Effect of split injection on diesel engine pollutants using multi-zone model

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A four zone model based on the existing two zone model is developed to predict the formation of the pollutants like nitric oxide, carbon monoxide and soot from the fuel injection data and engine geometry. The four zones are fuel zone, stoichiometric burning zone, product/air zone and a non-burning zone outside the spray. Whitehouse combustion model and Annand's heat transfer model are used for the prediction of combustion parameters like pressure and temperature of the engine. Equilibrium calculations and rate kinetics are used for the rate calculation of nitric-oxide. Nagle Strickland constable oxidation mechanism has been used for predicting the formation and emission of soot.

Split Injection method is used for the control of nitric oxide. In split injection, injection of fuel is divided into two steps, the pilot injection of small quantity and main injection of larger quantity. Different proportions of fuel and different crank angle intervals between the end of pilot injection and the beginning of main injection are tried. The optimised combination of proportion of 30-70 with crank angle interval of 5° is established. An exhaustive parametric study is conducted using this four zone model to study the effect of design and operating conditions of engines on the formation of NO, CO and soot. The predicted results are highly in comparison with the published findings. Hence, it is concluded that the model can be effectively used for the development of engines.

A two zone combustion model, for the calculation of heat release was suggested by Baluswamy. The effect of fuel injection characteristics and heat transfer phenomenon on combustion characteristics was also suggested.

Khan and Wang suggested that an increase in the rate of fuel mixing, in combination with a retard in timing, may be used to reduce the emissions of NO from diesel engines without affecting exhaust smoke levels and without any substantial increase in specific fuel consumption.

Taro Aoyama et al. suggested that temperature distribution measurement enabled the characterization of the nitric-oxide reduction mechanisms for two methods by injection control; injection timing retard and split injection. Split injection delays the development of high-temperature regions. Nitric-oxide is reduced by controlling the temporal development of the localized high temperature regions. The soot formation is kinetically controlled and soot oxidation is represented by a model which has a combination of laminar kinetic and turbulent mixing times. Soot appears to be controlled near TDC by mixing and by kinetics as the exhaust is approached.

The bulk of the oxides of nitrogen (NOₓ) emission from a diesel engine is nitric oxide (NO). Nitric oxide is formed mostly in nearby premixed zones, where both oxygen level and temperature are high. In addition, the premixed nature of the first part of the diesel combustion process is more favourable to NOₓ production, than in the droplet burning during the later stages. The nitric oxide produced in the early part of the premixed combustion is not destroyed as the temperature falls, as the kinetic rate of the reaction is too low.

Carbon monoxide emissions from the combustion of organic material in diesel engines are only significant if the available oxygen is insufficient to allow complete combustion to carbon dioxide. Invariably excess air is available during the diesel combustion, and hence the level of emission of carbon monoxide is low.

Regarding soot reduction, it is shown that reduced soot formation is due to the fact that the soot producing rich regions at the spray tip are not replenished when the injection is terminated and then retarded. This conclusion is used in the present work on the portion related to split injection.

In the present work, split injection phenomena has been incorporated in the developed four zone combustion model for exhaustive study of the effect
of different split injection proportions such as 40-60, 35-65, 30-70, 25-75 and 20-80 and different crank angle intervals such as 3°, 4°, 5°, 6° and 7° on the control of pollutants like nitric-oxide and soot. Exhaustive study of different split injection proportions and crank angle intervals on the control of nitric-oxide, has been the original work of this present work which is different from the existing split injection available in the literature.

Theoretical Consideration

Fuel-Jet Penetration

The development of the fuel jet in the diesel combustion chamber is based on steady flow semi-infinite free jet and modified for transient jet. The fuel-Jet penetration is given by

\[ X_{\text{max}} = 0.685 \times 2.42 \left( \frac{\Delta P}{\rho_i} \right)^{0.5} \text{dn.t}^{0.5} \]  \hspace{1cm} (1)

Volume of fuel spray

The volumes of fuel consist of the conical part of half cone angle \( \theta \) and the bell shaped part added together.

Volume flow rate = \( 5.9902 \tan^2 \theta \sqrt{K.X.KF} \) \hspace{1cm} (2)

Combustion and heat release

Whitehouse combustion model is used in the present work. The combustion period is assumed to consist of two periods, i.e., pre-mixed and diffusion. Whitehouse’s preparation rate equation has been used. The correlation is between the rate of preparation of the fuel, surface area of fuel droplets and partial pressure of oxygen.

\[ P = K' M_1^{1/3} M_0^{2/3} \rho O_2^{0.4} \text{ (kg/g/CA)} \]  \hspace{1cm} (3)

Arrenheius type equation is used for reaction rate of the prepared but unknown fuel as

\[ R = K'' \frac{PO_2}{N\sqrt{T}} e^{-ACT\int (P - R)dx} \text{ (kg/g/CA)} \]  \hspace{1cm} (4)

Eq. (4) covers the complete range of the combustion period. The value of the empirical constants in the reaction rate equations are chosen so that the initial period of low on negative heat release is effectively identical to the well known delay period.

Heat transfer

The heat transfer rate is calculated using Annand’s formula. The equation considers net heat transfer as the summation of both radiative and convective heat transfer.

\[ \frac{dQ_{\text{net}}}{dt} = [S_e H (T - TW) + S_C (T^4 - TW^4)] \]  \hspace{1cm} (5)

Throughout the cycle calculation (closed part) convective heat transfer is calculated from the non-burning zone. Radiative heat transfer is calculated from the burning zone from the beginning of injection. Convective heat transfers from the burning zone is calculated from the moment of impingement of the cylinder walls.

Rate kinetics of formation of nitric oxide

It is known a well-established fact that the formation of NO in an engine combustion chamber is a non-equilibrium process. Fourteen reactions (7 forward and 7 reverse) are considered for the rate calculation of the nitric oxide. The rate equation for NO is given by

\[ \frac{I}{V} \frac{d}{dt} [(NO) V] = 2(1 - \alpha_\theta^2) \times \left[ \frac{R_1}{R_1 + R_2 + R_3} + \frac{R_6}{R_4 + R_5 + R_7} \right] \]  \hspace{1cm} (6)

Split injection model for nitric oxide control

In split injection, injection of fuel is divided into two steps, the pilot injection of small quantity and main injection of larger quantity. It involves two variables. The first one is the apportioning of fuel between the pilot injection and the main injection. The second one is the crank angle spacings between the end of pilot injection and the start of main injection. Five different proportions of splits were tried, such as 40-60, 35-65, 30-70, 25-75 and 20-80. The second one is the crank angle spacings between the end of pilot injection and the start of main injection. Five crank angle gaps are tried, such as 3°, 4°, 5°, 6° and 7°CA.

Soot formation model

Soot formation model is developed by using the Nagle and Strickland-Constable oxidation model. The rate of change of soot mass is equal to the rate of formation less the rate of oxidation.

\[ \frac{dM}{dt} = \frac{dM_{\text{sf}}}{dt} - \frac{dM_{\text{so}}}{dt} \]

\[ \frac{dM_{\text{so}}}{dt} = \frac{6 M_{\text{ve}} \rho_s D_s}{M_s R_{\text{total}}} \]

\[ \frac{dM_{\text{sf}}}{dt} = K_s M_f \]
Results and Discussion

The model is capable of predicting various combustion properties such as pressure, incremental heat release, cumulative heat release, cumulative heat transfer, cumulative work done, various zone temperatures, emission characteristics of NO, CO and soot. The trends are in agreement with published results.

Effect of split injection proportions

The split injection reduces the ignition delay of the second injection to high temperature regions. Reducing ignition delay may reduce the quantity of premixed combustion. This will reduce the temperature of high temperature region leading to reduction in the NO concentration. The prediction of nitric oxide in the cylinder for normal and different split injection (gap 5° CA) is shown in Fig. 1. From Fig. 1, it is seen that NO concentration at EVO condition is reduced to 2600 ppm from 3320 ppm for 40-60 split, 2150 ppm for 30-70 split, 2100 ppm for 25-75 split and to 2040 ppm for 20-80 split. It is seen from Fig. 2 that the CO concentration at EVO condition is decreasing to about 4980 ppm from about 5550 ppm for 40-60 split. However it is increasing for all other proportions of split injections. The variation of the emission of soot seems to be marginal with respect to the varying proportions of split injections (Fig. 3).

Effect of crank angle intervals

Similarly out of the five CA intervals, NO concentration decreases with the increase of intervals from 3° CA to 7° CA because of reduced peak temperatures. From Fig. 4 it is seen that NO concentration is reduced to about 2360, 2230, 2150, 2050, 1870 ppm respectively for 3°, 4°, 5°, 6°, 7° CA (split 30-70) from about 3320 ppm of normal injection. However, CO concentration increase in the order of about 6100, 6400, 6340, 6320 and 6850 ppm respectively for 3°, 4°, 5°, 6°, 7° CA (split 30-70) from about 5550 ppm of normal injection as seen from

![Graph](image)

Fig. 1—Prediction of nitrile oxide in the cylinder for normal and different split injections (gap 5° CA).
Fig. 2—Prediction of carbon monoxide in the cylinder for normal and different split injections (gap $5^\circ$ CA).

Fig. 3—Prediction of soot in the cylinder for normal and different split injections (gap $5^\circ$ CA).
Fig. 4—Prediction of nitric oxide in the cylinder for normal and different CA intervals (split injection 30-70).

Fig. 5—Prediction of carbon monoxide in the cylinder for normal and different CA intervals (split injection 30-70).
**Fig. 6**—Prediction of soot in the cylinder for normal and different CA Intervals (split Injection 30-70).

**Fig. 7**—Predicted and experimental concentration of nitric oxide emission with power output.
Fig. 5. The variation in the emission of soot with respect to the CA intervals are seen to be negligible as shown in Fig. 6.

Fig. 7 shows the comparison of predicted and experimental nitric oxide emissions. A close correlation is seen between the experimental and predicted concentration of nitric oxide at both 1600 rpm and 2400 rpm. Fig. 8 shows the comparison of smoke level. The trend of predicted smoke level is similar to that of experimental results.

Conclusions
In general, this model for the calculation of pollutants, is useful for predicting the trends of nitric oxide, carbon monoxide and soot emissions, rather than absolute values.

It is found for retarded injection timing of 10° bTDC (Normal timing being 14° bTDC) with split injection of 30-70° (interval of 5° CA) NO concentration is reduced by about 20%, whereas a reverse trend of 5% is seen for soot concentration. Thus the split injection of 30-70 with a gap of 5° CA is optimum for the control of NO for this type of engines.

It is finally concluded that the developed multizone combustion model can be used as an efficient tool to calculate the effect of design and operating parameters on engine performance, nitric oxide emission and soot emission quickly and inexpensively.

Nomenclature
\[ \Delta P = \text{fuel injection pressure (bar)} \]
\[ d_n = \text{diameter of nozzle hole (m)} \]
\[ K = \text{kinematic momentum flux (m}^4/\text{s}^2) \]
\[ X = \text{penetration of jet (m)} \]
\[ K_F = \text{fusing factor} \]
\[ K^* = \text{a constant in the preparation rate equation} \]
\[ M_i = \text{mass of fuel injected} \]
\[ M_u = \text{mass of fuel unburnt} \]
\[ P_o = \text{partial pressure of oxygen} \]
\[ R = \text{rate of burning} \]
\[ T = \text{temperature of the gas} \]
\[ K^* = \text{a constant in the reaction equation} \]
\[ d_x = \text{crank angle step size} \]
\[ N = \text{engine speed} \]
\[ ACT = \text{index in the reaction rate equation} \]
\[ dQ_{\text{loss}} = \text{total heat loss over a step (kJ/step)} \]
\[ d_l = \text{length of step} \]
\[ S_c = \text{surface area for convective heat transfer (m}^2) \]
\[ S_r = \text{surface area for radiative heat transfer (m}^2) \]
\[ T_W = \text{cylinder wall temperature (k)} \]
\[ C = \text{annand's co-efficient for radiant heat transfer (kW/m}^2\text{K sec)} \]
\[ e = \text{NO/(NO)} \]
\[ R = \text{one way equilibrium rate of } P \text{ reaction} \]
\[ V = \text{volume of the burnt gas in the stoichiometric burning zone} \]
\[ M_f = \text{the fuel mass in grams} \]
\[ M_{\text{we}} = \text{carbon molecular weight (12 g/mol)} \]
\[ \rho_s = \text{soot density} \]
\[ D_s = \text{soot diameter (3 x 10 cm)} \]
\[ t = \text{time for penetration (s)} \]

References
7. Tarouzayam, Junichi Mizuta & Yasiro Oshima (1990), SAE paper No 900637.