

Assessment of total efficiency in adiabatic engines

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Abstract. The paper presents influence of ceramic coating in all surfaces of the combustion chamber of SI four-stroke engine on working parameters mainly on heat balance and total efficiency. Three cases of engine were considered: standard without ceramic coating, fully adiabatic combustion chamber and engine with different thickness of ceramic coating. Consideration of adiabatic or semi-adiabatic engine was connected with mathematical modelling of heat transfer from the cylinder gas to the cooling medium. This model takes into account changeable convection coefficient based on the experimental formulas of Woschni, heat conductivity of multi-layer walls and also small effect of radiation in SI engines. The simulation model was elaborated with full heat transfer to the cooling medium and unsteady gas flow in the engine intake and exhaust systems. The computer program taking into account 0D model of engine processes in the cylinder and 1D model of gas flow was elaborated for determination of many basic engine thermodynamic parameters for Suzuki DR-Z400S 400 cc SI engine. The paper presents calculation results of influence of the ceramic coating thickness on indicated pressure, specific fuel consumption, cooling and exhaust heat losses. Next it were presented comparisons of effective power, heat losses in the cooling and exhaust systems, total efficiency in function of engine rotational speed and also comparison of temperature inside the cylinder for standard, semi-adiabatic and full adiabatic engine. On the basis of the achieved results it was found higher total efficiency of adiabatic engines at 2500 rpm from 27% for standard engine to 37% for full adiabatic engine.

1. Introduction

Measurement of heat transfer in internal combustion engines encounters great difficulties due to unsteady heat flow from the changeable temperature of the hot gas in the cylinder to the cooling medium, in most cases water. The biggest temperature of the cylinder charge takes place at the end of the combustion process at initial period of expansion stroke. On the other hand the lowest temperature of the charge occurs during intake stroke. Sometimes temperature of the cooling medium is higher than temperature of the cylinder charge. From technical point of view there is problem with measurement of changeable temperature in the cylinder and therefore also assessment of the heat flows. Increasing of total efficiency of IC engines requires a decreasing of thermal losses to the cooling system, decreasing of exhaust losses (lower energy flowing into outflow system) and decreasing of friction losses (increasing of mechanical efficiency). The most interesting is lowering of heat transfer from the gas inside the cylinder to a cooling medium (water or air). In order to achieve higher thermal efficiency the adiabatic processes should occur in engine. During last many years much research works were done for increasing of engine efficiency by using materials with lower conductivity in order to decrease heat transfer. The problem was presented for example by Kamo [9] for diesel engine in 1987. His study concerned the problem of utilization high exhaust energy in adiabatic engine. His work helped the Cummins Engine Company, Inc. and the U S. Army to develop



an adiabatic turbo-compound engine during the last nine years [10] by using exhaust gas energy. The researchers from Ocean & Ship Foundation (Japan) [4] by insulation of the diesel engine fuelled by CNG and applying of recovering turbine improved engine efficiency from 42% to 57.5%. Another researcher Khoshnavan [5] carried out the CFD calculations of heat transfer in the diesel engine with ceramic coating on the cylinder liner. The calculations were next verified by experimental work on single research engine. Many researchers used adiabatic engines for checking of influence of higher temperature on combustion of biofuels. Such work was done by scientists from BIT Rajshahi and Jadavpur University [6] on semi-adiabatic diesel engine fuelled by vegetable oil. They found that exhaust temperature, CO emission and smoke have increased, but engine thermal efficiency and NO_x has decreased. The adiabatic engines both SI and CI indicate higher temperature inside the cylinder which influences on exhaust gas emission. The researcher Gosai and Nagarsheth [7] during their research work on diesel adiabatic engine found a few percent decrease of molar concentration of CO₂, HC and CO were decreased in comparison to standard diesel engine. Also smoke density was reduced about 39.5% due to zirconium coating on the cylinder liner. In this case also thermal efficiency was increased. Predicting of work parameters of four-stroke adiabatic engine was carried out by Reddy and Pandurangadu [8]. They also found higher exhaust gas losses due to higher combustion temperature, but they achieved higher thermal efficiency. Influence of different ceramic materials such as SiO₂, Al₂O₃, ZrO₂, SiC, Si₃N₄, which were used as coating surfaces with thickness 0.5 mm in combustion chamber in diesel engine was presented by Turkish scientists in the work [11]. They confirmed about 3% increase of engine power at high rotational speed and about 10% lower heat transfer rate.

This paper concerns a determination of influence thermal barrier on engine parameters and heat balance which is caused by ceramic coating on inner surfaces of the combustion chamber (cylinder liner, piston and cylinder head). Mathematical model of heat transfer to the cooling medium by convection, conductivity and radiation enables calculation of engine thermodynamic processes and prediction of cooling and exhaust heat losses. Theoretical studies of adiabatic engines help to develop a new design of such engine. The study was carried out only for SI four stroke engine, where all previous works were done on diesel engines.

2. Heat transfer in piston engines

The thermodynamic model of heat exchange in piston internal combustion engines takes into account changeable temperature of the cylinder charge and constant temperature of the cooling medium. In this paper the water is considered as cooling medium, because most of the modern engines are currently equipped with liquid cooling system. In order to increase total efficiency of the engines the difference between higher and lower heat sources should reach higher value. Usually higher temperature T_{max} of the combustion process influences on higher total efficiency.

$$\eta_0 = \frac{T_{max} - T_{min}}{T_{max}} = 1 - \frac{T_{min}}{T_{max}} \quad (1)$$

Heat transfer in the piston engines is carried out through three phenomena: convection, radiation and conductivity. Usually calculation is carried out for assessment of heat transfer in IC engines. Temperature of the charge in the cylinder changes during piston motion from value near 3000 K to 350 K in SI engine, thus the heat stream to the cooling medium changes rapidly and fluctuation of heat transfer can be defined in a function of crank rotation. Diagram showing change of temperature in the cylinder walls and cooling medium is presented in Fig. 1. The cylinder wall consists two layers: the first with lower conductivity and thickness g_c in mostly cases as ceramic coating and second layer with bigger thickness g_l made from cast iron with higher conductivity. The surface area of heat exchange on the cylinder liner changes according to the piston movement. However the surfaces of heat transfer through the piston and cylinder head do not changes. The heat transfer depends on convection process in the cylinder and cooling medium and cannot be controlled by engine geometry and materials, but the heat flow resistance can be reduced by applying of wall material with different conductivity. Heat

transfer as a result of radiation is only due the temperature difference between the gas and walls and emissivity of the surfaces and the cylinder gas.

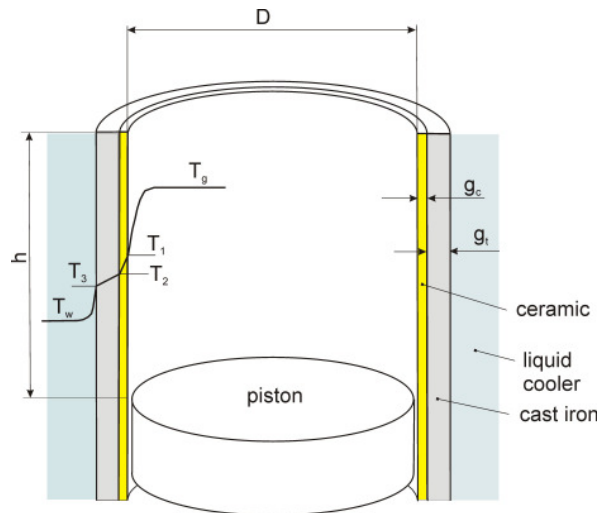


Figure 1. Schematic temperature course during heat transfer in IC Engines with ceramic coating on the cylinder liner.

In order to decrease the heat flow stream from the cylinder wall to water it is considered application of the special coating with the material of lower conductivity, usually a ceramic coating. The surface heat flow rate \dot{q} through the wall with thickness l and wall conductivity λ can be expressed as follows:

$$\dot{q} = -\lambda \frac{dT}{dl} \quad [\text{W/m}^2] \quad (2)$$

For constant wall conductivity λ this expression can be written as a function of the temperature difference ΔT , thickness g of the wall or the heat transfer resistance R_λ :

$$\dot{q} = -\lambda \frac{\Delta T}{g} = -\frac{\Delta T}{R_\lambda} \quad (3)$$

Real surface heat stream from the gas inside the cylinder to the liquid cooling medium through the wall depends on thermal resistance during convection and conductivity of the wall layers. Total heat flow resistance for flat walls can be written as follows:

$$R_t = R_{\alpha 1} + R_{\lambda 1} + R_{\lambda 2} + R_{\alpha 2} = \frac{1}{\alpha_1} + \frac{g_c}{\lambda_1} + \frac{g_t}{\lambda_2} + \frac{1}{\alpha_2} \quad (4)$$

where: $R_{\alpha 1}$ - convection resistance in the cylinder,

$R_{\alpha 2}$ - convection resistance in the cooling medium,

$R_{\lambda 1}$ - conductivity resistance in the ceramic layer,

$R_{\lambda 2}$ - conductivity resistance in the cast iron layer,

α_1, α_2 - convection coefficient of gas near the walls and cooling medium, respectively,

λ_1, λ_2 - conductivity coefficient of the ceramic and cast iron layers,

g_c, g_t - thickness of ceramic coating and cylinder sleeve, respectively.

In reality heat flow occurs through the cylindrical walls and for this case the flow resistance is not a linear function of wall thickness but for multi-layer walls is expressed as follows:

$$R_{\lambda} = \frac{r_i}{\lambda_i} \ln \frac{r_{i+1}}{r_i} \quad (5)$$

where: r_i, r_{i+1} - inner and outer radius of the layer walls, respectively,
 λ_i - conductivity of layer material.

Convection coefficient α_1 inside the cylinder (heat flow from the gas to the inner cylinder wall) can be calculated using Woschni experimental formulas for intake, compression, expansion and exhaust processes given in different sources [1, 3]. On the other hand inflow of the heat to the liquid medium is a linear function of convection coefficient α_2 and can be obtained from Nusselt number, which is a function of Reynolds and Prandtl numbers. However, the simple expression as a function of water velocity given by Heywood [1] was used. Convection coefficient for heat outflow from the bottom surface of the piston head is calculated using Grashoff and Prandtl numbers for laminar flow from the crankcase side. Temperature of the gas inside the crankcase is almost constant (about 350 K) and gas flow near the piston walls is laminar.

Knowing all heat transfer resistances from the cylinder gas to the external cooling medium the surface heat flow rate \dot{q} (without radiation) can be determined from (1). The changeable temperature of the cylinder gas is obtained from simulation process of engine work with taking into account unsteady gas flow in inlet and outlet systems. At such assumptions temperature of internal cylinder wall T_1 and temperature T_2 can be determined from the following expression:

$$T_1 = T_g - \frac{\dot{q}}{\alpha_1} \quad T_3 = T_w + \frac{\dot{q}}{\alpha_2} \frac{r_1}{r_3} \quad (6)$$

where: $r_1 = 0.5D$ and $r_3 = r_1 + g_c + g_t$

Radiation heat between cylinder gas containing also soot and walls is determined from the following formula given by Horlock and Winterbone [2]:

$$\dot{q}_r = \frac{F_b}{F_1} \sigma_0 \varepsilon_z [T_g^4 - T_1^4] \quad (7)$$

where $\sigma_0 = 5.67$ is Boltzman constant, ε_z is emissivity of central body, F_b and F_1 are central and surroundings surfaces, respectively.

3. Research object

The simulation research was carried out on SI four stroke engine SUZUKI DR-Z400S, which geometrical parameters are presented in Table 1.

Table 1. Geometry of simulation engine based on SUZUKI DR-Z400S

Geometrical parameters	Data
Cylinder diameter	90 mm
Stroke	62,6 mm
Compression ratio	8
Number of valves	2+2
Opening and closing of inlet valve	20° CA BTDC/ 45° CA ABDC
Opening and closing of exhaust valve	40° CA BBDC / 19° CA ATDC

In order to perform the simulation test of influence of ceramic coating on the combustion chamber surfaces on engine work parameters the calculation computer program was made by author, which takes into account all thermodynamic processes taking place during one engine cycle. The combustion processes was modelled by using Viebe function and gas flow in engine ducts was treated as an

unsteady flow with taking into account the waveform of pressure. For comparison of all considered cases of the tests the coefficients in Viebe function were assumed with the same value. However heat release depends also on there initial temperature of the charge in the cylinder. Validation of the assumed combustion model for all calculation models is required in the future. In this work the Viebe coefficients a and m were taken from the experimental work done before on the conventional engine Suzuki by Soczowka [12] with using of the following exponential Vibe formula:

$$x_b = 1 - \exp \left[a \left(\frac{\varphi - \varphi_b}{\Delta\varphi_b} \right)^m \right] \quad (8)$$

where: x_b - fuel burnt ratio,
 φ - current angle of crank rotation,
 φ_b - crank angle of beginning of fuel burning,
 $\Delta\varphi_b$ - duration of crank angle rotation of full combustion process.

The following values of coefficients were taken from calibration of the standard engine: $a = -6.908$ and $m = 3$. At higher temperature at the end of compression process in the adiabatic engine and semi-adiabatic engine one can expect knocking problem. The knocking phenomenon can be reduced by decreasing of compression ratio, however, which leads to lower engine total efficiency.

The purpose of this work a special attention was paid to heat transfer from the cylinder gas to the water as a cooling medium with constant temperature 357 K flowing around the cylinder with velocity 0.8 m/s. Input data containing many constant parameters were read by the program from the text table. The results of calculation were transferred to the output files giving many thermodynamic parameters as a function of crank angle rotation for given engine speed, constant ignition point and combustion duration. Convergence calculations were provided by the iterative cycle work until the indicated pressure difference achieved an assumed value. The calculations were made for changing a thickness of the ceramic coating with constant low conductivity 5 W/m and for cylinder sleeve made from cast iron with constant conductivity 45 W/m. The cylinder head and piston were treated as an aluminium alloy with conductivity equal 180 W/m. For comparison of calculation results only changing of ceramic coating was considered. The purpose of the calculations was to determine the effect of adiabatic process on engine work parameters, especially total engine efficiency. Three cases of four stroke engine were compared: standard engine (without ceramic coating), full adiabatic engine (without cooling effect) and semi-adiabatic (with changeable ceramic coating).

4. Influence of ceramic thickness on engine work parameters

The first stage of calculation of was determination of influence of thickness of the ceramic coating on four-stroke engine work parameters, which were carried out at 3000 rpm and air excess ratio $\lambda = 1$ for whole range of thickness from 0 to 2 mm. The thickness equal 0 mm of the coating means that only the cast iron cylinder sleeve is the thermal barrier for conductivity. Figure 2 presents variation of mean indicated pressure and specific fuel consumption as a function of thickness of ceramic coating on all surfaces of combustion chamber (cylinder walls, cylinder head and piston head), wherein conductivity of the ceramic coating were constant and amount 5 W/m. It was found increasing of mean indicated pressure only 0.2 bar (near 2%) with increasing of the ceramic coating thickness from 0 to 2 mm. On the other hand increasing of this value causes a decreasing of specific fuel consumption about 3%. Figure 3 presents courses of cooling heat losses, exhaust heat losses and engine total efficiency for engine with combustion chamber covered with different thickness of the ceramic coating at constant rotational speed 3000 rpm.

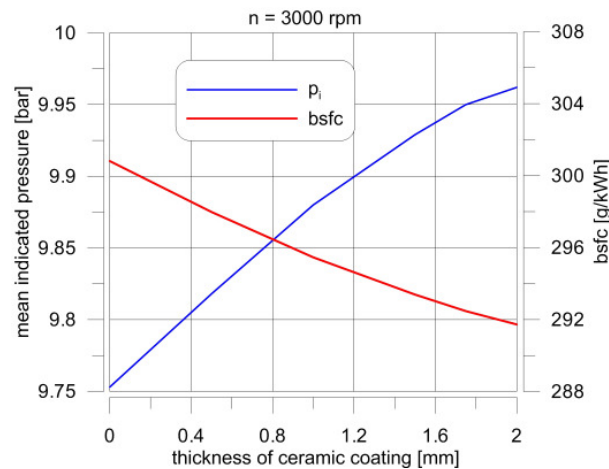


Figure 2. Influence of ceramic coating thickness on mean indicated pressure and specific fuel consumption.

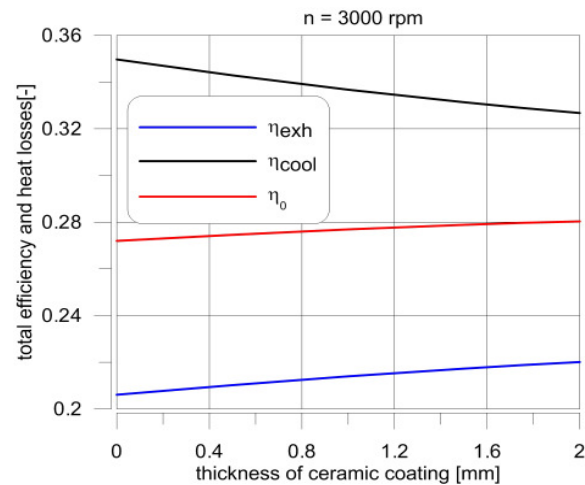


Figure 3. Exhaust and cooling heat losses and total efficiency versus thickness of ceramic coating.

After increasing of ceramic coating thickness the heat transfer to the cooling liquid is decreased but at the expense of increasing the amount of the exhaust heat. On the other hand the increasing of total efficiency is seen from 27% to 28%. It was observed lowering of engine power for three considered cases at 3000 rpm (Fig.4). In standard engine (without ceramic coating) the cooling heat losses amount about 35% of total heat released from fuel during combustion process.

5. Adiabatic engine versus standard engine

Further simulation studies were carried out on three types engines: 1) fully adiabatic, 2) with thickness of the ceramic coating equal 1 mm and 3) standard engine at wide throttle opening ($\lambda=1$) and different rotational speed. Figure 4 presents effective power of engines on speed characteristic.

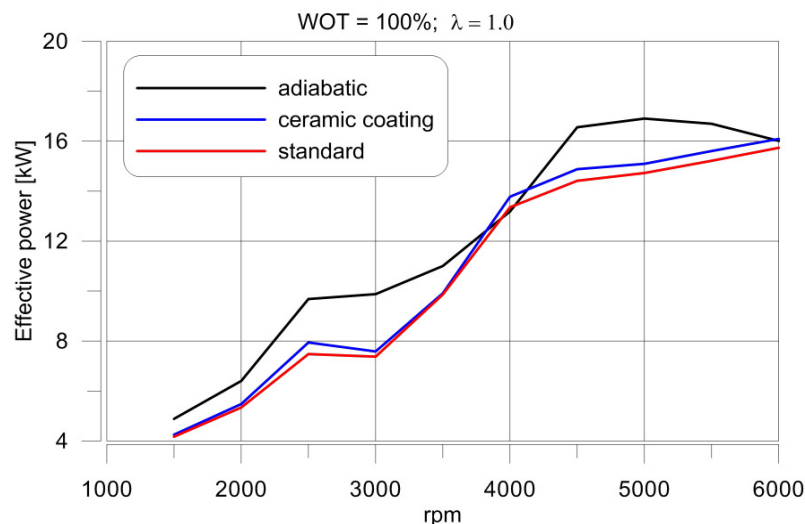


Figure 4. Comparison of effective power for three engines cases.

The adiabatic engine indicates higher power in whole range of rotational speed. The highest difference between standard and adiabatic engine amounts 2.5 kW at 3000 and 4500 rpm (increase about 33% and 17%, respectively). The cooling heat losses can be reduced by covering of the combustion chamber with layer of material of low conductivity. It was found a decreasing of cooling heat losses

with increasing of rotational speed (Fig. 5). In the adiabatic engine these losses theoretically amount zero.

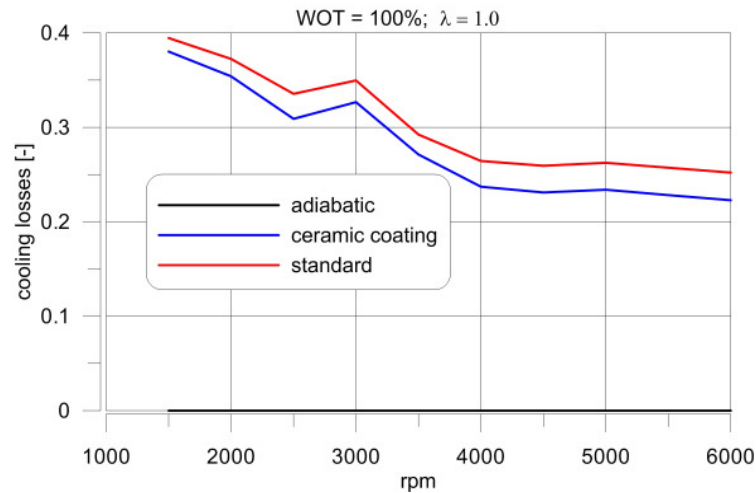


Figure 5. Comparing of cooling heat losses for three engine types.

In the adiabatic engine these losses theoretically amount zero. The engine with ceramic coating of the combustion chamber indicates decreasing of the cooling heat about 3 %. It is not as much as was expected. The decreasing of the cooling heat influences on higher amount of the exhaust heat at the increase of rotational speed. In the engine with full adiabatic processes of the working cycle the exhaust heat losses amount almost 50% of total delivered energy from fuel (Fig. 6). In the standard engine these losses amount only 28% at 4000 rpm. The engine with semi-adiabatic processes (ceramic thickness 1 mm) indicates about 8% increase of energy in the exhaust system. Increasing of exhaust energy can be used in cogeneration systems but in the engine the first step is using this energy for driving the turbocharger for obtaining a higher engine power.

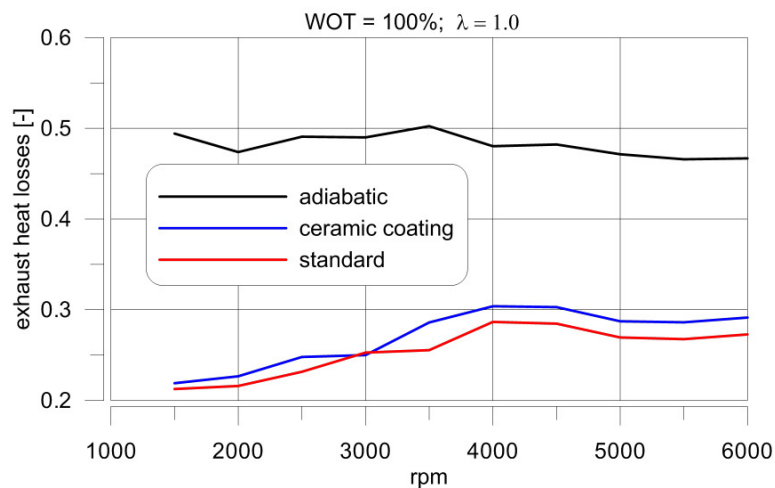


Figure 6. Comparing of exhaust heat losses for three engine cases.

The engine work is assessed by determination of total efficiency. The computer program calculates the mechanical work and total energy delivered with gasoline by knowing its caloric value. Figure 7 presents courses of total efficiency for three considered engine cases. The adiabatic engine has a greatest efficiency at lower rotational speeds compared to the standard engine approximately 35% but at higher rotational speeds only 13%. Covering of the combustion chamber surfaces with a thin ceramic coating (1 mm) will increase the total efficiency about 4% in comparison to the standard engine. The adiabatic processes in SI engine cause an increase of internal energy, because there is any

heat transfer to the cooling medium. In such engine temperature of the cylinder gas reaches value about 3000 K, which is about 250 K higher than in the standard engine (Fig. 8).

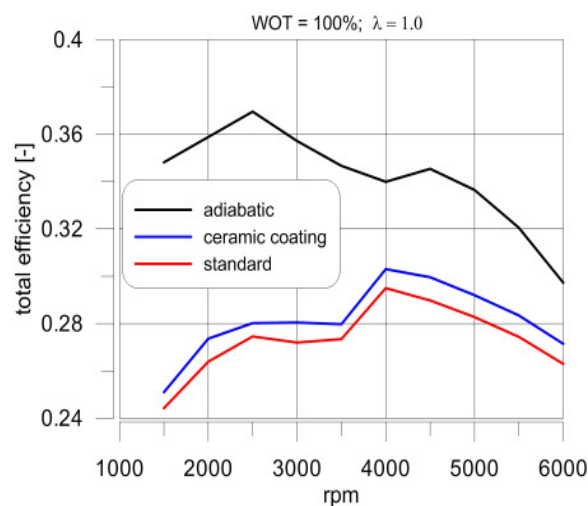


Figure 7. Variation of total efficiency for three engines cases.

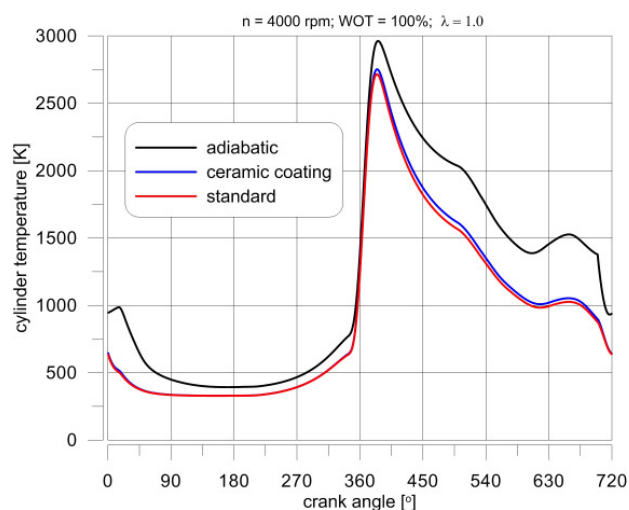


Figure 8. Comparison of cylinder gas temperature for three engine cases at 4000 rpm and WOT.

During all engine processes this temperature is always higher even during intake stroke. This phenomenon has a big influence on thermal stresses of all engine elements, especially on the exhaust valves. Such high exhaust temperature is too high for all turbocharger's elements.

6. Summary

The presented work shows a certain aspects of applying the ceramic coating for adiabatic processes in SI engines, which was considered mostly in diesel engines in the past. On the basis of heat transfer mathematical model the simulation of work cycle of three SI engine cases was made for different initial conditions. One of the effects of the work is elaboration of computer program for analyzing the adiabatic engine work. The achieved results of the numerical studies give the following conclusions:

1. The full adiabatic engine without heat transfer to the cooling medium indicates higher engine power than standard engine from 17% at higher rotational speed to 33% at lower rotational speed.
2. Increasing of the ceramic thickness coating on the combustion chamber walls gives a linear increase of mean indicated pressure, but the increment is only 2% at thickness 2 mm. Technology of ceramic covering is expensive and so low yield energy does not compensate the cost of this technology.
3. The adiabatic engines influences on higher temperature of the cylinder charge and high exhaust heat losses. However the exhaust energy can be used to drive a turbocharger and also utilized in cogeneration systems.
4. Almost a half of delivered energy from fuel is discharged with exhaust gases for the adiabatic engine, when in semi-adiabatic only 28% of total energy is discharged to the outflow.
5. The calculations indicated a lowering of cooling heat losses with increasing of rotational speed both for standard and semi-adiabatic engine.
6. Total yield of energy is possible only for full adiabatic engine with ceramic coating with a conductivity close zero.

Future work concerning the adiabatic SI engine should be conducted on experimental test in order to calibrate the parameters of combustion process especially to determine the Vibe coefficients and possibility of knock combustion due to higher temperature at the end of compression process.

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