Utilization of Oxygen-Enriched Air in Diesel Engines: Fundamental Considerations

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ABSTRACT
Utilization of oxygen-enriched air in diesel engines holds potential for low exhaust smoke and particulate emissions. The majority of the oxygen-enriched-air combustion-related studies so far are experimental in nature, where the observed results are understood on an overall basis. This paper deals with the fundamental considerations associated with the oxygen-enriched air-fuel combustion process to enhance understanding of the concept. The increase in adiabatic flame temperature, the composition of exhaust gases at equilibrium, and also the changes in thermodynamic and transport properties due to oxygen-enrichment of standard intake air are computed. The effects of oxygen-enrichment on fuel evaporation rate, ignition delay, and premixed burnt fraction are also evaluated. Appropriate changes in the ignition delay correlation to reflect the effects of oxygen-enrichment are proposed. The notion of oxygen-enrichment of standard intake air as being akin to leaning of the fuel-air mixture is refuted on the basis of the fundamentally different requirements for the oxygen-enriched combustion process.

INTRODUCTION
Current engine design and development strategies revolve around the need to reduce engine emissions to legislated limits. Engine-out emissions serve as a pointer to the efficacy of in-cylinder combustion-related processes. The concept of oxygen-enrichment aims at limited substitution of the nitrogen in air by oxygen to achieve low emission levels. Because of the increased oxygen content, additional fuel is burned. The resulting increase in power output is a beneficial offshoot, though it is not attempted for its own sake. Oxygen-enrichment of combustion air provides an opportunity to achieve ignition with minimum amounts of premixed fuel, because it reduces the ignition delay period under all operating conditions. As a result, the peak cylinder pressure is low. Oxygen-enrichment of standard intake air also promotes combustion with alternative fuels, as well as low-grade and water-emulsified fuels (Sekar et al. 1990). However, oxides of nitrogen (NOx) emissions would be higher with oxygen-enrichment because of the accompanying higher combustion temperatures. The level of technological complexity, economics, and NOx emissions limit govern the oxygen-enrichment level. Complete substitution of air by oxygen is not attempted, despite its theoretical superiority, because of the economics of oxygen generation, technical difficulties associated with implementation in internal combustion (IC) engines, and metallurgical considerations.

The concept of oxygen-enrichment has its genesis in spark ignition (SI) engine applications (e.g., Wartinbee 1971; Quader 1978). At present, attention is more critically focused on compression ignition (CI) engines because of the diverse fields of application. Studies concerning effects of oxygen-enrichment on both Direct-Injection (DI) and Indirect-Injection (IDI) diesel engines have been carried out, with particular emphasis on the DI variety. Ghjoel et al. (1983) and Reader et al. (1995) have studied the effects of oxygen-enriched combustion air in an IDI diesel engine. Ghjoel et al. (1983) varied the oxygen content in the intake between 21 and 40 percent by volume and evaluated the engine performance and emissions at constant engine speed and injection timing while changing the fueling rate. They reported a large decrease in ignition delay period, reduced combustion noise, decreased HC and CO emissions, and a substantial drop in smoke levels. The NOx emissions were found to increase proportionately with oxygen-enrichment. They observed that fuel consumption, power output, and exhaust temperature remained constant, which was rather unexpected in the light of the usual effects of oxygen-enrichment. The findings of Reader et al. (1995) were in complete agreement with those of
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From these parameters, the mixture quality is decided as the relative percentage of oxygen at the expense of nitrogen. For a given engine displacement and amount of intake air, there exist three different operating regimes, based on air composition, which includes processes like dilution of air such that

\[
\frac{\text{oxygen}}{\text{fuel}}_{\text{amb}} > \frac{\text{oxygen}}{\text{fuel}}_{\text{OE}}
\]

2. Increasing both the oxygen content in the air and the fuel input while proportionately decreasing nitrogen concentration in the air such that

\[
\frac{\text{oxygen}}{\text{fuel}}_{\text{amb}} = \frac{\text{oxygen}}{\text{fuel}}_{\text{OE}}
\]

3. Increasing the oxygen content of air by proportionately decreasing the nitrogen content in the air and disproportionately increasing the fuel input such that

\[
\frac{\text{oxygen}}{\text{fuel}}_{\text{amb}} < \frac{\text{oxygen}}{\text{fuel}}_{\text{OE}}
\]

(The subscripts, amb and OE, stand for conditions with ambient and oxygen-enriched combustion air, respectively.)

Varying the composition of air in terms of oxygen and nitrogen contents is expected to cause changes in its thermodynamic and transport properties, ignition delay, flame temperature, exhaust gas composition, and fuel-air mixing characteristics that may be of importance in furthering the understanding of the oxygen-enrichment concept. These characteristics, evaluated by using appropriate correlations, are described in the subsequent sections.

**Thermodynamic Properties**

**Density:** In the case of oxygen-enrichment, the definition of volumetric efficiency is modified in the presence of additional oxygen content in the air. This can be described as apparent volumetric efficiency (AVE) and is defined as:

\[
\text{AVE} = \frac{\text{Volumetric flow rate of oxygen-enriched intake air}}{\text{Rate of change of engine cylinder volume}}
\]

The AVE as defined in Equation 6 includes the effect of manifold temperature on charge density. Both the altered compositions of intake air and higher in-cylinder temperatures due to oxygen-enrichment lead to changes in the density of the charge. The change in density has so far been attributed to higher in-cylinder temperatures due to oxygen enrichment, which is applicable in the quasi-steady working period of the engine cycle. However, at a given temperature prior to combustion, the relative molecular mass (RMM) of air changes with the oxygen-enrichment, and thus, the density. The variation in density with various levels of oxygen-enrichment was computed on the basis of RMM.

**Specific Heat Capacity:** The effect of reformed air composition on the ratio of specific heats is not reported in the literature. A preliminary calculation is needed to qualitatively estimate the change, following Kothandaraman and Subramanyam (1989).

**Transport Properties**

The two transport properties of importance are viscosity and thermal conductivity, which influence the flow and heat-transfer-related processes. Due to oxygen-enrichment, the overall temperature after combustion will be raised as a consequence of...
higher flame temperature. This would increase the heat transfer losses and cooling requirements in the engine. The estimation of transport properties was attempted to highlight the significance of oxygen-enriched combustion. The dynamic and kinematic viscosities, as well as the thermal conductivity, were computed by following Kothandaraman and Subramanyam (1989). The mixture's thermodynamic and transport properties were estimated, using the square-root rule, by following Spalding (1963).

**Flame Temperature and Equilibrium Composition**

In the present work, a computer program developed by Olikara and Borman (1975) was used, with suitable modifications necessitated by oxygen-enrichment, to compute adiabatic flame temperature and equilibrium composition. The change in molar ratio of nitrogen-to-oxygen is included with oxygen-enrichment. The scheme limits the number of product species to 12. However, it gives a fair degree of accuracy without obscuring the physics of the problem. The adiabatic flame temperature and equilibrium composition were calculated with different equivalence ratios and at various oxygen-enrichment levels. The difference between oxygen-enrichment and lean burn combustion is explained through equilibrium composition calculations.

**Phase Change (Fuel Evaporation) Rate**

The transfer number concept, suggested by Spalding (1963), is used as the basis to compute the phase change rate. The transfer number (B) is defined as the difference in the values of any conserved property in terms of species concentrations in the gas stream and the adjoining stream. This transfer number, which is a driving force for mass transfer, can be understood as being analogous to the potential difference required for the flow of electric current. When the transfer number is estimated by using mass conservation equations, it is called the mass transfer number, Bm, and if estimated by using enthalpy conservation equations, it is called the enthalpy transfer number, Bh. These transfer numbers can be estimated with and without combustion.

A transfer number greater than zero implies mass transfer into the considered phase (i.e., evaporation of fuel and transfer of fuel vapors into air), whereas a transfer number less than zero implies condensation of air and dilution of fuel, a condition not realized in IC engine combustion.

The evaporation and envelope flame (diffusion) combustion of a fuel droplet are frequently treated by assuming a slowly varying sequence of steady states (i.e., quasi-steady assumption). However, in an engine combustion chamber, the conditions at the gas/liquid interface may undergo appreciable fractional changes in a period of the order of the characteristic diffusion time n / D, where D is the droplet's initial radius at that instant and D is the diffusion coefficient of the fuel. For example, a 100-μm diesel fuel droplet requires a characteristic diffusion time of a millisecond or so. Even when the vapor composition and temperature are essentially constant at the droplet surface, the starting transient may occupy an appreciable fraction of the total droplet lifetime. These transient effects become quite important when local conditions at the vapor/liquid interface approach thermodynamic critical conditions. The transfer numbers for droplet evaporation with and without combustion are estimated using a transient analysis. The fuel's partial pressure is calculated following Rosner and Chang (1973), and the one-third rule of Sparrow and Gregg (1958) is used to calculate the properties at reference temperature in transfer number calculations (Mehta et al. 1985).

**Ignition Delay**

Prediction of the ignition delay period for different engine geometries under various operating conditions and fuel types has been investigated for a long time. However, the variation of air composition on ignition delay has not been a common feature of most of the earlier correlations. From the many existing correlations, only those formulated by Fujimoto (1980) and Hiroyasu (1985) have explicitly considered the effect of oxygen concentration in the intake air in terms of the partial pressure of oxygen (P02), as given below:

\[ \tau_{id} = a \cdot 1.23 \left( \frac{P_{02}}{0.21P_0} \right)^{-1.6} \exp \left( \frac{E_a}{RT} \right) \]  

where a = 0.0276 and Ea/R = 7280 K.

Diesel fuel (C16H34) with a Cetane number of 45 was employed in deriving the above correlation. When used in IC engines, this correlation requires an input of cylinder temperature and pressure. These values could be suitably taken at the end of compression. However, a better estimate is possible by incorporating the injection timing effects, which can be reflected through the values of temperature and pressure at the instant of injection. Also, from the operating regimes described in Equations 3 through 5, the contents of oxygen and fuel in the cylinder are key components when oxygen-enriched combustion air is used. Hence, they should be considered for a realistic estimate of ignition delay period. In the present work, the ignition delay correlation suggested by Hiroyasu (1985) was modified to provide a consistent understanding of the oxygen-enrichment and to reflect the changes in fuel-to-oxygen ratio due to oxygen-enriched air as:

\[ \tau_{id} = p^{-1.23} \left( \text{FOR} \right)^{n_1} \exp \left( \frac{E_a}{RT} \right) \]  

where FOR is the local fuel-to-oxygen ratio (on a mass basis), n1 is a constant, p and T are taken at the instant of fuel injection, and the values of 'a' and Ea/R are the same as in Equation 7. The value of n1 is determined by curve-fitting the experimental data. On the basis of experimental data obtained on a single-cylinder Caterpillar engine (Sekar et al. 1991), an average value of -1.15 is recommended for n1.

**Fuel-Air Mixing Rate - Multizone Approach**

The fuel-air mixing process in diesel engines is significantly slower than the kinetics of fuel oxidation during the greater portion of the combustion process; therefore, the dominant combustion mechanism in the diesel engine is mixing-controlled. The heterogeneity of the fuel-air mixture before the onset of ignition causes the local fuel-air ratio to be extremely low in the regions where fuel evaporation occurs. Initial ignition has the advantage of high oxygen concentration around molecular groups...
of fuel. To anticipate the pattern of heterogeneity in the charge is an important prerequisite for the development of an efficient combustion system (Andree and Pachernegg 1969). The present work pursues this approach further to predict the temporal and spatial distribution of the fuel-air mixture. DI diesel engines employ multi-hole injector nozzles and high injection pressures, thereby attaining a higher fuel mass flow rate and a larger fraction of fuel in the spray fringes, where possibilities of premixing are higher. The ignition delay time is generally longer than the mixing time, so ignition delay controls the premixed phase combustion. The premixed combustion fraction is evaluated on a more consistent basis by considering the amount of fuel injection and the mass fraction of ignitable mixture prepared during the ignition delay period only. At any instant, these mixture fractions can be put in one of four categories to relate them to engine combustion and emission characteristics:

- **Overmixed zone**: ($\phi \leq 0.3$)
- **Ignitable fuel-lean zone**: $(0.3 < \phi \leq 1.0)$
- **Ignitable fuel-rich zone**: $(1.0 < \phi < 3.0)$
- **Undermixed zone**: $(\phi > 3.0)$

At the end of the ignition delay period, when the in-cylinder pressure and temperature attain values that can sustain combustion, the mass fraction of ignitable fuel prepared during the ignition delay period is consumed. The unignitable mass fraction that is outside the flammability limits has to undergo further mixing with the surrounding air and the products of combustion contributed from the burned mass fraction. Since the mixing quality can be identified in terms of ignitable (rich and lean) and unignitable mass fractions at any instant during the spray mixing and combustion process, they are estimated here to determine the effect of oxygen-enrichment on the mixture preparation prior to ignition. The flammability limits for diesel combustion are generally taken as $0.3 < \phi < 3.0$ (Shahed et al. 1975) through an approximation with oxygen-enrichment. The oxygen flammability limits are known to be wider than the air flammability limits. The lean limit for flammability is unaffected at higher pressures and with oxygen-enrichment, but the rich limit increases in these cases. The values of rich limits with oxygen-enrichment are not readily available for diesel fuels; hence, the values associated with standard air flammability limits continue to be used.

In order to reflect the increased complexities associated with oxygen-enrichment, the local fuel-air mixture quality is predicted by a time-marching process model. A multizone, phenomenological model is formulated, using appropriate process correlations. Spray growth is computed by using the spray penetration equation suggested by Dent (1971). A semi-cone angle is taken as $11^\circ$, as recommended by Abramovich (1963) for a non-burning fuel spray. Fuel-air mixing calculations are based on mean injection velocity and an air entrainment rate equation, following Ricou and Spalding (1961). The multizone configuration of the spray is arrived at by dividing the fuel injection process into a number of intervals of $1^\circ$ CA duration and assuming the distribution of each of these packets follows a similarity law for concentration of fuel as proposed by Abramovich (1963). The details of the complete model can be found in Mehta et al. (1996). This modeling procedure provides a fuel-air distribution in terms of the local equivalence ratio in each zone. With an assumption of uniform cylinder pressure and temperature prior to combustion, these equivalence ratio distribution histories form the basis to estimate the amount of mixture prepared for burning under stoichiometric conditions. Depending upon the local equivalence ratio and cylinder pressure and temperature conditions, the local burning temperature, expressed as adiabatic flame temperature in various spray zones, is computed following Olikara and Borman (1975). The droplet size distribution in terms of Sauter mean diameter is included. The detailed droplet evaporation calculations are avoided by using the assumption of instantaneous evaporation. The model does not include the effects of swirl on fuel-air mixture formation. The ignition delay is either an input value or can be estimated by using Hiroyasu's correlation as expressed in Equation 7. The engine details and other inputs used in the calculations are specified in Table 1.

### Characterization of Premixed Combustion Phase

Diesel combustion is essentially a mixing control process. However, the role of the premixed combustion phase in diesel engines has acquired considerable significance from an emission standpoint. The mixing pattern in this pre-ignition phase is evaluated to gain a better understanding of the processes to follow during the combustion period. In the present work, an attempt is made to bring the oxygen sensitivity into burn rate calculations via the premixed fraction, using Watson's correlation (Watson et al. 1980). The fraction of the injected fuel that burns in premixed phase $\beta$ at a given speed, if related to the trapped fuel-air equivalence ratio $\psi_{\text{trapped}}$ and ignition delay period $\tau_{\text{id}}$ in ms, is:

$$\beta = 1 - k_1 \psi_{\text{trapped}}^{k_2} \tau_{\text{id}}^2$$

(9)

where $k_1$ and $k_2$ are engine-specific empirical constants. The typical recommended values of these constants are 0.9, 0.35, and 0.4, respectively, as referred to in Heywood (1988). At varying oxygen-enrichment levels, the stoichiometric oxygen-to-fuel ratio will be

$$\text{OFR}_{\text{stoi}} = \frac{\text{mass of oxygen}}{\text{mass of fuel}}$$

(10)

The details of the complete model can be found in Mehta et al. (1996). This modeling procedure provides
The actual oxygen-to-fuel ratio and $t_{id}$ are estimated from the multizone model developed in this work and the ignition delay equation (Equation 7), respectively. This enables a qualitative inference to be drawn from oxygen-enrichment considerations. The values of premixed burnt fraction $\beta$ are estimated for various levels of oxygen-enrichment, using Equation 9. These values are only representative for the study of the oxygen-enrichment effects.

**Burn Rate**

It is well recognized that the oxygen-enrichment of standard intake air alters the combustion characteristics of fuel-air mixtures. This change in combustion process can be viewed in two ways: (i) based on equilibrium considerations, where the equivalence ratio is the controlling parameter; and (ii) based on kinetic considerations, where both the equivalence ratio and the temperature are controlling parameters. In an equilibrium approach, the infinite reaction rate is implicit, and hence, the effect of reaction kinetics through temperature is marginal. When oxygen-enriched air mixes with fuel, the rates of reaction increase. This effect can be better explained through the understanding of chemical reaction rates.

Assanis et al. (1993) have attempted to adopt the Double-Wiebe and Watson's burning rate calculation procedure for an oxygen-enriched air-fuel combustion system. However, they found both of these classical correlations unsatisfactory in the diffusion-burning phase. Also, in the tail region of combustion, the gradual drop in energy release rate could not be obtained. They also observed that the second function in Watson's correlation is not flexible enough to fit an oxygen-enriched combustion profile. They proposed a novel correlation with an additional degree of freedom in the original Wiebe function, in the form of a free exponent to predict the combustion tail properly. The applicability of the burn rate model suggested by Assanis et al. (1993) and also the correlations suggested by Miyamoto et al. (1985) and Huang et al. (1994) are tested for oxygen-enriched combustion in this study.

**RESULTS AND DISCUSSION**

The typical results in the present work are obtained and analyzed from the viewpoint of understanding of oxygen-enrichment effects on various engine processes. These results are discussed below.

**Effect on Thermodynamic and Transport Properties**

It has been reported (Karim et al. 1965) that oxygen-enrichment has no effect on thermodynamic and transport properties. However, a fresh estimation was undertaken to corroborate these findings. When oxygen content in the air increases from 21 to 31% by volume, the density of air increases by 1.4% because of an increase in the RMM. Although the change in density is marginal due to variation in the RMM, this effect is of significance, where the higher molecular mass of reformed air will provide higher density at a given temperature prior to combustion. Because of the effect of an increase in the in-cylinder temperature on combustion in the oxygen-enriched air-fuel system, a decrease in density is expected, and this has been reported (Maxwell et al. 1993). Hence, the temperature effect is a more dominant factor than the RMM for density variations with oxygen-enriched intake air. The effects of oxygen-enrichment on specific heat capacity and specific heat ratio are negligible (not shown), corroborating the results reported earlier (Karim et al. 1965).

The variations in thermal conductivity with oxygen-enrichment were marginal, as shown in Figure 1. The slight increase in thermal conductivity with oxygen enrichment at the corresponding flame temperature explains the higher heat transfer losses. Perhaps this effect may account for a reduction in brake thermal efficiency, as reported by Wartinbee (1971) and Quader (1978), in an SI engine. On the other hand, the changes in both the dynamic and kinematic viscosities with oxygen-enrichment are negligible (not shown).

![Fig. 1 Variation of thermal conductivity with oxygen-enrichment](image)

**Effect on Flame Temperature and Equilibrium Composition**

The computed values of adiabatic flame temperature with equivalence ratio at various oxygen concentrations are shown in Figure 2. It is observed that the maximum flame temperature occurs at different equivalence ratio values greater than stoichiometric when the oxygen concentration in air is increased. The maximum flame temperature is higher with higher oxygen concentration in the air, and so is the equivalence ratio for these maximum flame temperatures, as shown in Figure 2.

![Fig. 2 Variation of adiabatic flame temperature with fuel-air equivalence ratio at various levels of oxygen-enrichment](image)
the usual claim that oxygen-enrichment is akin to lean-mixture operation. Had this claim been true, the excess O\(_2\) concentration should have shown an increase in the products. In diesel combustion, the analogy of oxygen-enrichment with lean-burn conditions becomes obscure due to the heterogeneous nature of the charge. Hence, the oxygen-enrichment effect should be viewed as an effect related to the changes in nitrogen-to-oxygen ratio in air and oxygen-to-fuel ratio in the mixture, rather than as an equivalent lean air-fuel ratio. The increased OH concentration with oxygen-enrichment suggests that the HC emissions would be reduced, which has been generally reported in the literature. The peak NO concentration occurs at leaner mixtures with oxygen-enrichment than with standard air. This can be attributed to higher flame temperatures at higher oxygen concentration levels and to higher N or O concentrations at mixtures leaner than standard air. These equilibrium composition calculations form the basis of NO and soot oxidation calculations in the emission models. The need for an approach based on chemical kinetics is clearly felt when the oxygen-enrichment concept is examined through equilibrium considerations.

**Effect on Phase Change (Fuel-Evaporation) Rate**

The rate at which fuel changes from the liquid to the vapor phase, prior to combustion, is important from the mixture preparation standpoint. The effect of oxygen-enrichment on phase change rate is estimated from this standpoint; the results are shown in Figure 4. The change in fuel mass fraction (see Figure 4) at the fuel-oxidant interface has no significant effect on the mass transfer number, but changing the enthalpy transfer number influences the transfer rate (point of intersection of \(B_m\) and \(B_h\) curves). The higher the transfer number value, the higher will be the mass transfer driving potential and hence the rate. A similar trend is observed for the variation with the ratio of fuel-air interface temperature (\(T_w\)) and the critical temperature (\(T_{cr}\)) of the fuel (Figure 4).
Effect on Ignition Delay Period

A reduction in ignition delay with oxygen-enrichment has been a universal experimental observation made by several investigators (Ghojel et al. 1983; Watson et al. 1990; Sekar et al. 1990; Reader et al. 1995). There is, however, no reported direct attempt to propose an ignition delay correlation incorporating the oxygen-enrichment effect. An attempt, therefore, has been made in this work to correlate the available ignition delay data. The proposed ignition delay correlation, given in Equation 8, has been used to compute the ignition delay period for varying levels of oxygen-enrichment. No attempt has been made to adjust the value of empirical constant ‘a’ appearing in the correlation to match the predicted and experimental results. Experimental data were obtained from the test results on a single-cylinder Caterpillar engine (Sekar et al. 1991). The results are presented in Figure 5. The predicted ignition delay, using the proposed correlation, shows a qualitative agreement with the experimental data but consistently underpredicts compared with experimental values at both engine load conditions. Efforts to universalize the correlation have been only partially successful and could not be pursued due to the lack of adequate published data. For that purpose, a large data set is essential; such a task may be attempted later. The qualitative trends of oxygen-enrichment effects on ignition delay with Hiroyasu’s correlation and the proposed correlation are observed to be similar. However, the quantitative data using Hiroyasu’s correlation considerably overpredicted, compared with both experimental and proposed correlation ignition delays. The changes in ‘FOR’ due to oxygen-enrichment and the variation of characteristic pressure and temperature (at the instant of injection) incorporated in the proposed correlation are attributable to the observed quantitative differences when compared to Hiroyasu’s original correlation.

![Fig. 5 Variation of ignition delay with oxygen-enrichment](image)

Effect on Fuel-Air Mixture Quality

The variation of ignitable fuel mass fraction prepared during the ignition delay period for different levels of oxygen-enrichment obtained from the multizone, spray-mixing model is shown in Figure 6. The ignitable fuel mass fractions have been estimated from the start of injection to the instant of ignition. Hence, if the instants of ignition for varying levels of oxygen-enrichment are plotted, as in Figure 6, a delay line is obtained, which represents the instant of ignition at each oxygen level.

The estimated values of the premixed burnt fraction for various oxygen-enrichment levels are summarized in Table 2, along with other useful parameters referred to in this work. The ignition delay period presented in Table 2 appears to be long, as computed using Hiroyasu’s correlation (Equation 7) instead of the proposed correlation (Equation 8). Because it is difficult to know ‘FOR’ at the point of ignition, the delay period itself needs to be estimated. For quantitative comparisons, more experimental data are being sought to predict the ignition delay period and the corresponding premixed burnt fraction for various oxygen-enrichment levels. The ignitable fuel mass fraction is estimated by using a model that predicts the charge heterogeneity (spatial distribution). At a given oxygen concentration level, the variation of the premixed burnt fraction with ignitable fuel mass fraction prepared during the ignition delay period is shown in Figure 7. This figure indicates a very useful relationship between premixed burnt mass fraction and the ignitable fuel mass fraction prepared during the delay period.

It is also observed (see Figure 8) that increasing oxygen-enrichment reduces the premixed burnt fraction. This suggests that there will be a smoother pressure rise with oxygen-enrichment. This expectation is in conformity with reported observations in several experimental studies about reduced peak pressures with oxygen-enrichment (Watson et al. 1990; Sekar et
Table 2. Summary of results predicting the effects of oxygen-enrichment

<table>
<thead>
<tr>
<th>Oxygen (volume percent)</th>
<th>Stoichiometric oxygen-to-fuel ratio (OFRsto)</th>
<th>Ignition delay (degree crank angle, (\tau_{id}))</th>
<th>Trapped oxygen-to-fuel ratio (\Phi_{trapped})</th>
<th>Trapped equivalence ratio (\Phi_{trapped})</th>
<th>Premixed burnt fraction (\beta)</th>
<th>Ignitable fuel mass fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>21</td>
<td>3.482</td>
<td>25</td>
<td>11.961</td>
<td>0.291</td>
<td>0.601</td>
<td>0.947</td>
</tr>
<tr>
<td>23</td>
<td>3.814</td>
<td>19</td>
<td>10.504</td>
<td>0.363</td>
<td>0.519</td>
<td>0.920</td>
</tr>
<tr>
<td>25</td>
<td>4.146</td>
<td>17</td>
<td>9.962</td>
<td>0.416</td>
<td>0.473</td>
<td>0.907</td>
</tr>
<tr>
<td>27</td>
<td>4.477</td>
<td>15</td>
<td>9.938</td>
<td>0.450</td>
<td>0.430</td>
<td>0.875</td>
</tr>
<tr>
<td>29</td>
<td>4.808</td>
<td>13</td>
<td>8.775</td>
<td>0.547</td>
<td>0.354</td>
<td>0.834</td>
</tr>
<tr>
<td>31</td>
<td>5.140</td>
<td>12</td>
<td>8.455</td>
<td>0.607</td>
<td>0.336</td>
<td>0.777</td>
</tr>
</tbody>
</table>

al. 1990: Assanis et al. 1993). The ability to correlate model parameters with this feature elucidates the usefulness of the present work. The stoichiometric contour of the oxygen-to-fuel ratio can be considered as a typical representation of the mixing pattern in the spray. Figure 9 shows a plot of stoichiometric contours of the oxygen-to-fuel ratio at various oxygen-enrichment levels. This figure suggests that the movement of the burning zone is characterized by the stoichiometric contour of the oxygen-to-fuel ratio. It can be seen that the burning zone will be closer to the edge of the spray than to its center with increased oxygen-enrichment. This variation is significant because it alters the local burning characteristics in various spray zones around the stoichiometric contour within the flammability limits. This may possibly reveal a suitable relationship between combustion and emission characteristics. This relationship must be further investigated and established as charge heterogeneity is duly accounted for.

CONCLUSIONS

In the present work, a process-based, time-marching multizone model for a quiescent DI diesel engine has been developed, and a correlation for ignition delay and a qualitative relationship of the premixed burnt fraction with oxygen-enrichment have been successfully achieved. In addition, fundamental insight has been gained concerning the effects of oxygen-enrichment on engine combustion. In summary, the effects of oxygen-enrichment are:

1. Negligible effects on specific heat capacity, the ratio of specific heats, and dynamic and kinematic viscosity. The increase in charge density due to variation in RMM is very slight (<2%).
2. Marginal increase in thermal conductivity with increasing oxygen-enrichment for any given flame temperature.
3. Higher maximum adiabatic flame temperatures with higher oxygen concentrations in air. The fuel-air equivalence ratios are also higher for the corresponding maximum flame temperatures.
4. Insignificant effect on mass transfer number, but an increase in enthalpy transfer number.
5. Reduction in ignition delay. The ignition delay correlation proposed in terms of fuel-to-oxygen ratio is:

\[
\tau_{id} = a \cdot (\text{FOR})^{n1} \cdot \exp\left(\frac{E_A}{RT}\right)
\]

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REFERENCES


