ANALYSIS OF THERMAL BARRIER COATED PISTONS IN THE COMSOL AND THE EFFECTS OF THEIR USE WITH WATER + ETHANOL DOPED BIODIESEL

by

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In this study, the thermal analysis of an aluminum piston coated with $MgOZrO_2$ to create a thermal barrier with the COMSOL multiphysics program and the changes in exhaust gas temperature, fuel consumption, and engine torque values obtained as a result of engine test experiments were examined. For this purpose, the $MgOZrO_2$ coated and uncoated piston engine was started with biodiesel and 5% water + 15% ethanol doped biodiesel fuel at engine speeds of 1000 rpm, 1500 rpm, 2000 rpm, and 2500 rpm. In the thermal analysis results obtained in the COMSOL, it was found that the temperature values increased in the upper regions of the coated pistons. Likewise, in engine experiments, increased exhaust gas temperature and engine torque showed a tendency to decrease fuel consumption values. It has been observed that the data obtained in the analysis in the COMSOL program are in parallel with the results of the engine experiments.

Key words: *COMSOL Multiphysics, thermal barrier coating, engine test, biodiesel*

Introduction

Most of the recent studies on internal combustion engines focus on reducing fuel consumption values [1-3], reducing exhaust emissions [4-6] and improving combustion efficiency by replacing engine materials [7, 8]. In the studies conducted at this stage, it is generally stated that the combustion efficiency in the cylinder is increased by coating the piston and valve surfaces with materials with low thermal conductivity with different methods and that there are decreases in exhaust emissions [9].

In recent years academic studies in internal combustion engines, artificial intelligence estimate [10, 11], optimization [12, 13] and computer-assisted design and analysis environments [14, 15] is also supported. The researchers aim to perform analyzes without entering the laboratory environment with calculations based on this type of mathematical modelling. Thus, many test procedures are being tried to be reduced in academic studies and industrial production stages.

The COMSOL program is a simulation software that helps engineering, production and scientific research organizations manage physics-based modelling through verification and optimization of processes and devices. The platform enables users to create custom modelling workflows, making it easy to share data between multiple models, including electromagnetic,

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heat transfer, structural mechanics, fluid-flow, and more dec with this program, researchers usually see that fluid and heat transfer [16-20] analyses are performed. In the articles examined, it can be seen that the results of such studies are quite close to the real results. All these studies together show that the COMSOL is used for various analyzes in internal combustion engines. As is known, engine pistons are produced by pouring AlSi purchases. There are many studies aimed at increasing engine performance and reducing exhaust emissions by reducing the thermal conductivity of pistons made of AlSi alloys [21-24].

In this study, the pistons were coated with Nicocray, SiC, and $MgOZrO_2$ to create a thermal barrier. Previously, the analyzes performed in solidworks were repeated in this study with the COMSOL program. In the literature reviews, it has been seen that the COMSOL Multiphysics program is not used for thermal analysis on such coated pistons. In addition, by adding water + ethanol to biodiesel in a coated piston engine, the effect of the water-containing fuel mixture on the exhaust gas temperature fuel consumption and the change in engine torque values in a coated engine was studied. Thermal depreciation, which will be reduced by water, has been tried to be covered through a thermally coated engine.

Materials and methods

Coating materials

While the 3-D design of the material was made in the COMSOL Multiphysics program, the standard piston was defined as aluminum silicon material. This program has a powerful interactive physical interfaces for modelling different devices. It can also simplify the merging of thermal, electrical, and structural analyzes, which are necessary for the current design. Firstly, 150 μ thick NiCoCrAlY material was coated on the piston material as an interconnection coupler, and in the next step, the coating process was carried out with 300 μ thick $MgOZrO_2$ materials, fig. 1.

Figure 1. Thermal barrier coating thickness

Coating materials were added to the proposed piston model, respectively. The properties of coating materials are given in tab. 1. In real coating conditions, the materials to be coated should be grinded on the surface as much as the coating material. Therefore, the actual coating conditions were taken into account and the entire length of the material was not changed after coating.

Table 1. Properties of the substrate and coating materials [25]

Parameters	Piston (AlSi)	Bond coat (NiCoCrAIY)	$MgOZrO_2$
Density [kgm^{-3}]	2700	7320	5500
Young's modules [GPa]	69	225	200
Poisson's modules	0.33	0.30	0.32
Thermal conductivity [$Wm^{-1}K^{-1}$]	155	6	2
Thermal expansion coefficient 10^6 [$°C^{-1}$]	21	12	8
Specific heat [$Jkg^{-1}K^{-1}$]	960	501	418

Analysis method

For analysis, the piston of a single-cylinder four-stroke Diesel engine was modelled in 3-D in COMSOL Multiphysics program. The mathematical model of the modelled piston was created with the *MESH* command in the COMSOL simulation program. The mathematical set-up model is shown in fig. 2. Analyzes were made by defining the piston as AlSi material. The oil film and transmission coefficient of the coil are neglected. The analysis process consists of the following steps:

- Program set-up (initialization).
- Defining parameters,
- Building geometry
- Defining materials
- Defining Mesh
- Configuring study

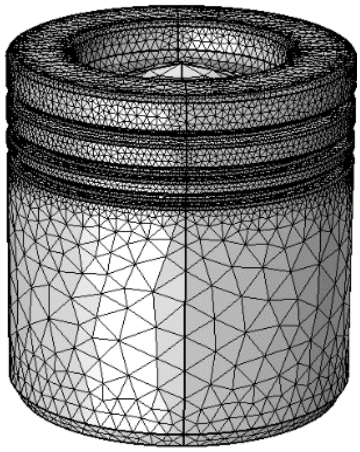

Figure 2. The finite element mesh model

In single cylinder four-cycle motors, values relevant to the temperature changes within cylinder are included in many literature studies. In these studies, the temperatures affecting the piston had increased due to the temperature on coated and uncoated pistons. In the literature researches performed, the analyses were performed based on the past experiences and measurements of the authors. In this way, the inside temperature was estimated to be 650 °C with a convection coefficient of 800 W/m^{2}K. Lateral surface temperature of the piston was specified as 300 °C with a convection coefficient of 230 W/m^{2}K. Ring temperatures of the piston are defined 160 °C with a convection coefficient of 200 W/m^{2}K. Piston skirt and pin temperatures are defined 85 °C with convection coefficient of 60 W/m^{2}K [26].

Mathematical modelling of thermomechanical behaviour

The process is situated on the subsection of the structures into elements with mathematically described characteristics. Thermal loading involves the primary calculations of temperatures using limit conditions on gas side, coolant side, and air side of piston cylinder. The construction of finite element approach begins from the variation explanation of the problem and then using appropriate shape function a number of algebraic equations are improved which are equal to the number of nodal elements in the problem domain.

In Cartesian form, the heat conduction equation is expressed:

$$\rho c_p \frac{\mathrm{d}T}{\mathrm{d}t} + \frac{\mathrm{d}}{\mathrm{d}x}\left(-k_x \frac{\mathrm{d}T}{\mathrm{d}x}\right) = Q \tag{1}$$

Multiply eq. (1) by x^2 to prevent division by zero at $x = 0$:

$$x^2 \rho c_p \frac{\mathrm{d}T}{\mathrm{d}t} + \frac{\mathrm{d}}{\mathrm{d}x}\left(-k_x x^2 \frac{\mathrm{d}T}{\mathrm{d}x}\right) = x^2 Q \tag{2}$$

Using the dimensionless x-co-ordinate by scaling the equation ensures the choice to quickly change it:

$$\hat{x} = \frac{x}{w_x}, \quad \frac{\mathrm{d}}{\mathrm{d}x} = \frac{1}{w_x}\frac{\mathrm{d}}{\mathrm{d}\hat{x}} \tag{3}$$

Introducing the dimensionless co-ordinate, and substituting in eq. (2) leads to:

$$\hat{x}^2 \rho c_p \frac{\mathrm{d}T}{\mathrm{d}t} + \frac{\mathrm{d}}{\mathrm{d}\hat{x}}\left(-\frac{k_x \hat{x}^2}{w_x}\frac{\mathrm{d}T}{\mathrm{d}\hat{x}}\right) = \hat{x}^2 Q \tag{4}$$

To apply eq. (4), equation 1-D version of equation interface given in eq. (5) was used:

$$\begin{gathered} e_a \frac{\mathrm{d}^2 u}{\mathrm{d}t^2} + d_a \frac{\mathrm{d}u}{\mathrm{d}t} + \nabla\Gamma = F \\ e_a = 0 \\ d_a = \hat{x}^2 \rho c_p \\ \Gamma = -\frac{k_x \hat{x}^2}{w_x}\frac{\mathrm{d}T}{\mathrm{d}\hat{x}} \\ Q = 0 \end{gathered} \tag{5}$$

In case $x = 0$, there is no flow. A heating and cooling expression with a heat transfer coefficient h_s [Wm^{-2}K^{-1}] for the heat flux [Wm^{-2}] on the $x = 1$ surface:

$$q_{\text{in}} = h_s\left(T_{\text{ext}} - T\right) \tag{6}$$

Since the flux as eq. (5), and:

$$-k_x \frac{\mathrm{d}T}{\mathrm{d}\hat{x}} = h_s\left(T_{\text{ext}} - T\right) \tag{7}$$

therefore:

$$g = -\frac{\hat{x}^2}{w_x} h_s\left(T_{\text{ext}} - T\right) \tag{8}$$

Engine tests

For engine tests, the engine whose characteristics are shown in tab. 2 was used. Experiments were repeated with coated pistons on the engine, first with coated pistons, and then with coated pistons.

Table 2. The characteristics of the experimental engine

Engine	Four strokes, direct injection, air-cooled and naturally aspirated
Model	186 FAG
Number of cylinder	1
Intake system	Naturally aspirated
Bore x stroke	86 × 70 mm
Total displacement	406 cm^3
Compression ratio	18:1
Maximum power	7 kW (3600 rpm)
Pressure of injection	19.6 ±0.49 MPa
Fuel delivery advance angle	21 °CA bTDC

The engine experiments were carried out in the experimental set-up given in fig. 3. The loading operations were carried out on the principle of electricity generation. Biodiesel (B) used in engine experiments was obtained from a company that sells it commercially. The second experimental fuel was obtained by adding 5% water + 15% ethanol (BWE) by volume to the biodiesel fuel for the experimental fuels. The fuels prepared in different volumetric ratios were mixed by ultrasonic method in a 50 °C water bath for 2 hours. As a result of this process, the fuel mixtures were rested for 2 hours and it was seen that they did not undergo phase decomposition.

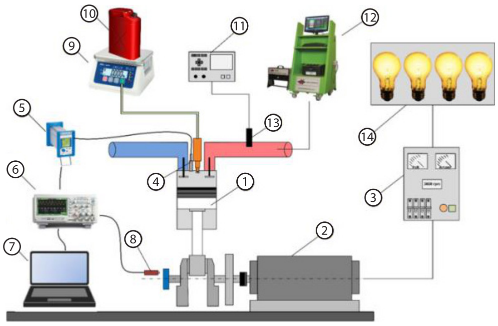

Figure 3. Schematic of the experimental set-up; *1 – Diesel engine, 2 – generator, 3 – generator control panel, 4 – cylinder pressure sensor, 5 – charge amplifier, 6 – oscilloscope, 7 – computer, 8 – crank encoder, 9 – precision scale, 10 – fuel tank, 11 – data logger, 12 – exhaust gas analyzer, 13 – K-type thermocouple, 14 – lamp load unit*

In the graphs where the experimental results are expressed, B refers to 100% biodiesel, BWE refers to biodiesel with 5% water + 15% ethanol additives. Some properties of the resulting fuel mixtures have been tested and the results are given in tab. 3. Engine experiments were repeated at 1000 rpm, 1500 rpm, 2000 rpm, and 2500 rpm engine speeds in a mixture of two fuels for coated and coated pistons. During the experiments, fuel consumption, exhaust gas temperature, engine torque and fuel consumption values were measured. The exhaust gas temperature is measured by a *K*-type thermocouple, the fuel consumption value is measured by mass with the help of scales.

Table 3. Characteristics of experimental fuels

Test fuel	Lower heating value [$kJkg^{-1}$]	Kinematics viscosity [mm^2s^{-1}] at 40 °C	Density [gcm^{-3}] at 15 °C	Flash point [°C]
B	36.2	4.7	879	106
BWE	33.4	3.6	885	125

Results and discussion

The COMSOL analysis results

The simulation process was carried out in two-stages, initially the aluminum micro beam was designed and its displacement was carried out for three different input potentials. In the second stage, displacements were performed for Cu, Ni, and Pt beams instead of aluminum material for similar input potentials. The support points of the micro beams at both ends are fixed on a substrate and electrical potential is applied through the pads. When the fig. 4 extracted from the analysis results was examined, it was seen that the highest temperature value on the uncoated piston was around 425 °C, and in the coated engine, this temperature value increased to 585 °C. In addition, the temperature value in the uncoated piston has recovered at some point, while the temperature value in the coated engine has started to be optimally distributed in the upper piston region.

Engine test results

Coated and uncoated engine experiments were repeated with B and BWE fuel mixtures. The exhaust gas temperature and NO_x emissions data obtained with each fuel mixture were graphed and discussed in this region.

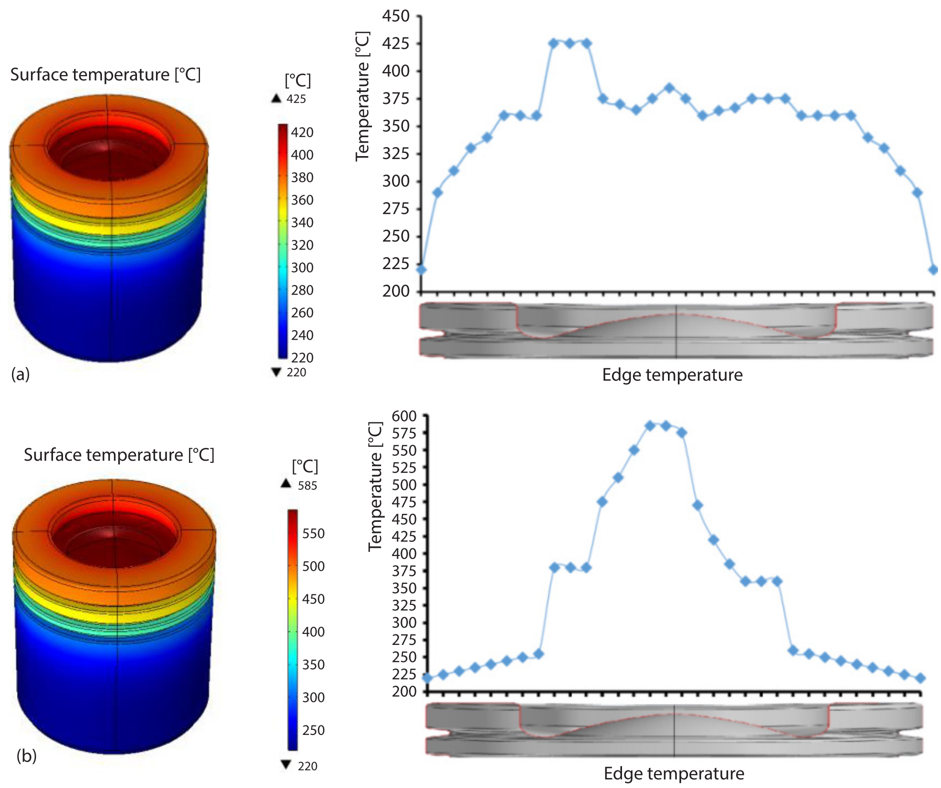

Figure 4. The results of the analysis of uncoated (a) and coated (b) pistons of the COMSOL program

Figure 5 shows the variation of exhaust gas temperatures. Exhaust gas temperatures in internal combustion engines, the exhaust gas temperature is considered to be an indicator of combustion in the cylinder [27]. There are many studies explaining the increase in exhaust gas temperature in engines with thermal barrier coating with an increase in combustion efficiency or an increase in combustion time [28]. According to the COMSOL analysis results given in fig. 4, it is seen that more temperature values are formed on the coated pistons. The data obtained in the experimental results also support the data of the COMSOL program. Because in this study, the exhaust gas temperature values increased at all engine speeds compared to the uncoated piston with the use of B fuel in the engine covered with a thermal barrier. Along with the use of the BWE fuel mixture, there was a tendency to decrease compared to those in coated and uncoated engines. This can be explained by the ratio of water in the fuel mixture. In the study, the lowest exhaust gas temperature was obtained with 154 °C at 1000 rpm engine speed with BWE fuel mixture, while the highest temperature value was measured as 302 °C with B fuel at 2500 rpm engine speed. The results of the study are similar to those of the [29] study in the literature.

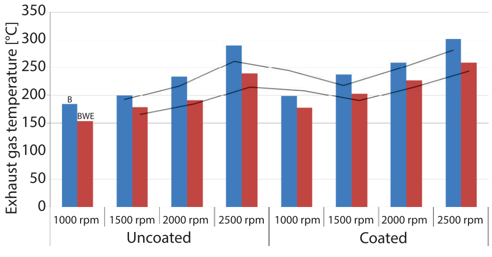

Figure 5. Change of exhaust gas temperature value

Figure 6 shows the changes in engine torque values at different engine speeds between the B and BWE fuel mixtures of coated and uncoated pistons. Engine torque is the thrust force of the pressure on the piston caused by the combustion of fuel and air taken into the cylinder. An increase in torque in internal combustion engines also means an increase in the useful work that will be achieved. Along with the coating of the engine pistons, an increase in engine torque values was observed with the use of B fuel at all engine speeds. Along with the use of the BWE fuel mixture, a decrease in engine torque values is observed. However, the decrease in uncoated pistons caused by the use of BWE fuel mixtures could be prevented by the use of coated pistons. In internal combustion engines, an increase in the combustion end temperature in the cylinder is an important parameter for increasing engine torque [30]. This situation is similar to the temperature increase value that is also revealed in the thermal analysis in the COMSOL program. In addition, the thermal barrier of the fuel, whose thermal value decreases with the addition of water + ethanol, and the engine torque value increased slightly. The highest engine torque value was obtained as 17.6 Nm at a motor speed of 2500 rpm in a coated engine with B fuel, while the lowest torque value was obtained as 9.4 Nm at a motor speed of 1000 rpm with a mixture of BWE fuel in an uncoated engine.

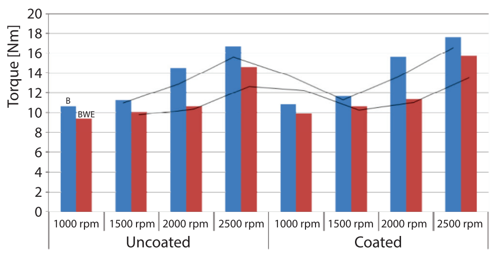

Figure 6. Engine torque change

Figure 7 shows the changes in engine fuel consumption values at different engine speeds with B and BWE fuel mixtures of coated and uncoated pistons. Along with the use of coated pistons, the specific fuel consumption value has tended to decrease at all engine speeds and fuel mixtures. It is expected that there will be a decrease in fuel consumption value as an output of increased engine torque due to the fact that pistons with thermal barriers retain heat [31]. It has been observed that the temperature increase obtained from the analysis results in the COMSOL is also supported by fuel consumption values. In addition, the fact that the water + ethanol content added to the B fuel and the reduced thermal value increased with the coated piston also supports the results. As a result of engine tests, the lowest BSFC value was obtained as 278 g/kWh at an engine speed of 2500 rpm with B fuel, while the highest BSFC value was measured as 403 g/kWh at an engine speed of 1000 rpm with a fuel mixture of BWE.

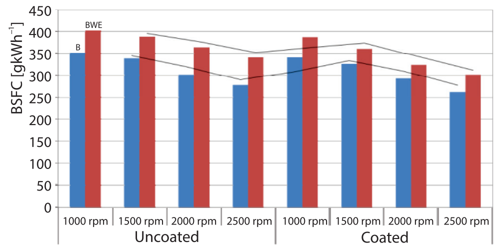

Figure 7. The BSFC exchange

Conclusions

As a result of engine experiments with coated ($MgOZrO_2$) and uncoated (AlSi) pistons, the following findings were obtained are as follows.

- In the COMSOL Multiphysics program, temperature differences were found in the pistons that were thermally analyzed as coated ($MgOZrO_2$) and uncoated (AlSi). It was observed that the temperature value increased by 37.6% in the upper region of the coated piston compared to the uncoated piston.

- The exhaust gas temperature has increased with the use of coated pistons in all fuel mixtures and engine speeds. The highest rate of increase was achieved with BWE fuel at an engine speed of 2000 rpm at a rate of 18.84%.
- The BSFC value decreased with the use of coated pistons in all fuel mixtures and engine speeds. The highest reduction rate was achieved at an engine speed of 2000 rpm with the use of B fuel with a rate of 2.9%.
- With the use of coated pistons, an increase in engine torque values was observed at all engine speeds and in different fuel mixtures. The highest increase rate was achieved with a mixture of BWE fuel in a coated piston with a ratio of 7.53%.
- Diversifying the work in this field under different engine conditions and with different fuel mixtures will be beneficial for the future of the work.

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