

W pracy przedstawiono wyniki badań oraz analizę termiczną zaworów wykonanych z różnych materiałów. Porównywano zawory monolityczne (ze stali zaworowej) i bimetalowe wykonywane tą samą technologią, przy czym w zaworach bimetalowych zewnętrzna warstwa była zrobiona ze stali zaworowej, a wewnętrzna ze stali 45. Przedstawiono wyniki pomiarów nagrzewania zaworów i zmierzone temperatury na powierzchni zaworu, a także w prowadnicy. Przeprowadzono obliczenia modelowe z wykorzystaniem metody elementów skończonych, rozkładu temperatur w zaworze umieszczonym na stanowisku badawczym oraz podczas pracy silnika. Przeanalizowano również wpływ szczeliny między prowadnicą a zaworem na odprowadzanie ciepła (szerokość szczeliny i jej smarowanie). Do analiz zbudowano model zaworu wraz z prowadnicą. Na podstawie analizy ciepła wydzielanego w komorze spalania i kanale wylotowym wyznaczono warunki wymiany ciepła. Przedstawiono wyniki analiz i porównano je z wynikami badań. Stwierdzono, że w przypadku stosowania zaworów bimetalowych ilość ciepła odbierana od ścianek komory spalania i z kanału wylotowego jest większa, co pozwala na stosowanie ich w silnikach bardziej obciążonych cieplnie. Zastosowanie tego typu zaworów pozwala również na obniżenie kosztów ich wytwarzania.