THE EFFECTS OF DIFFERENT ENGINE MATERIAL PROPERTIES ON THE PERFORMANCE OF A DIESEL ENGINE AT MAXIMUM COMBUSTION TEMPERATURES

by

Yuksel PALACI and Guven GONCA*

Naval Architecture and Marine Engineering Department, Yildiz Technical University, Besiktas, Istanbul, Turkey

Original scientific paper
https://doi.org/10.2298/TSCI180916164P

In this study, the influences of various engine materials such as palladium, titanium, thorium, zirconium, vanadium, alumina, aluminum bronze, copper, iron (gray cast), manganese, nickel, cobalt, and carbon steel on the effective efficiency and effective power with respect to the variation of equivalence ratio at the maximum combustion temperatures. In-cylinder gas temperatures have been determined with respect to the melting temperatures and the performance values have been calculated with respect to the variation of the gas temperatures. The results indicated that alumina provides the maximum performance values as aluminum bronze gives the minimum performance values due to the combustion temperatures. Furthermore, the equivalence ratios which give the maximum performance characteristics have been parametrically described. The obtained results can be assessed by engine designers and manufacturers to choose suitable engine material.

Key words: engine material, performance, combustion temperatures, Diesel engine, equivalence ratio

Introduction

[11-16] performed a couple of studies on the Miller cycle Diesel engines and steam-injected Diesel engines. Li et al. [17] decreased pollutant emissions simultaneously using an effective approach and it was expressed that premixed natural gas has a positive correlation with power output. Acikkalp et al. [18] analyzed a diesel-gas engine trigeneration system in Turkey by using exergy analysis. Vellaiyan and Amirthagadeswaran [19] optimized operating parameters of a Diesel engine operating with diesel-water emulsion fuel. Liu et al. [20] examined the impacts of injection timing and exhaust gas re-circulation combinations on the combustion characteristics and particulate matter emission of a Diesel engine operating on ethanol-diesel blends.

Although there are so many thermodynamic optimization works for the Diesel engines, material researches are insufficient. Novel advanced material technologies must be developed by the scientists for engine manufacturing by considering cost and environmental restrictions. In this report, the influences of structure materials of the Diesel engines such as palladium, titanium, thorium, zirconium, vanadium, alumina, aluminum bronze, copper, iron (gray cast), manganese, nickel, cobalt, and carbon steel on the performance characteristics have been parametrically examined with respect to the equivalence ratio variation. There is not any study in the literature investigating the different material properties on the engine performance of the Diesel engines. This study considers engine material properties and engine operating conditions altogether. Therefore, it is very important to make up for the deficiency in this field.

**Theoretical model**

This study carried out a performance examination for a dual cycle based Diesel engine which is constructed with different engine materials. The cycle is shown in fig. 1. Maximum melting temperatures of materials used for engine manufacturing are demonstrated in tab. 1.

![Theoretical model](image)

**Figure 1.** The P-V and T-S diagrams for the irreversible dual-diesel cycle

**Table 1.** Maximum melting point of materials used for engine manufacturing [21]

<table>
<thead>
<tr>
<th>Material</th>
<th>Maximum melting point, [°C]</th>
<th>Material</th>
<th>Maximum melting point, [°C]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Palladium</td>
<td>1555</td>
<td>Copper</td>
<td>1084</td>
</tr>
<tr>
<td>Titanium</td>
<td>1670</td>
<td>Gray cast iron</td>
<td>1204</td>
</tr>
<tr>
<td>Thorium</td>
<td>1750</td>
<td>Manganese</td>
<td>1244</td>
</tr>
<tr>
<td>Zirconium</td>
<td>1854</td>
<td>Nickel</td>
<td>1453</td>
</tr>
<tr>
<td>Vanadium</td>
<td>1900</td>
<td>Cobalt</td>
<td>1495</td>
</tr>
<tr>
<td>Alumina</td>
<td>2072</td>
<td>Carbon steel</td>
<td>1540</td>
</tr>
<tr>
<td>Aluminum bronze</td>
<td>1038</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

A numerical simulation of engine efficiency and power is performed. In the study, air intake pressure, $p_1$, intake temperature, $T_1$, engine speed, $N$, cycle temperature ratio, $\alpha$, cyl-
The effective efficiency and power can be expressed:

$$P_{ef} = \dot{Q}_{in} - \dot{Q}_{out} - R_l, \quad \eta_{ef} = \frac{P_{ef}}{\dot{Q}_{in}}$$  \hfill (1)$$

where the heat addition, $\dot{Q}_{in}$, at constant volume (2-3) and constant pressure (3-4), the heat rejection, $\dot{Q}_{out}$, at constant volume (5-1) and loss power by friction, $P_l$, [11] can be given:

$$\dot{Q}_{in} = \dot{Q}_{fc} - \dot{Q}_{ht} = \dot{m}_T \left[ \int_{T_i}^{T_f} C_v dT \right] =$$

$$= \dot{m}_T \left[ \left[ \frac{2.506 \cdot 10^{-11} T_i^3}{3} + 1.454 \cdot 10^{-7} \frac{T_i^{2.5}}{2.5} - 4.246 \cdot 10^{-7} \frac{T_i^2}{2} + 3.162 \cdot 10^{-5} \frac{T_i^{1.5}}{1.5} + \right. \right. \right.$$

$$\left. \left. \left. \left. 1.0433 T_i - 1.512 \cdot 10^4 \left( \frac{T_i^{-0.5}}{0.5} \right) + 3.063 \cdot 10^5 \left( -T_i^{-1} \right) - 2.212 \cdot 10^7 \left( -T_i^{-2} \right) \right] \right] \right]$$

$$= \dot{m}_T \left[ \int_{T_i}^{T_f} C_v dT \right]$$

$$\dot{Q}_{out} = \dot{m}_T \left[ \int_{T_i}^{T_f} C_p dT \right]$$

$$= \dot{m}_T \left[ \left[ \frac{2.506 \cdot 10^{-11} T_i^3}{3} + 1.454 \cdot 10^{-7} \frac{T_i^{2.5}}{2.5} - 4.246 \cdot 10^{-7} \frac{T_i^2}{2} + 3.162 \cdot 10^{-5} \frac{T_i^{1.5}}{1.5} + \right. \right. \right.$$

$$\left. \left. \left. \left. 1.330 T_i - 1.512 \cdot 10^4 \left( \frac{T_i^{-0.5}}{0.5} \right) + 3.063 \cdot 10^5 \left( -T_i^{-1} \right) - 2.212 \cdot 10^7 \left( -T_i^{-2} \right) \right] \right] \right]$$

$$P_l = \mu c_m^2 = \frac{Z + 48 \left( \frac{N}{1000} \right) + 0.4 c_m^2}{1200} \left[ \frac{V}{N} \right]$$  \hfill (4)$$

The other equations have been obtained from [22]. Where $Z$ is a constant which is related to friction [11] and it is 75, where $\mu$ is the friction coefficient, $c_m$ is the average piston velocity which is written:

$$c_m = \frac{SN}{30}$$  \hfill (5)$$

where $S$ [m] is the stroke, and $N$ [rpm] – the engine speed. The $\dot{Q}_{fc}$ states heat potential of the fuel injected into the cylinder and it is derived:
\( \dot{Q}_t = \dot{m}_t H_u \)  \( \text{(6)} \)

where \( H_u \) is the calorific value of the fuel, \( \dot{m}_t \) – the mass-flow rate of fuel per second and it is expressed:

\[ \dot{m}_t = \frac{m_s N}{120} \]  \( \text{(7)} \)

where \( \dot{Q}_{t,c} \) is the heat release and \( \dot{Q}_{ht} \) – the heat loss by heat transfer into cylinder wall and they are given:

\[ \dot{Q}_{t,c} = \eta_c \dot{m}_t H_u \]  \( \text{(8)} \)

\[ \dot{Q}_{ht} = h_{tr} A_{cyl} (T_{me} - T_W) = h_{tr} A_{cyl} \left( \frac{T_2 + T_3}{2} - T_W \right) \]  \( \text{(9)} \)

where \( \eta_c \) expresses efficiency of the combustion process. It is stated [23-25]:

\[ \eta_c = -1.44738 + \frac{4.18581}{\phi} - \frac{1.86876}{\phi^2} \]  \( \text{(10)} \)

where \( \phi \) expresses equivalence ratio and it could be given:

\[ \phi = \frac{m_a}{F_{st}} \]  \( \text{(11)} \)

where \( m_a \) [kg] is the mass of the air per cycle introduced into the cylinder during the intake process and \( F_{st} \) – the ratio of the fuel and air at stoichiometric combustion conditions. They are written:

\[ m_a = \rho_a V_a = \rho_a (V_T - V_{rg}) \]  \( \text{(12)} \)

\[ V_T = V_c + V_a = \frac{V_T r}{r - 1} \]  \( \text{(13)} \)

\[ V_c = \frac{V_T r}{r} = \frac{\pi d^2 S}{4} \frac{1}{r - 1} \]  \( \text{(14)} \)

\[ F_{st} = \frac{\nu(12.01\alpha + 1.008\beta + 16\gamma + 14.01\delta)}{28.85} \]  \( \text{(15)} \)

\[ \rho_a = f(T_i, P_i) \]  \( \text{(16)} \)

where \( V_c, V_a, V_T, \) and \( V_{rg} \) are volumes of compression, air, stroke, residual gas, and total cylinder, respectively, and \( \rho_{rg} \) – the residual gas density which is expressed:

\[ \rho_{rg} = f(T_{max}, P_i) \]  \( \text{(17)} \)

where \( T_{max} \) is the mean temperature of air-residual gas mixtures which is:
\[ T_{\text{mix}} = \frac{m_aT_a + m_{rg}T_{rg}}{m_a + m_{rg}} \]  

(18)

where \( R_a \) is the gas constant of the air, which is 0.287 kJ/kgK and \( R_{rg} \) – the gas constant of the residual gas, which is 0.293 kJ/kgK. The compression ratio, \( r \), of the engine is [26-29]:

\[ r = \frac{V_1}{V_2} \]  

(19)

The functional statements are acquired by using engineering equation solver [30]. The used fuel in the combustion model is diesel (C_{14.4}H_{24.9}) [31]. The \( \varepsilon \) signifies molar ratio of the fuel to air [32]:

\[ \varepsilon = \frac{0.21}{\psi - \frac{\gamma + \beta}{2} + \frac{\beta}{4}} \]  

(20)

where \( \psi \) is the carbon atom number, \( \beta \) – the hydrogen atom number, and \( \gamma \) – the oxygen atom number in the used fuel. The \( h_t \) is coefficient for the heat transfer and it is given [33]:

\[ h_t = 130V_{cyl}^{-0.06}T_{\text{m}}^{0.8}r_{\text{m}}^{0.4}(c_m + 1.4)^{0.8} \]  

(21)

where \( A_{\text{cel}} \) [m²] is the heat transfer area, \( \dot{m}_a \), \( \dot{m}_{rg} \), and \( \dot{m}_T \) [kgs⁻¹] – the flow rates of air, residual-gas, and total charge, respectively, which are:

\[ \dot{m}_T = \dot{m}_a + \dot{m}_f + \dot{m}_{rg} \]  

(22)

\[ \dot{m}_a = \frac{m_aN}{120} = \frac{\dot{m}_TF_{st}}{\phi} \]  

(23)

\[ \dot{m}_{rg} = \frac{m_{rg}N}{120} = \dot{m}_R_{RGF} \]  

(24)

\[ A_{\text{cel}} = \pi d S \frac{r}{r - 1} + \frac{\pi d^2}{2} \]  

(25)

where \( m_a \) [kg] is the mass of the air per cycle, \( m_{rg} \) [kg] – the mass of the residual-gas per cycle, \( T_W \) and \( T_{me} \) – the cylinder wall temperature and average combustion temperature, respectively, and \( C_V \) and \( C_P \) – the constant volume and constant pressure specific heats [33, 34]:

\[ C_p = 2.506 \times 10^{-11}T^2 + 1.454 \times 10^{-7}T^{1.5} - 4.246 \times 10^{-7}T + 3.162 \times 10^{-5}T^{0.5} + 1.3301 - 1.512 \times 10^4T^{-1.5} + 3.063 \times 10^7T^{-2} - 2.212 \times 10^7T^{-3} \]  

(26)

\[ C_V = C_P - R \]  

(27)

The relations for (1-2s) process and (4-5s) process are attained [35]:

\[ C_{V_i} \ln \left| \frac{T_2x}{T_1} \right| = R \ln |r|, \quad C_{V_i} \ln \left| \frac{T_5y}{T_4} \right| = R \ln \left| \frac{1}{r} \right| , \]  

(28)
Results and discussion

Figures 2 and 3 show the equivalence ratios, $\phi$, and different engine materials on the effective power. The maximum effective power enhances with raising melting point also the melting points of the materials enhance from palladium to alumina. Alumina provides maximum effective power as it has the maximum melting temperature. However, aluminum bronze has the minimum effective power since it has the minimum melting temperature. The melting temperature of the materials increases from aluminum bronze to carbon steel as can be observed in the fig. 2. However, the $\phi$ affects the engine power, it augments with enhancing $\phi$ to a specified point and then starts to diminish with enhancing $\phi$. The optimum equivalence ratio which gives the maximum engine power shifts right with respect to increasing melting temperatures. This result has been observed from aluminum bronze to carbon steel and from palladium to alumina in both of the figures.

Figures 4 and 5 show the equivalence ratios and different engine materials on the effective efficiency with respect to the equivalence ratio. It is clear that the maximum effective efficiency increases with increasing maximum melting temperatures. The maximum engine efficiency is obtained with alumina while the minimum effective power is attained with aluminum bronze as the maximum melting temperatures of the materials studied rises from alu-
minimum bronze to alumina. However, the efficiency is affected by the $\phi$. The engine efficiency first enhances with increasing equivalence ratio to a determined value and then begins to reduce with enhancing $\phi$. The optimum $\phi$ which provides the maximum effective efficiency shifts right with respect to enhancing melting temperatures. It increases from aluminum bronze to alumina.

Figures 6 and 7 show the variation of the engine power and efficiency with respect to the variation of the $\phi$ and different engine materials. The engine power and efficiency enhance altogether with changing materials. Aluminum bronze provides the minimum power and efficiency as it has the minimum melting temperature. However, the maximum performance characteristics are obtained with alumina.

In exceptional running conditions, when cylinder walls have a cooling system problem occurs, cylinder walls may reach the gas temperature at the specific location of the inner surface. This will cause melting and material deformation at this specific locations. The engine material can fail in a short time with hot deformation and wear. The material can fail under load which may be lower than yield strength of the material at high temperatures as a well known creep phenomena. As a conclusion, the maximum temperature of combustion gas can be taken as a melting temperature of the cylinder wall to avoid damage on the cylinder walls as an approach to possible cooling problem.

Conclusion

This work reports the effects of engine structure materials such as palladium, titanium, thorium, zirconium, vanadium, alumina, aluminum bronze, copper, iron (gray cast), manganese, nickel, cobalt, and carbon steel on the performance characteristics with respect to the equivalence ratio variation. The results showed that the maximum engine power and efficiency enhance with augmenting melting points. Therefore, while the alumina provides the maximum performance characteristics, aluminum bronze has the minimum performance characteristics due to melting temperatures. Moreover, the equivalence ratio has a considerable impact on the performance characteristics. They augment with raising equivalence ratio to a particular value and then start to diminish with increasing equivalence ratio. The optimum equivalence ratio which provides the maximum performance characteristics shifts right with respect to increasing melting temperatures. It increases from palladium to alumi-
This study has a remarkable originality and it can be used as an approach by engine manufacturers and designers.

**Acknowledgment**

The authors thank Turkish Academy of Sciences (TUBA) for financial supporting.

**References**


