Heat Loss and Thermal Stresses in DI Diesel Engine Using Functionally Graded Cylinder (FGMs)

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Abstract: In this paper, the analysis of cylinder made of Functionally Graded Material (FGM) is developed in the internal combustion engines to achieve low thermal conductivity of combustion chambers. The cylinder thickness is divided to many sub-cylinders that each of them is assumed as an isotropic layer. The heat conduction, temperature distribution and thermal stresses in cylinder wall are calculated by using the combination of finite element-finite difference methods then the results compared between various engine loads and speed conditions for a FGM cylinder and other existing cylinders for a typical diesel engine.

INTRODUCTION

The isolated surfaces are a new trend in the field of internal combustion engines. The surfaces of combustion chamber, cylinder wall and cylinder head, pistons and valves are isolating by using ceramic materials. The most important advantages are improvement of the engine performance, improving fuel economy and the elimination of the cooling systems. There are many researches, which present the advantages of the isolated surfaces applications in internal combustion engines [1, 2]. Kamo and Bryzik [3] have achieved a major breakthrough in diesel engine technology. Many governments, industries and academic sources worldwide have began to work in the area of adiabatic engine technology. The coatings of isolation materials used in the Low Heat Rejection (LHR) engine have a high temperature strength, high expansion coefficient, low friction characteristics, good thermal shock resistance, lightweight and durability [4]. Kamo and Bryzik used thermal isolating materials such as silicon nitride for isolating different surfaces of the combustion chamber. In their studies, an improvement in the performance of about 7% was observed [3]. Sekar and Kamo [5] developed an adiabatic engine for passenger cars and reported an improvement in the performance to the maximum extent of 12%. There are many results of isolated surfaces and ceramic materials application in internal combustion engines, which are illustrated the advantages in the engine performance [6-8].

Although nowadays the application of Thermal Barrier Coatings (TBCs) are so common in diesel engines liner, it is known that the lifetime of Thermal Barrier Coatings (TBCs) is limited by two basic failure mechanisms; thermal expansion mismatch...
between bond coat and top coat, and oxidation of the bond coat. The solution for these problems is the application of Functionally Graded Materials as a cylinder liner.

Functionally Graded Materials (FGMs) are new advanced heated resistant materials in modern technology. These kinds of materials have corrosion and erosion resistant properties and high fracture resistance as well as low thermal conductivity. The mechanical properties of FGMs vary continuously from one surface to the other surfaces. Therefore, the mechanical properties are considered coordinate dependent in the governing equations of temperature and displacements [9].

Hosseini et al. [10] carried out the determination of temperature distribution in functionally graded thick hollow cylinder by using analytical method. The temperature distribution is obtained by using Bessel functions. The comparisons between temperature distributions for various mechanical properties are also presented in their work. Jabari et al. [9] presented a general analysis of one-dimensional steady-state thermal stresses in a hollow thick cylinder made of Functionally Graded Material. In their work, the temperature distribution is assumed as a function of radius, with general thermal and mechanical boundary conditions along the inside and outside surfaces. They used the direct method to solve the heat conduction and Navier equations. Shahani et al. [11] solved analytically thermo-elasticity problem in a thick-walled cylinder using the Finite Hankel Transform. Time dependent thermal boundary conditions are assumed in the inner surface of the cylinder. They derived the quasi-static solution of the thermoelasticity problem analytically.

**MATHEMATICAL MODELING AND FORMULATION**

The heat transfer rates from the burned gas to the walls depend on the instantaneous differences between gas and wall temperatures. For the present study, the following usual assumptions are made concerning wall temperature computations which were successfully used in [12]:

1. All cylinder surfaces are at a uniform temperature. 2. Heat transfer by conduction through the walls is one-dimensional. The one-dimensional treatment is justified, since temperature varies much more rapidly in directions perpendicular to the surface. The assumption of one-dimensional heat transfer over the engine cycle is reasonable for engines. In order to calculate the heat transfer rate and thermal stresses during a complete engine cycle, the unsteady heat conduction equation and navier equation must be solved with the appropriate boundary conditions for a hollow cylinder with inner radius of \( r_i \) and outer radius of \( r_o \). As mentioned before by using multi-layer composite method, the wall thickness has divided to number of elements which material properties stay constant over each layer. The heat transfer and navier equation are as below [9]:

\[
\frac{1}{r} \frac{\partial}{\partial r} (Kr \frac{\partial T}{\partial r}) = \rho c \frac{\partial T}{\partial t}
\]  

(1)

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\[
(2\mu + \lambda X \frac{\partial^2 u}{\partial r^2} + \frac{1}{r} \frac{\partial u}{\partial r}) \frac{\partial u}{\partial r} = \beta \frac{\partial T}{\partial r} + \rho \frac{u}{r}
\]

(2)

\[
\mu = \frac{E}{2(1 + \nu)}, \quad \frac{E}{(1 + \nu)(1 - 2\nu)}, \quad \frac{E}{(1 + \nu)(1 - 2\nu)}
\]

(3)

\[
\beta = (3\lambda + 2\mu)c
\]

At \( r = r_i \): \( -k \frac{\partial T}{\partial r} \bigg|_{r=r_i} = h_i (T_m - T_i) \) and \( \sigma_{ri} = 0 \)

(4)

At \( r = r_o \): \( T_m = T_{wo} \) and \( \sigma_{ro} = 0 \)

(5)

Where \( k \) is the thermal conductivity, \( r \) is cylinder radius, \( \rho \) and \( C \) are the density and the specific heat respectively and \( T \) denotes the temperature. Also \( E \) and \( \nu \) represent the elastic modulus and poison ratio respectively. Finally \( \alpha \) shows the thermal expansion coefficient. In order to solve this equations one should use the appropriate boundary condition. It is subjected to the boundary condition of the inside wall surface to be exposed to the gas temperature, heat transfer coefficient and gas pressure which vary periodically in time [12]. The temperature on the outer cylinder radius is assumed to be same as the coolant temperature, which was used, in previous works such as [13]. To solve equation (1) and (2) the combination of finite element-finite difference method has used, with the aim of backward scheme in time domain [14]. In FGM cylinder mechanical properties varies in radial direction with a specific volume fraction. Mechanical properties in FGM cylinder are assumed as follows:

\[
P = P_c + (P_m - P_c) \times \left( \frac{r - r_i}{r_o - r_i} \right)^{\nu - \pi}
\]

(6)

Where "\( P " \) is material property, "\( r " \) is a non-negative volume fraction exponent and subscripts "\( c " \) and "\( m " \) stand for ceramic and metal respectively.

**ENGINE DESCRIPTION AND MATERIAL PROPERTIES OF CYLINDER WALL**

The specifications of the single-cylinder diesel engine used in this study are shown in Table 1.

<table>
<thead>
<tr>
<th>Table 1: Engine specification [12]</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Diesel-Lister LV1</strong></td>
</tr>
<tr>
<td>Direct inject (DI)</td>
</tr>
<tr>
<td>1 Four-Stroke</td>
</tr>
<tr>
<td>85.73 mm</td>
</tr>
<tr>
<td>82.56 mm</td>
</tr>
<tr>
<td>18 : 1</td>
</tr>
<tr>
<td>1000–3000 rpm</td>
</tr>
</tbody>
</table>
Table 2: Properties of candidate materials of cylinder liner [15].

<table>
<thead>
<tr>
<th>Material</th>
<th>Partially Stabilized Zirconia</th>
<th>Plasma sprayed Cr2O3</th>
<th>NiCrAlY</th>
<th>Silicon Nitride Graphite</th>
<th>Cast Iron (ferrographite)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bulk density, g/cm³</td>
<td>5.7</td>
<td>5.0</td>
<td>5.5</td>
<td>3.2</td>
<td>7.0</td>
</tr>
<tr>
<td>Thermal conductivity, W/mK</td>
<td>3.05</td>
<td>2.6</td>
<td>10</td>
<td>20.9</td>
<td>33</td>
</tr>
<tr>
<td>Specific heat, KJ/kg.K</td>
<td>0.450</td>
<td>0.59</td>
<td>0.450</td>
<td>0.67</td>
<td>0.5</td>
</tr>
<tr>
<td>Elastic Module (MPa)</td>
<td>200</td>
<td>110</td>
<td>195</td>
<td>310</td>
<td>200</td>
</tr>
<tr>
<td>Thermal Expansion Coefficient (1/°C)</td>
<td>10.26e-9</td>
<td>7.4e-6</td>
<td>14e-5</td>
<td>3.2e-6</td>
<td>11.7e-4</td>
</tr>
<tr>
<td>Poisson Ratio</td>
<td>0.13</td>
<td>0.21</td>
<td>0.31</td>
<td>0.24</td>
<td>0.27</td>
</tr>
</tbody>
</table>

There exist different cases for construction the cylinder liner. The material properties used in this work are listed in Table 2. In the cylinder model with thermal barrier coating, the coating contains 0.2 mm topcoat of Cr2O3 and 0.4 mm bond coat of PSZ. The bond coat provides a surface texture to promote adhesion of the top coat and reduce the coefficient of thermal expansion between the top coat and the metallic substrate. In the FGM cylinder model, the ceramic used in the inner radius is Mg-PSZ and the metal used for outer radius is super alloy NiCrAlY. Four different volume fractions 0.5, 1, 2 and 3 have been considered for FGM cylinder.

RESULTS

Temperature Distribution and Heat Release

The temperature distribution and heat transfer rate are calculated for three engine speeds 1500, 2000 and 2500 rpm with various loads 20%, 40% and 60% of full engine load.

Figures 1, 2 and 3 display the transient temperature fluctuation at different points in the wall thickness of cylinder liner for 40% of full load at the speed of 1500 rpm for cast iron liner, PSZ ceramic liner and FGM cylinder respectively. These figures show the temperature fluctuation with respect to first point of the cycle (the temperature difference between each point and first point of the cycle). It can be concluded that in FGM cylinder, the temperature fluctuation of cylinder wall surface is increased in comparison with the metal and ceramic cylinder, whereas the corresponding temperature of inside cylinder wall is reduced significantly in comparison with the two mentioned cases. In the case of FGM cylinder, Figure 3 shows that by depth exceeding of about 0.6 mm, an obvious temperature variation can be seen hardly. This means, that the heat conduction over the mentioned depth obeys a kind of pseudo steady state.

Figure 4 illustrates that the heat transfer absorbed or rejected versus crank angle, for the case of 40% of the full load at the speed of 2000 rpm for the cast iron liner and the FGM cylinder. The areas under these curves are showing the associated heats. The heat flows in and out of the body periodically, because of the temperature differences between gas and wall surface due to their phasing. It can clearly be seen that in FGM cylinder the rate of heat transfer is reduced in the comparison with a metallic cylinder.

Figure 5 shows the total heat loss to coolant water for different candidate materials at the speed of 2000 rpm and different operation loads within 10 minutes after engine operation under cold starting. By using FGM cylinder with different volume fraction, decreasing of about 25-40% can be achieved in heat loss in comparison with cast iron cylinder at the speed of 1500 rpm. The similar values are 41-61% at 2000 rpm and 50-68% at 2500 rpm, whereas the Cr2O3 coating can only reduce heat release up to 9.5% at 1500 rpm, 17% at 2000 rpm and 22% at 2500 rpm.

Figure 6 indicates the maximum wall surface temperature for candidate materials at 2000 rpm with various loads. It is clear that maximum and minimum surface temperatures are subjected to ceramic and cast iron cylinder respectively. In the FGM cases, cylinder wall temperature is located between these two cases.
Figure 7 presents the percentages of heat loss reduction for various candidate liner materials compared with cast iron in the case of 60% of full load at different engine speeds.

**Thermal Stresses**

The thermal stresses are calculated for different engine loads and speeds due to combination of thermal and mechanical boundary conditions.

Figures 8 to 13 show the radial and hoop stresses in the cylinder wall at 1500 rpm and 40% load over crank angle for different materials. It can coarsely conclude that the FGM cylinder diminishes thermal stresses in cylinder wall compared with the ceramic cylinder.
Figures 14 and 15 show the radial and hoop stresses by the maximum inner cylinder pressure at 2500 rpm and 20% full load. These two plots show that the maximum and minimum stresses are denoted to ceramic and metal cylinder respectively. It is obviously, that by using the FGM cylinder, the thermal stresses will decrease in contrast to the ceramic cylinder. This is one of the most important advantages of FGM cylinders comparing to the ceramic cylinders.

It is clear that by reducing thermal stresses, probability of crack growth and thermal fatigue in cylinder wall would be reduced, which it leads to decreasing of maintenance and service costs. The other advantages of using FGM cylinders in combustion engines are the optimization ability referring thermal conduction and mechanical strength.

CONCLUSION

In this paper, heat loss to cooling system and the wall temperature of cylinder are analyzed for a FGM cylinder in a typical direct injection diesel engine by using of the combination of finite element and finite difference methods for various loads and speeds. In addition, transient thermal stresses are considered due to the combination of thermo-mechanical boundary conditions in cylinder wall thickness for different materials. The material in thickness direction is assumed and each layer is considered as an isotropic material. The continuity conditions are satisfied at the interfaces between layers. The continuity condition is assumed to be in plane strain condition. The conclusions can be outlined as following:

1. By using FGM cylinder, temperature fluctuation of cylinder wall surface will increase compared with those of metal and ceramic cylinder, but the corresponding temperature fluctuation inside the wall will significantly reduce compared with two mentioned cases.

2. The thermal stresses and temperature distribution are determined in FGM cylinder of diesel engines by using multilayer method. There are some comparisons in thermal stress and temperature fields for various kinds of FGM and existing material in cylinder application.

REFERENCES