A novel exergy analysis of spray injection angle of compression ignition engine

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Abstract

A comprehensive study was carried out to determine the exergy efficiency with regard to variation of spray injection angle (aiming to the bowl) and engine speed. For engine performance and spray structure analysis, 3D CFD simulation of engine according to Deutz Diesel engine was applied and in-house code was used to acquire exergy, irreversibility, and second law efficiency. Second law efficiency was calculated for different spray angle- engine speed strategies and 31.12%, 27.2%, and 29.17% are attributed to 130, 140, and 150 deg of injection angle under 1500 rpm, respectively. In terms of engine performance, i.e. IMEP, ISFC, and T, the best indices are of 130 deg equal to 15.4 bar, 0.6856 Kg/Kwh, and 2074.97K under 1500rpm, respectively. Instant irreversibility rate possesses higher amount of peak value for 130 deg, while 140 deg shows higher mean irreversibility rate over CA period. The highest mean irreversibility rate was reported at 2500 rpm-140 deg case.

Keywords: CFD; Spray guided injection; Exergy; Irreversibility; Swirl chamber

1. Introduction

Needless to say, energy conservation and management is vital issue, hence presentation of framework within which both frugality and high efficiency can be accomplished seems inevitable. Energy evaluation of ICEs alone, fails to pinpoint the key elements governing inefficiency and combustion deficiency since energy evaluation enables us just to quantify the output of the system. The exergy analysis especially in engine application is useful since it can be used to curb the sources of irreversibility or weaknesses regarding transferring the heat of combustion to a practical work, which is turned into a mechanical shaft work. Exergy survey is an attempt to identify, thus avoid energy waste via heat transfer with exhausted gas from manifold. Recently assessment of operational parameters in devices of energy field has drawn attention through exergetic and energetic means. In this regard, few dozen surveys have been done for the parametric case studies to analyze the behavior of engines under the influence of several factors listed in [1-5]. In addition, several papers examine exergetic analyses in solar plants [6], wind turbine system [7], coal gasification technology [8], etc. A broad spectrum of availability and irreversibility work was covered with engine and combustion process [9-12].

The review on the consideration of the first and second law in the ICEs led to the following conclusions: The effect of n-heptane and natural gas blends were surveyed in HCCI engines from the second thermodynamic law viewpoint [13]. A complete chemical kinetic mechanism was utilized in order to analyze the availability of system for varied EGR and natural gas percentage addition. They proved that the natural gas addition bounds to lowering exergy destruction along with second law efficiency augmentation. Ozkan et al. [14] discussed the effect of pre-injection timing on diesel engine’s exergetic and energetic performance elaborately. Their results point out that by applying appropriate pre injection, no perceptible influence can be noticed on thermal and exergetic efficiency, but NOx emissions were reduced significantly by 7.4%. A novel crank-angle resolved exergy analysis methodology was utilized for determination of the optimal operating condition of gasoline fueled HCCI engine [15]. It was observed that the equivalence ratio should be preserved at high values for majority of engine conditions while pressure was used to regulate engine load. Moreover, it was indicated that combustion timing has to be such adjusted as to be placed just before the sharp increase of unburned species losses. Jafarmadar [16] carried out exergy analysis in combustion chamber of the IDI diesel engine. The results demonstrated 56% and 77% of total irreversibility stems from main chamber combustion in part and full load mode of engine operations, respectively.

The investigation elaborates on the interaction between different terms of exergy terms and energetic concepts while the spray injection angle is varied for CI diesel engine while 1500 and 2500 rpm engine speed was applied. The second law was proposed in various useful work, irreversibility, and chemical and total availability terms. Contour maps of temperature and CA based on availability and irreversibility was presented. It
is the first that exergetic terms are plotted against each other to deduce a general trend. Among 6 cases with different speed and injection angle, 130deg-1500 rpm shows optimal exergetic efficiency; however, higher emission was issued.

2. Geometrical definition and Numerical simulation

The swirl combustion chamber of diesel engine has positive characteristics such as low NOx emission, low noise, and high engine speed [17-19]. The schematic of combustion chamber with guided injected spray was illustrated in Fig. 1. Three sprays of 130, 140, and 150deg with respect to x-axis are shown. As seen, 140deg aimed at central spot of swirl chamber, 130deg being injected near pedestal section which makes counter clockwise spray diffusion whereas 150deg being injected near squish zone with clockwise swirl motion of the spray. Boundary condition, dead state condition, flow and emission simulation sub-models, and engine specifications are briefly summarized in Table 1, 2. 3-dimensional gridding of the chamber with sufficient 23242 numbers of mostly unstructured cells was constructed (Fig. 2). The veracity of simulated results is validated according to pressure courses of 1500 and 2500 rpm engine speeds.

3. Computational implementation of the second law

Exergy is defined as an attribute representing the capability of a system in transforming a given amount of energy at prescribed condition to useful work. In other words, exergy determines the maximum useful work attained from a system, which is plausible when a reversible process can be established between the initial and final point. The reversible process yields the maximum work when the system reaches a thermodynamic equilibrium with surrounding. The maximum extractable work depends on both ambient condition and the characteristics of the system. In this sense, total exergy is classified as thermo mechanical exergy and chemical exergy. The latter concerns thermal and physical
equilibrium with environment with temperature and pressure potential release and the former governs the state when no chemical reaction tendency of the working fluid and the environment exists. In the case of the engines, all the components of the working medium have to be either oxidized (e.g. fuel, CO, H), or reduced (e.g. NO, OH), in a reversible manner as the system approaches the dead state. The only components of the system, which cannot react chemically with the atmosphere are O2, N2, CO2 and H2O [20,21]. The thermo mechanical, chemical, and total exergies are formulated as follows:

\[ E_{ch} = T_0 \sum_i m_i R_i \ln \left( \frac{X_i}{X_i^0} \right) \]  
\[ E_{xm} = E - P_0 V - T_0 S - \sum_i \mu_i^0 m_i \]

where \( m_i, X_i \) and \( \mu_i^0 \) are the mass flow, mass fraction, and chemical potential of species \( i \) obtained at restricted dead state. Here, \( \mu_i \) is chemical potential associated with restricted dead state, moreover, \( \mu_i^0 \) and \( X_i^0 \) are chemical potential, and mass fraction associated with actual dead state condition for the species \( i \). \( P_0, T_0 \) are the pressure and temperature at dead state conditions, accordingly. The total availability is the sum of chemical and thermo-mechanical availability:

\[ E_x = E_{ch} + E_{xm} = E - P_0 V - T_0 S - \sum_i \mu_i^0 m_i \]

The rate of indicated work exergy is quantified as given:

\[ \frac{dE_{ext}}{dt} = (P - P_0) \frac{dV}{dt} \]  
\[ \frac{dV}{dt} \] denotes volume change of cylinder volume with crank angle and \( P \) is the instantaneous pressure of the cylinder obtained by first law analyzed data. \( E_{ext} \) represents the exergy of heat release within cylinder. The exergy of heat release rate can be presented by \( (dQ/d\theta) \) is heat release rate:

\[ \frac{dE_{ext}}{d\theta} = (1 - \frac{T_0}{T}) \frac{dQ}{d\theta} \]  
Irreversibility is denoted by I term that is the availability destruction concerning the combustion process in the chamber given as:

\[ \frac{dI}{d\theta} = \frac{T_0}{T} \sum_i \frac{\mu_i}{T_0} \frac{dm_i}{d\theta} \]

The chemical availability of the \( C_6H_{12}O_6 \) liquid fuel is calculated by the following formula [22]:

\[ A_{ch} = A_{ch,m} = LHV \left[ 1.0410 + 0.01728 \frac{x}{y} + 0.0432 \frac{y}{x} \right] \]

\[ LHV \] in the above Eq. is the low heat value of the fuel. Note that \( w \) is the water content of the fuel.

\[ LHV = [33.91 + 125.6x - 2.51(9x - w)] \]

In order to quantify the second law efficiency of the engine the following formula is applicable:

\[ \eta_{II} = \frac{E_{x, output}}{E_{x, input}} = \frac{A_{ch}}{A_{ch,ch}} \]

4. Results and Discussion

Injection angle variation leads to change in fuel flow behavior into nozzle. Spray structure undergoes changes in terms of SMD and penetration since nozzle geometry was modified. SMD and liquid kinetic energy of the spray were taken into account as to evaluate spray characteristics injected into bowl section of the piston.

Exemplary temperature contour map for the case of 1500rpm and 150deg was depicted in Fig. 3. It is evident that increasing pressure and temperature increases the total exergy. Increasing the temperature and pressure lead to increasing the difference of thermo-mechanical potential with the surrounding atmosphere. Contour maps of different exergy and irreversibility on the crank angle and temperature basis were examined in Figs. 4-6, Figs. 7-9, and Figs. 10-12 for the 1500rpm-150deg, 1500rpm-130deg, and 2500rpm-150deg, respectively. The main conclusions can be mentioned as follows:

Comparison between A-dl/dt of Fig. 5 and Fig. 11 graphs (constant angle, different engine speed): Crank angle contours are stretched horizontally with engine speed increase which demonstrates more irreversibility rate increase with increasing engine speed. This is mainly due to increasing speed of combustion process that reduces efficient exploitation of furnished heat. The most availability irreversibility range of distribution for Fig. 5 and Fig. 11 pertains to 750 and 780˚CA, respectively. Increasing CA from 700 to 780 caused more availability-irreversibility interaction effect taking 2500 rpm-150 deg case into account.

Comparison between temperature gradients in dl/dt-A graphs of Fig. 6 and Fig. 12 (temperature based): in both cases, increasing temperature led to the increment of both availability and irreversibility. Temperature gradients are stretched vertically with higher engine speed of 2500-rpm. Furthermore, considering 2500 rpm, the constant temperature lines are perpendicular after 800˚K and at each constant temperature, irreversibility increases irrespective of pressure level. It is seen that temperature curves are quite smooth under 1500 rpm speed.

Comparison between B-out-A-in of Fig. 4 and Fig. 10 graphs: 690˚CA contributes to the chemical exergy and useful work to the great extent for 1500 rpm whereas 690˚CA covers negligible area of chemical exergy and useful work. For the same range of chemical availability, higher useful work production is achieved for 1500 rpm engine speed. Note that the highest work production is resulted at different crank angles for 1500 and 2500 rpm cases.

Comparison between Fig. 4 and Fig. 7 graphs (constant speed, different injection angle): lower useful work was achieved for 150deg, although crank angle contours for 130deg is stretched diagonally. Irreversibility and availability values are more extended for 130deg than that of 150 deg. More availability-irreversibility discrepancy is associated with 750 and 770˚CA for 150 deg and 130 deg, respectively.
Table 1. Boundary conditions, dead state characteristics, and simulation sub-models

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Head temperature</td>
<td>550.15˚K</td>
</tr>
<tr>
<td>Piston temperature</td>
<td>575.15˚K</td>
</tr>
<tr>
<td>Cylinder temperature</td>
<td>475.15˚K</td>
</tr>
<tr>
<td>Dead state pressure</td>
<td>1.01325 bar</td>
</tr>
<tr>
<td>Dead state temperature</td>
<td>290.15˚K</td>
</tr>
<tr>
<td>Spray breakup</td>
<td>Wave</td>
</tr>
<tr>
<td>Combustion model</td>
<td>ECFM-3Z</td>
</tr>
<tr>
<td>Turbulence model</td>
<td>k-\varepsilon</td>
</tr>
<tr>
<td>Evaporation</td>
<td>Dukowicz</td>
</tr>
<tr>
<td>NO</td>
<td>Extended Zeldovich</td>
</tr>
<tr>
<td>Soot</td>
<td>Kennedy-Hiroyasu-Magnussen</td>
</tr>
<tr>
<td>Wall treatment</td>
<td>Hybridized wall</td>
</tr>
<tr>
<td>Heat transfer wall mode</td>
<td>Standard wall function</td>
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<tr>
<td>Residual gas ratio</td>
<td>0.5</td>
</tr>
<tr>
<td>Fuel injection quantity (mg/cycle)</td>
<td>31.3</td>
</tr>
</tbody>
</table>

Table 2. 1.8L Ford diesel engine specifications

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bore\times stroke</td>
<td>82.5x 82 mm</td>
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<tr>
<td>Displacement</td>
<td>438 cm³/cylinder</td>
</tr>
<tr>
<td>Compression ratio</td>
<td>19.5:1</td>
</tr>
<tr>
<td>Swirl ratio @ IVC</td>
<td>3</td>
</tr>
<tr>
<td>Rail pressure</td>
<td>540-1255 bar (based on engine speed)</td>
</tr>
<tr>
<td>Nozzle geometry</td>
<td>5x0.15 mm</td>
</tr>
<tr>
<td>Bowl diameter</td>
<td>0.0483m</td>
</tr>
<tr>
<td>Bowl depth</td>
<td>0.0144m</td>
</tr>
<tr>
<td>Clearance</td>
<td>0.86mm</td>
</tr>
<tr>
<td>Number of nozzle holes</td>
<td>4</td>
</tr>
<tr>
<td>Injection start timing</td>
<td>3˚CA BTDC</td>
</tr>
<tr>
<td>Injection spray angle</td>
<td>130, 140, 150deg</td>
</tr>
</tbody>
</table>

Figure 3. Temperature contour map for exergy based on cylinder pressure
Figure 4. The interaction pattern between useful work exergy and total chemical exergy for 150deg-1500 rpm scenario: CA based

Figure 5. Mapping plot between total exergy and irreversibility rate for 150deg-1500 rpm couple: CA based

Figure 6. The variations of tractive power efficiency (%) with respect to iterations for ICA algorithm
Figure 7. The interaction pattern between useful work exergy and total chemical exergy for 130deg-1500 rpm scenario: CA based

Figure 8. Mapping plot between total exergy and irreversibility rate for 130deg- 1500 rpm couple: CA based

Figure 9. Mapping plot between irreversibility and exergy for 130deg- 1500 rpm: Temperature based
Figure 10. The interaction pattern between useful work exergy and total chemical exergy for 150deg-2500 rpm scenario: CA based

Figure 11. Mapping plot between total exergy and irreversibility rate for 150deg - 2500 rpm couple: CA based

Figure 12. Mapping plot between irreversibility and exergy for 150deg - 2500 rpm: Temperature based

5. Conclusion

The results of the paper was prepared in two manners: first numerical work has been performed to obtain the results of pressure, temperature, species content used for combustion and the products of combustion, then the variation in engine (spray injection into the bowl of CI diesel engine) is considered. Secondly, the obtained results of numerical considera-
tion were used to compute the various exergy and irreversibility terms with the help of in-house developed code. Although 130 deg of spray injection angle showed superiority in most of the exergy concepts, but it showed higher rate of pollutant production such as NOx and soot used for the second law analysis. The spray structure showed close correlation with that of exergy efficiency and combustion characteristics. Different availability-irreversibility scatter range was recognized on CA basis. Furthermore, a regression analysis was carried out for six different cases and the best accurate and fitting equation in terms of total availability based on CA was found.


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