Determination of optimum speed of an internal combustion engine by exergy analysis

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Abstract: In this study, energy and exergy analysis are applied to the experimental data of an internal combustion engine operating on the conventional Otto cycle. The data are collected using an engine test unit which enables accurate measurements of fuel flow rate, combustion air flow rate, engine load, engine speed and all the relevant temperatures. Energy and exergy efficiencies are calculated for different engine speeds and compared. Results indicate that energy efficiency is maximum at a speed of 2040 rpm whereas exergy efficiency is maximum at a speed of 2580 rpm.

Keywords: exergy analysis; exergy efficiency; internal combustion engine.


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Biographical notes: Lutfi Kokturk received his BS degree in mechanical engineering from the Ankara Engineering–Architecture State Academy in 1977 and in 1999 he received his MS degree in mechanical engineering (energy sciences) from the Zonguldak Karaelmas University, Turkey. He is currently working as a Mechanical Engineer in the Directorate of Civilisation in Bartin, Turkey.
1 Introduction

An exergy-based performance analysis is the performance analysis of a system based on the second law of thermodynamics that overcomes the limit of an energy-based analysis. Exergy is defined as the maximum theoretical useful work obtained as a system interacts with an equilibrium state. Exergy is generally not conserved as energy but destroyed in the system. Exergy destruction is a measure of irreversibility that is the source of performance loss. Therefore, an exergy analysis assessing the magnitude of exergy destruction identifies the location, the magnitude and the source of thermodynamic inefficiencies in a thermal system. This provides useful information to improve the overall efficiency and cost effectiveness of a system and/or comparing the performance of the two systems.

Recent studies (Dunbar and Lior, 1994; Dunbar et al., 1992) show that almost a third of the energy of a fossil fuel is destroyed during the combustion process in power generation. This has caused a renewed interest in exergy analyses, since effective management and optimisation of thermal systems is emerging as a major modern technical problem (Bejan et al., 1996). The equations for the second law analysis of a thermodynamic system are presented and discussed thoroughly (Dunbar et al., 1992) and are used to analyse the operation of power plants (Dunbar et al., 1991; Kopac, 2000; Lazzaretto and Tsatsaronis, 1999; Toffolo and Lazzaretto, 2002). For internal combustion engines, early work (Flynn et al., 1984; Primus et al., 1984) on the evaluation of the global engine operation using second-law techniques was followed by detailed energy and exergy destroyed calculations during the diesel engine cycle (Rakopoulos et al., 1993; Rakopoulos, 1993; Rakopoulos and Kyritsis, 2001). Second-law arguments have been used to evaluate novel engine concepts (Flynn et al., 1984), to investigate the effect of the operating parameters on efficiency (Kopac et al., 2001; Rakopoulos et al., 1993), and more recently, to reveal interesting aspects of the transient engine operation (Rakopoulos and Giakoumis, 1997). The overall energy and exergy balance during an engine cycle are studied analytically (Beratta and Keck, 1983; Bedran and Beratta, 1985). The exergy analysis has been used on a general system in Dincer (2000), Gogus and Ataer (1999), Gogus et al. (2002), Ozdoğan and Arikol (1995) and Stapleton (2001).

The objective of this study is to determine the optimum speed of an Otto cycle engine using combined energy and exergy analysis.

2 Theory

A schematic control volume for an open system is shown in Figure 1. Energy, entropy and exergy balances for such a system under transient conditions are given by Equations (1), (2) and (3).
Energy balance:

$$\sum_i \dot{m} h - \sum_j \dot{m} h + \sum_s \dot{Q} - \dot{W} = \Delta U_{\text{system}}$$  \hspace{1cm} (1)

Entropy balance:

$$\sum_i \dot{m} s - \sum_j \dot{m} s + \sum_s \frac{\dot{Q}}{T} + \dot{S}_{\text{gen}} = \Delta S_{\text{system}}$$  \hspace{1cm} (2)

Exergy balance:

$$\sum_i \dot{m} e - \sum_j \dot{m} e + \sum_s \dot{Q} \left(1 - \frac{T_o}{T}\right) - \dot{W} - \dot{E}_d = \Delta E_{\text{system}}$$

$$\dot{E}_d = T_o \dot{S}_{\text{gen}}$$  \hspace{1cm} (3)

e in Equation (3) is flow exergy per unit mass and is defined as follows:

$$e = e_{\text{tm}} + e_{\text{ch}}$$  \hspace{1cm} (4)

where $e_{\text{tm}}$ and $e_{\text{ch}}$ are thermomechanical and chemical exergy, respectively. Thermomechanical exergy is defined as follow (Çengel and Boles, 1998; Kotas, 1985):

$$e_{\text{tm}} = h - h_o - T_o(s - s_o),$$  \hspace{1cm} (5)

where h and s are flow enthalpy and flow entropy per unit mass at the relevant temperature and pressure. Assuming the ideal solution assumption is valid, the specific chemical exergy for a multicomponent stream can be calculated as follows:

$$\tilde{e}_{\text{ch}} = \sum_{i=1}^j y_i (\tilde{e}_{\text{ch}})_i$$  \hspace{1cm} (6)

where $y_i$ is the mole fraction of component i in the mixture and $(\tilde{e}_{\text{ch}})_i$ is its specific chemical exergy. The definition of specific chemical exergy for each component...
depends on whether the component exists in the environment. If a component exists in the environment and the environment is also an ideal solution, then

\[(\hat{\varepsilon}_{ch})_i = \tilde{R}T_o \ln \frac{y_i}{y_i^e},\]

where \(y_i^e\) is the mole fraction of component \(i\) in the environment. If a given component does not exist in the environment, then its chemical exergy must be calculated by considering a chemical reaction where this component reacts with a species in the environment and is completely converted into species all of which also exist in the environment. For example, a hydrocarbon, \(C_aH_b\), has the following specific chemical exergy:

\[
\hat{\varepsilon}_{C_aH_b} = \left( \tilde{g}_{C_aH_b} + \left( a + \frac{b}{4} \right) \tilde{g}_{O_2} - a \tilde{g}_{CO_2} - \frac{b}{2} \tilde{g}_{H_2O} \right) + \tilde{R}T_o \ln \left( \frac{(y_{O_2}^e)^{a+b/4}}{(y_{CO_2}^e)^a (y_{H_2O}^e)^{b/2}} \right).
\]

The definition of environment adopted in this study is shown in Table 1 (Kotas, 1995).

<table>
<thead>
<tr>
<th>Component</th>
<th>Mole fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>N₂</td>
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</tr>
<tr>
<td>O₂</td>
<td>0.2035</td>
</tr>
<tr>
<td>CO₂</td>
<td>0.000345</td>
</tr>
<tr>
<td>H₂O</td>
<td>0.0303</td>
</tr>
<tr>
<td>CO</td>
<td>0.000007</td>
</tr>
<tr>
<td>SO₂</td>
<td>0.000002</td>
</tr>
<tr>
<td>H₂</td>
<td>0.000005</td>
</tr>
<tr>
<td>Other</td>
<td>0.0091455</td>
</tr>
</tbody>
</table>

3 Experimental studies

Experiments were conducted on an existing test unit at the Mechanical Engineering Department of Zonguldak Karaelmas University. The test engine was type 8601 running on gasoline. A schematic diagram of the test unit is shown in Figure 2. The experimental set up enabled accurate measurements of fuel, combustion air, cooling water flow rates of gas calorimeter, engine load and speed and inlet and outlet temperatures for each stream. Experimental results for different engine speeds between 990 and 3480 rpm are summarised in Table 2.
**Energy analysis:**

Fuel energy is given by:

\[ Q_f = \dot{m}_f H_u \]  

where \( H_u \) is the lower heating value and \( \dot{m}_f \) is the mass flow rate of fuel, respectively.

Effective power of engine, \( N_e \) is

\[ N_e = \omega \tau \]  

where \( \omega \) and \( \tau \) are angular velocity and torque, respectively.

The angular velocity is related to rpm according to

\[ \omega = \frac{\pi n}{30} \]  

and torque is determined by Cussons Automotive (1993).

\[ \tau = 0.286 \text{ L} \]
**Table 2**

Experimental results

<table>
<thead>
<tr>
<th>Speed, $n$ (rpm)</th>
<th>Load, $L$ (N)</th>
<th>Torque, $\tau$ (Nm)</th>
<th>Air flow rate, $V_a$ (l/min)</th>
<th>Mass flow rate of fuel, $m_f$ (g/sec)</th>
<th>Mass flow rate of calorimeter cooling water, $m_{cw}$ (kg/h)</th>
<th>Temperature of surroundings, $T_a$ (°C)</th>
<th>Temperature of exhaust gases, $T_{e1}$ (°C)</th>
<th>Entrance temperature of exhaust gases to the calorimeter, $T_{c2}$ (°C)</th>
<th>Exit temperature of exhaust gases from the calorimeter, $T_{c3}$ (°C)</th>
<th>Entrance temperature of the cooling water of calorimeter, $T_{w2}$ (°C)</th>
<th>Exit temperature of the cooling water of calorimeter, $T_{w3}$ (°C)</th>
<th>Temperature at outer surface of the engine, $T_s$ (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>990</td>
<td>395</td>
<td>103</td>
<td>790</td>
<td>1.251</td>
<td>569</td>
<td>16</td>
<td>500</td>
<td>285</td>
<td>22</td>
<td>22</td>
<td>10</td>
<td>80</td>
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<tr>
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<td>472</td>
<td>135</td>
<td>1916</td>
<td>2.310</td>
<td>1006</td>
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<td>129</td>
<td>2402</td>
<td>2.584</td>
<td>1008</td>
<td>16</td>
<td>650</td>
<td>490</td>
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<td>40</td>
<td>10</td>
<td>80</td>
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<td>2580</td>
<td>413</td>
<td>124</td>
<td>2952</td>
<td>3.165</td>
<td>992</td>
<td>16</td>
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<td>3.687</td>
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<td>16</td>
<td>750</td>
<td>605</td>
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<td>10</td>
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<tr>
<td>3480</td>
<td>336</td>
<td>103</td>
<td>2714</td>
<td>4.182</td>
<td>775</td>
<td>16</td>
<td>780</td>
<td>656</td>
<td>80</td>
<td>80</td>
<td>10</td>
<td>80</td>
</tr>
</tbody>
</table>

Determination of optimum speed of an internal combustion engine
where \( L \) is the measured engine load. Combining Equations (11) and (12), the effective power of the engine can be expressed as follows:

\[
N_e = \frac{m}{30} \tau.
\]

then specific fuel consumption, \( b_c \) is

\[
b_c = \frac{m_r}{N_e}.
\]

**Total exhaust heat, \( \dot{Q}_e \)**

The heat content of the exhaust gas in the system can be expressed as the sum of three constituent parts:

1. heat loss between the exhaust manifold and the exhaust gas heat exchanger
2. heat extracted in the exhaust gas heat exchanger
3. residual heat in the gases leaving the exhaust gas heat exchanger.

The overall heat in the exhaust gases expressed as a rate of energy flow is given by:

\[
\dot{Q}_e = \dot{m}_e c_{pg}(T_{e1} - T_{e2}) + \frac{\dot{m}_e c_{pg}(T_{e2} - T_{e3})}{2} + \frac{\dot{m}_e c_{pg}(T_{e3} - T_a)}{3},
\]

where: \( \dot{m}_e \) = mass flow rate of exhaust gas; \( c_{pg} \) = specific heat of exhaust gas; \( \dot{m}_{gw} \) = mass flow rate of water; \( c_{pw} \) = specific heat of water; \( T_{e1} \) = exhaust gas temperature at engine; \( T_{e2} \) = exhaust gas temperature at inlet to calorimeter; \( T_{e3} \) = exhaust gas temperature at outlet from calorimeter; \( T_{w1} \) = cooling water inlet temperature; \( T_{w2} \) = cooling water outlet temperature; \( T_a \) = ambient air temperature.

Taking a heat balance of the exhaust gas calorimeter neglecting losses:

\[
\dot{m}_e c_{pg} (T_{e2} - T_{e3}) = \dot{m}_{gw} c_{pw} (T_{w2} - T_{w1}),
\]

\[
\therefore \dot{m}_e c_{pg} = \frac{\dot{m}_{gw} c_{pw} (T_{w2} - T_{w1})}{(T_{e2} - T_{e3})}.
\]

Substituting this expression in the overall equation:

\[
\dot{Q}_e = \frac{\dot{m}_{gw} c_{pw} (T_{w2} - T_{w1})}{(T_{e2} - T_{e3})} (T_{e1} - T_a).
\]

**Total heat loss (cooling water heat to radiation heat), \( \dot{Q}_{tl} \)**

\[
\dot{Q}_{tl} = (\dot{Q}_{cw} + \dot{Q}_e)
\]

**Energy efficiency, \( \eta_l \)** is given by:

\[
\eta_l = \frac{\text{Useful output}}{\text{Energy input}} = \frac{N_e}{\dot{Q}_f}.
\]

**Exergy analysis:**

Exhaust gas exergy (\( \dot{E}_e \)) is the sum of the thermomechanical and chemical exergy of each component and is calculated by Equations (4) to (8) using calculated exhaust gas compositions.
Heat exergy, $\hat{E}_Q$

$$\hat{E}_Q = \dot{Q} \left( 1 - \frac{T_0}{T} \right). \quad (19)$$

Work exergy, $\hat{E}_W$

$$\hat{E}_W = \dot{W} = N_c. \quad (20)$$

Fuel exergy, $\hat{E}_f$

$$\hat{E}_f = \dot{m}_f e_{ch,f}. \quad (21)$$

Exergy efficiency, $\eta_H$

$$\eta_H = \frac{\text{Exergy recovered}}{\text{Exergy supplied}} = \frac{N_c}{\dot{E}_s} = 1 - \frac{\text{Exergy destroyed}}{\text{Exergy supplied}} = 1 - \frac{\dot{E}_d}{\dot{E}_s}. \quad (22)$$

The supplied exergy and the recovered exergy, $\dot{E}_s$ and $\dot{E}_R$ are given by:

$$\dot{E}_s = \dot{E}_f; \quad \dot{E}_R = N_c + \dot{E}_e + \dot{E}_{Q1}. \quad (23)$$

4 Results and discussion

The numerical values given in Table 2 were used as input to conduct energy and exergy analysis of the engine for different speeds. The results of the energy analysis are presented in Figures 3 and 4 and Tables 3, 4 and 5. Similarly, the results of the exergy analysis are presented in Figures 5 and 6 and Tables 6 and 7.

Figure 3: Specific fuel consumption versus engine speed
Figure 4  Effective power versus engine speed

![Effective power versus engine speed graph](image)

Table 3  Effective power and specific fuel consumption versus engine speed

<table>
<thead>
<tr>
<th>Speed, n (rpm)</th>
<th>Effective power, $N_e$ (kW)</th>
<th>Specific fuel consumption, $b_e$ (g/kWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>990</td>
<td>10.68</td>
<td>422</td>
</tr>
<tr>
<td>1530</td>
<td>21.63</td>
<td>384</td>
</tr>
<tr>
<td>2040</td>
<td>27.56</td>
<td>338</td>
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<td>2580</td>
<td>33.50</td>
<td>340</td>
</tr>
<tr>
<td>3000</td>
<td>35.50</td>
<td>374</td>
</tr>
<tr>
<td>3480</td>
<td>37.50</td>
<td>401</td>
</tr>
</tbody>
</table>

Table 4  Energy balance for different speeds

<table>
<thead>
<tr>
<th>Speed, n (rpm)</th>
<th>Fuel energy, $Q_f$ (kW)</th>
<th>Effective power, $N_e$ (kW)</th>
<th>Exhaust heat, $Q_e$ (kW)</th>
<th>Total heat loss, $Q_{t1}$ (kW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>990</td>
<td>53.42</td>
<td>10.68</td>
<td>14.60</td>
<td>28.14</td>
</tr>
<tr>
<td>1530</td>
<td>98.64</td>
<td>21.63</td>
<td>39.20</td>
<td>37.81</td>
</tr>
<tr>
<td>2040</td>
<td>110.25</td>
<td>27.56</td>
<td>50.57</td>
<td>32.12</td>
</tr>
<tr>
<td>2580</td>
<td>135.15</td>
<td>33.50</td>
<td>66.70</td>
<td>34.94</td>
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<td>157.43</td>
<td>35.49</td>
<td>78.77</td>
<td>43.17</td>
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<tr>
<td>3480</td>
<td>178.57</td>
<td>37.50</td>
<td>83.55</td>
<td>57.50</td>
</tr>
<tr>
<td>Speed, $n$ (rpm)</td>
<td>Fuel energy (%)</td>
<td>Energy efficiency (%)</td>
<td>Exhaust heat (%)</td>
<td>Cooling water heat (%)</td>
</tr>
<tr>
<td>------------------</td>
<td>-----------------</td>
<td>-----------------------</td>
<td>------------------</td>
<td>-----------------------</td>
</tr>
<tr>
<td>990</td>
<td>100</td>
<td>19.99</td>
<td>27.33</td>
<td>52.68</td>
</tr>
<tr>
<td>1530</td>
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<td>21.93</td>
<td>39.74</td>
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<td>45.87</td>
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</tr>
<tr>
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<tr>
<td>3480</td>
<td>100</td>
<td>21.00</td>
<td>46.79</td>
<td>32.21</td>
</tr>
</tbody>
</table>

Figure 5  Breakdown of exergy

![Breakdown of exergy](image)

- $n = 990$ rpm; $\eta_B = 22.78\%$
- $n = 1530$ rpm; $\eta_B = 25.48\%$
- $n = 2040$ rpm; $\eta_B = 29.69\%$
- $n = 2580$ rpm; $\eta_B = 30.52\%$
- $n = 3000$ rpm; $\eta_B = 27.84\%$
- $n = 3580$ rpm; $\eta_B = 26.01\%$
Figure 6  Energy efficiency, exergy efficiency and breakdown of exergy destroyed versus engine speed

![Figure 6](image)

Table 6  Exergy balance for different speeds

<table>
<thead>
<tr>
<th>Speed, $n$ (rpm)</th>
<th>Fuel exergy, $E_f$ (kW)</th>
<th>Work exergy, $N_w$ (kW)</th>
<th>Exhaust exergy, $E_e$ (kW)</th>
<th>Heat loss exergy, $E_Q$ (kW)</th>
<th>Exergy destroyed, $E_d$ (kW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>990</td>
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<td>5.48</td>
<td>4.38</td>
<td>36.21</td>
</tr>
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<td>1530</td>
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<td>21.63</td>
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<td>5.89</td>
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<td>5.00</td>
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<td>33.01</td>
<td>6.72</td>
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<td>36.56</td>
<td>8.96</td>
<td>106.50</td>
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</table>

Table 7  Breakdown of exergy for different speeds

<table>
<thead>
<tr>
<th>Speed, $n$ (rpm)</th>
<th>Fuel exergy (%)</th>
<th>Exergy efficiency (%)</th>
<th>Work exergy (%)</th>
<th>Exhaust exergy (%)</th>
<th>Heat loss exergy (%)</th>
<th>Exergy destroyed (%)</th>
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</thead>
<tbody>
<tr>
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<td>18.82</td>
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</tr>
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<td>25.48</td>
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<td>16.48</td>
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<td>100</td>
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<td>19.77</td>
<td>19.27</td>
<td>4.72</td>
<td>56.24</td>
</tr>
</tbody>
</table>

M. Kopac and L. Kokturk
Analysis of Figures 3 and 4 reveals that as the effective power delivered by the engine increases with speed, the amount of fuel consumed per unit of energy produced to go through a minimum. For two different engine speeds, namely 2040 and 2580 rpm, specific fuel consumption is almost the same (338 and 340 g/kWh). Energy efficiency is also a maximum (25.00 and 24.63%) for these speeds. In fact, energy efficiency as a function of engine speed can be deduced from specific fuel consumption as a function of engine speed; where the former exhibits a maximum, the latter goes through a minimum. As far as the energy analysis is concerned, there is no significant difference between 2040 and 2580 rpm as the optimum speed, but the exergy analysis clearly indicates that 2580 rpm is the optimum since it is associated with a higher exergy efficiency.

There are different sources of irreversibility (or destruction of exergy) associated with the operation of an internal combustion engine, combustion itself being a major source. Exergy destruction due to combustion depends on temperature, pressure and air to fuel ratio (Caton, 2000).

In this study, the ratio of the mass of air to the mass of fuel (AF) increases up to an engine speed of 2580 rpm and it decreases after this speed. The ratio of the exergy destruction or irreversibility decreases with an increase in the mass of air to the mass of fuel ratio (AF) for a combustion process. Other sources of irreversibility, such as friction and heat transfer across a temperature difference, are also expected to increase with an increase in engine speed. The observation of a minimum in exergy destruction is due to the fact that the exergy content of the exhaust heat also increases with engine speed. Hence 2580 rpm should be considered as the true optimum, provided that exhaust recovery devices may be employed to utilise the exergy of hot exhaust gases.

5 Conclusions

This study presents both experimental measurements and analytical modelling based on energy and exergy analyses for an internal combustion engine operating on the conventional Otto cycle. The experimental data were collected for fuel flow rate, combustion air flow rate, engine load, engine speed and all the relevant temperatures in an engine test unit. Energy and exergy efficiencies are calculated for different engine speeds and compared. Determination of the optimum engine speed should not be based on energy analysis alone. The results of this study reveal that a combined energy and exergy analysis provides a much better and more realistic answer.

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References


**Nomenclature**

- $b_e$: Specific fuel consumption, g/kWh
- $c_{p,w}$: Heat capacity of cooling water, kJ/kgK
- $e$: Total exergy, kJ/kg
- $e_{ch}$: Chemical exergy, kJ/kg
- $\dot{e}_{ch}$: Chemical exergy, kJ/kmol
- $e_{tm}$: Thermomechanical exergy, kJ/kg
- $\dot{E_d}$: Exergy destroyed, kW
- $\dot{E_e}$: Exhaust exergy, kW
- $\dot{E_f}$: Fuel exergy, kW
- $\dot{E}_Q$: Heat exergy, kW
- $\dot{E}_s$: Exergy supplied, kW
- $\dot{E}_{system}$: Exergy of system, kW
- $\dot{E}_W$: Work exergy, kW
- $\tilde{g}$: Gibb’s free energy, kJ/kmol
- $h$: Enthalpy, kJ/kg
- $h_o$: Enthalpy at environmental condition, kJ/kg
- $H_u$: Lower heating value, kJ/kg
- $L$: Engine load, N
- $m_a$: Mass flow rate of combustion air, kg/s
- $\dot{m}_f$: Mass flow rate of fuel, kg/s
- $\dot{m}_{gw}$: Mass flow rate of cooling water of gas calorimeter, kg/s
- $n$: Speed of engine, rpm
- $N_e$: Effective power of engine, kW
- $P$: Pressure, kPa
- $P_o$: Environmental pressure, kPa
- $Q$: Heat transfer, kW
- $Q_e$: Exhaust heat, kW
\(Q_f\) Fuel energy, kW
\(Q_{gw}\) Cooling water heat for gas calorimeter
\(Q_{cw}\) Cooling water heat, kW
\(Q_r\) Radiative heat, kW
\(\dot{Q}_{t1}\) Total heat loss, kW
\(R\) Universal gas coefficient, kJ/kmol K
\(s\) Entropy, kJ/kg K
\(s_o\) Entropy at environmental condition, kJ/kg K
\(\Delta S_{\text{system}}\) Entropy change of system, kW/K
\(\dot{S}_{\text{gen}}\) Entropy generation of system, kW/K
\(T\) Temperature, K
\(T_a\) Temperature of air, K
\(T_o\) Environmental temperature, K
\(T_e\) Exhaust gas temperature, K
\(\Delta U_{\text{system}}\) Internal energy change of system, kW
\(W\) Work of control volume, kW
\(v\) Specific volume, m\(^3\)/kg
\(y_i\) Mole fraction of component i in the exhaust gas
\(y_i^{e}\) Mole fraction of component i in the environmental
\(\eta\) Energy efficiency
\(\eta_I\) Exergy efficiency
\(\tau\) Engine torque, Nm
\(\omega\) Angular velocity, 1/s

Indices

\(a\) Air
\(f\) Fluid
\(gw\) Cooling water of gas calorimeter
\(i\) Inlet, component
\(j\) Outlet, number of component
\(o\) Reference environment
\(e\) Environment, exhaust
\(s\) Surface, supplied