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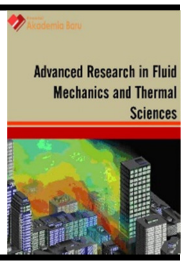

Taguchi Analysis of Combustion of Diesel and Bio-Diesel Blend utilizing Homogeneous Reactor Model

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ABSTRACT

In the current work, the effect of engine parameters on the performance of a diesel engine fuelled with diesel-biodiesel blend has been assessed. Homogeneous Reactor model (HRM) was utilized to compute the combustion parameters for a single cylinder diesel engine with unit aspect ratio and capacity of one-litre. The rate of pressure rise has a significant influence on the peak pressure generated, power produced and the degree of smooth transmittance of forces to the piston during the power stroke. The rate of pressure rise can be defined in terms of the crank angle increments since crank angle displacement is an indication of the engine speed. The pressure rise with respect to the crank angle increments were calculated based on three factors namely compression ratio, injection time and boost pressure that were selected for analysis of the diesel engine combustion at three significant levels. A L_9 array was used to analyse the response of pressure-crank angle gradient "dp/dθ" as the output variable. From the Taguchi analysis of the effect of the three parameters, injection timing was the most dominant factor for the rise in the pressure gradient followed by boost pressure ratio and compression ratio as the lowest dominant factors. A contour of dp/dθ showed injection timing of 12° BTDC as the most optimum timing for maximum rise in pressure.

1. Introduction

Diesel engines have become the mainstay of the heavy commercial vehicle and earth moving automobiles. Diesel engines under impending threat of fuel depletion have found solace in blending of petro-based diesel with bio-diesel[1–6]. While blending diesel with bio-diesel offers several challenges of diminished calorific value, quasi-immiscibility, higher viscosity and enhanced hygroscopic nature, additives or nano-catalysts are essential to improve the blend properties so that the performance of the Diesel engine handling such blends is not compromised [2,7–9]. Quality of the blend also depends on the energy content, density, lubricity, cold flow properties and

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sulphur content. Cetane number indicates the fuel's ignition delay and in turn the tendency of diesel knock. Hence the blended fuel has to offer a higher cetane rating [5]. Dual fuel engines utilizing straight chain alcohols and diesel have also been rigorously explored to answer the steep depletion of petro-based fuels [10,11]. With the latest research oriented towards identification of novel fuels, the impetus towards optimizing the performance of the existing engines with such fuels and minimized emission due to any such modifications attain primary importance. Diesel engine operating parameters - compression ratio, air-fuel ratio, injection timing, injection pressure, boost pressure majorly affect the performance[1,10-13]. Performance parameters of diesel engines comprising of brake thermal efficiency, exhaust gas temperature, brake specific fuel consumption, volumetric efficiency, mechanical efficiency have been analyzed with respect to different operations using Taguchi's technique [1,13-15]. While evaluating the phases of combustion in diesel engines, the chemical kinetics and progress of combustion during premixed combustion phase and mixing controlled combustion phase majorly influence the engine performance parameters [4]. The rate of combustion pressure rise with respect to the crank angle increment ($dp/d\theta$) is an important indicator of the two prime phases of diesel engine combustion. In the current work, Taguchi's technique is employed to analyze $dp/d\theta$ as the response variable depending on three parameters- compression ratio, boost pressure and injection timing at three levels using a L_9 array.

2. Methodology

2.1 Chemical Modelling

Combustion reactions occur between the fuel and the oxidizer species. For diesel engines, since air is used as the oxidizer, Chemical kinetics [18] combined by thermodynamics can be employed to compute the reaction rates and in turn the extent of completion of combustion reactions. According to the collision theory of chemical reactions, the imminent collision between reactant species i.e. air and fuel molecules is essential in order to react and form the product species. Hence higher concentrations of reactant species would ensure more collisions. Diesel and bio-diesel blends can be considered to be a mixture of different hydrocarbons reacting with air during the combustion. The air-fuel ratio (A/F) was taken as 110% stoichiometric for a 90:10 blend of diesel and bio-diesel (methyl ester). A single cylinder diesel engine with unit aspect ratio and capacity of one cubic decimeter was considered for the model. The general chemical relation for estimating the stoichiometric air-fuel ratio of a particular fuel is given in Equation (1).

Among the different engine operational parameters, the compression ratio (ratio of the sum of the clearance and stroke volumes to the clearance volume) plays an important role in the pressure rise [5]. Compression ratios for engines cannot be varied during the engine operation since the bore and stroke geometry, type and geometry of the combustion bowl on the piston crown as well as the head gasket thickness are fixed once the engine assembly is complete. The Injection timing represents the introduction of the fuel species into a highly charged atmosphere of air as the piston approaches the Top Dead Centre at the end of the compression stroke. Since the injection timing decides the extent of the delay period to overcome the physical and chemical delay and the onset of the diffusion flame reactions, optimum timing for the desired rate of pressure rise is essential [19]. During engine operation, the injection timing remains fixed, although the timing could be incremented by adjusting the fuel Injection coupler near the mounting on the timing gears [5]. The volumetric efficiency of compression ignition engines can be improved by boosting the intake air to increase the available oxygen content followed by an intercooling step to regulate the initial temperature conditions [20]. The boost pressure can be conveniently expressed as a ratio relative to ambient pressure or as an absolute pressure in relevant SI units. During engine operation, the boost pressure may be varied continuously between pre-defined limits by metering the exhaust gases passing through the turbine region of the turbocharger or by controlling the rotational speed of the supercharger.

$$C_xH_yO_z + a(O_2 + 3.76N_2) \rightarrow xCO_2 + yH_2O + 3.76aN_2 \quad (1)$$

The rate of the reaction '*r*' is given by Eq. 2 where '*k(T)*', the reaction rate coefficient is given by the Arrhenius equation (Eq. 3) in which pre-exponential factor 'A' depends on the physical properties of the reaction like molecular sizes, angular effects, average molecular speeds. '*E*' is the activation energy, '*R*' is the gas constant and '*T*' is the absolute temperature.

$$r = k(T)\left[C_xH_yO_z\right][O_2 + 3.76N_2]^a \quad (2)$$

$$k = Ae^{(-E/RT)} \quad (3)$$

$$k_r = A_rT^{n_r}\, e^{(-E_r/RT)} \quad (4)$$

For a system of reactions '*r*', the Arrhenius equation can be modified as per Eq. 4. 'n_r' is a dimensionless power coefficient indicating the temperature dependency of the specific reaction[18]. For a system containing '*i*' species and '*r*' reactions, the Eq. 2 can be re-written as Eq. 5.

$$r_r = \pi_i^{N_i} c_i^{v_{i,r}} k_r \quad (5)$$

The stoichiometric coefficient '$v_{i,r}$' is defined for each of the species '*i*' with concentration 'c_i' participating in reaction '*r*'. The production or consumption 'ω_i' of all species in the closed system can be given by Equation 6.

$$\omega_i = \sum_r^{N_r} v_{i,r}k_r \quad (6)$$

The chemical kinetics can be utilized for combustion simulation by employing suitable values for the initial conditions of fuel and oxidizer, pressure, temperature. These values translate over time evolving as the reactants get transformed into the products of combustion.

2.2 Homogeneous Reactor Model

HRM is based on the Plug Flow Reactor (PFM) model considering the conditions within the combustion chamber to be homogeneous at all times. HRM involves a set of zero-dimensional time-dependent differential equations, solving the energy conservation and species balances [18]. Newton's method was used to solve the matrix system of equations and higher order backward differential functions were utilized to resolve the time. The pressure is calculated as a function of the piston movement and of the pressure increase due to chemical reactions. The pressure can be calculated from the equation of state (Eq. 7).

$$p = \frac{\rho RT}{\bar{M}} \quad (7)$$

Since the combustion process in the engine was modeled on the basis of premixed combustion phase and mixing controlled combustion phase, owing to the closed period over these phases, the inflow and outflow computations were omitted and a closed system was considered. The conservation equation for the chemical species is given by Eq. 8.

$$\frac{dY_i}{dt} = \frac{M_j}{\rho} \sum_{k=1}^{N_r} v_{j,k} r_k \tag{8}$$

$$m \sum_{j=1}^{N_s} \left(u_j \frac{M_j}{\rho} \sum_{k=1}^{N_r} v_{j,k} r_k \right) + h_g A_{wall}(T - T_{wall}) + p \frac{dV}{dt} + m c_v \frac{dT}{dt} = 0 \tag{9}$$

The conservation equation for the energy is given by Eq. 9 '$v_{j,k}$' is the stoichiometric coefficient for species '*j*' in reaction '*k*'and 'r_k' is the reaction rate of reaction '*k*'. 'Y_j', 'u_j' and 'M_j' are the mass fraction, specific internal energy and the mole mass respectively, of species '*j*'. 'A_{wall}' is the in-cylinder wall area and 'h_g' is the heat transfer coefficient which is obtained with the Woschni correlation given by Eq.10 [21]. '*V*', '*p*', '*T*', 'T_{wall}' and '*t*' represent the cylinder pressure, instantaneous volume, in-cylinder temperature, cylinder wall temperature and time.

$$h_g = 3.26 B^{-0.2} p^{0.8} T^{0.55} U^{0.8} \tag{10}$$

The expression for heat transfer coefficient is given by Eq. 9 where '*B*' is the engine bore, '*U*' is the average gas velocity which is proportional to the mean piston speed 'U_{piston}'. For compression stroke, Eq. 11 gives the relation between the average gas velocity and mean piston speed[21].

$$U = 2.28 U_{piston} \tag{11}$$

Eq. 12 gives the instantaneous volume where 'L_{cr}' is the connecting rod length and 'R_{ct}' crank throw radius.

$$V = V_c + \frac{\pi B^2}{4} \left(L_{cr}(1 - \cos(\theta)) + R_{ct} + \sqrt{L_{cr}^2 - R_{ct}^2 sin^2(\theta)} \right) \tag{12}$$

The rise in pressure during the premixed combustion phase and the mixing controlled combustion phase was computed for different values of compression ratio, boost pressure and injection timing through changing the volume from one time-step to the other. To minimize the computation time, a downsampling algorithm to reduce the number of stochastic particles was employed while conserving the statistical parameters of the ensemblage[18,22]. The crank angle increment of 0.5° was selected for the computation steps by keeping the initial conditions consistent for all steps. The computations weres carried out on MATLAB 15.

2.3 Taguchi Analysis

Taguchi technique used a standard orthogonal array based on the total number of degree of freedom, number of factors and level of each factor[16]. The characteristic used to specify the effect of the parameters on the response variable is the Signal-to-Noise ratio (η_{ij})[1]. In the present study, an orthogonal array (L_9) was considered with compression ratio, boost pressure and injection timing varied at three levels each (Table 1). The Taguchi analysis was carried out on Minitab 15 version. '*dp/dθ*' being the response variable, its response was determined for the three engine operational factors. The S/N ratio with a higher-the-better characteristics was computed by the software in line with Eq. 13, where y_{ij} is the i^{th} response of j^{th} experiment, *n* is the total number of the tests and *s* is the standard deviation[1].

$$\eta_{ij} = -10 \log\left[\frac{1}{n} \sum_{j=1}^{n} \frac{1}{y_{ij}^2}\right] \tag{13}$$

Table 1
Description of the three engine operating parameters and levels

Engine Parameter	Levels		
	1	2	3
Compression ratio	14	15	16
Boost pressure (bar)	1	1.5	2
Injection timing (BTDC)	9°	12°	15°

3. Results

The P-θ plots for injection timing of 9° BTDC for varying conditions of boost pressure and compression ratio are shown in Figure 1. As the compression ratio is increased, the pressure rise was accelerated by increasing the boost pressure. On increasing boost pressures, the pressure peaks were found to increase. On increasing the injection timing to 12° BTDC, the rise in pressure was found to be highly pronounced for the different compression ratios (Figure 2). Higher boost pressure was found to further elevate the pressure peaks. For the injection timing 15° BTDC, the rise in pressure was found to be subsiding as compared to 12° BTDC but higher than that at 9° BTDC.

Over-advanced timing in this case was not beneficial in achieving an intended rise in pressure w.r.t crank angle. The release of heat energy has to be consistent with the force transmitted to the piston during the power stroke. However, faster release of heat energy has more time available for dissipation to the cylinder walls decreasing the force transmitted and in turn the pressure rapidly falls in the combustion chamber. The increase in boost pressure for over-advanced injection timing did not affect the pressure rise. However, achieving highest value of peak pressure in the case of 12° BTDC would also lead to the highest peak temperature which would adversely affect the NO_x emission while reducing CO and HC emission [18]. Higher the peak temperature inside the combustion chamber, depending on the crank angle departure from the top dead centre, the dissociation of atmospheric nitrogen and secondary reactions to yield oxides of nitrogen like nitrogen dioxide and nitrogen oxide contribute to the increase in NO_x emission[19]. Hence from the emission standpoint, the optimum injection timing becomes a vital parameter with a trade-off between the CO and HC emission and NO_x emission.

Figure 3 shows the P-θ plots for a retarded injection timing of 15° BTDC. The pressure and temperature of the charge are very high as the piston nears the TDC. The fuel species would be sprayed into a highly charged atmosphere which brings down the delay period for the diffusion flame kernel to develop and engulf the surrounding unburnt species of air and fuel particles. But the time needed for completing all the stages of combustion is limited and the percentage of species remaining unburnt will be higher widening the after-burn period. The degree of heterogeneity is also higher rendering oxygen starvation for some of the fuel species. Hence, all of the thermal energy associated with the fuel quantity is not released, causing higher CO and HC emission. Irrespective of the boost pressure, the peak pressure does not vary significantly. Hence, for optimum injection timing, boosting the intake air either through supercharging or turbocharging may not offer an advantage in terms of the peak pressure. However, the higher quantity of free air transpired through the engine may increase the volumetric efficiency and ensure a lean mixture with sufficient oxygen for fuel species in turn reducing the extent of CO emission.

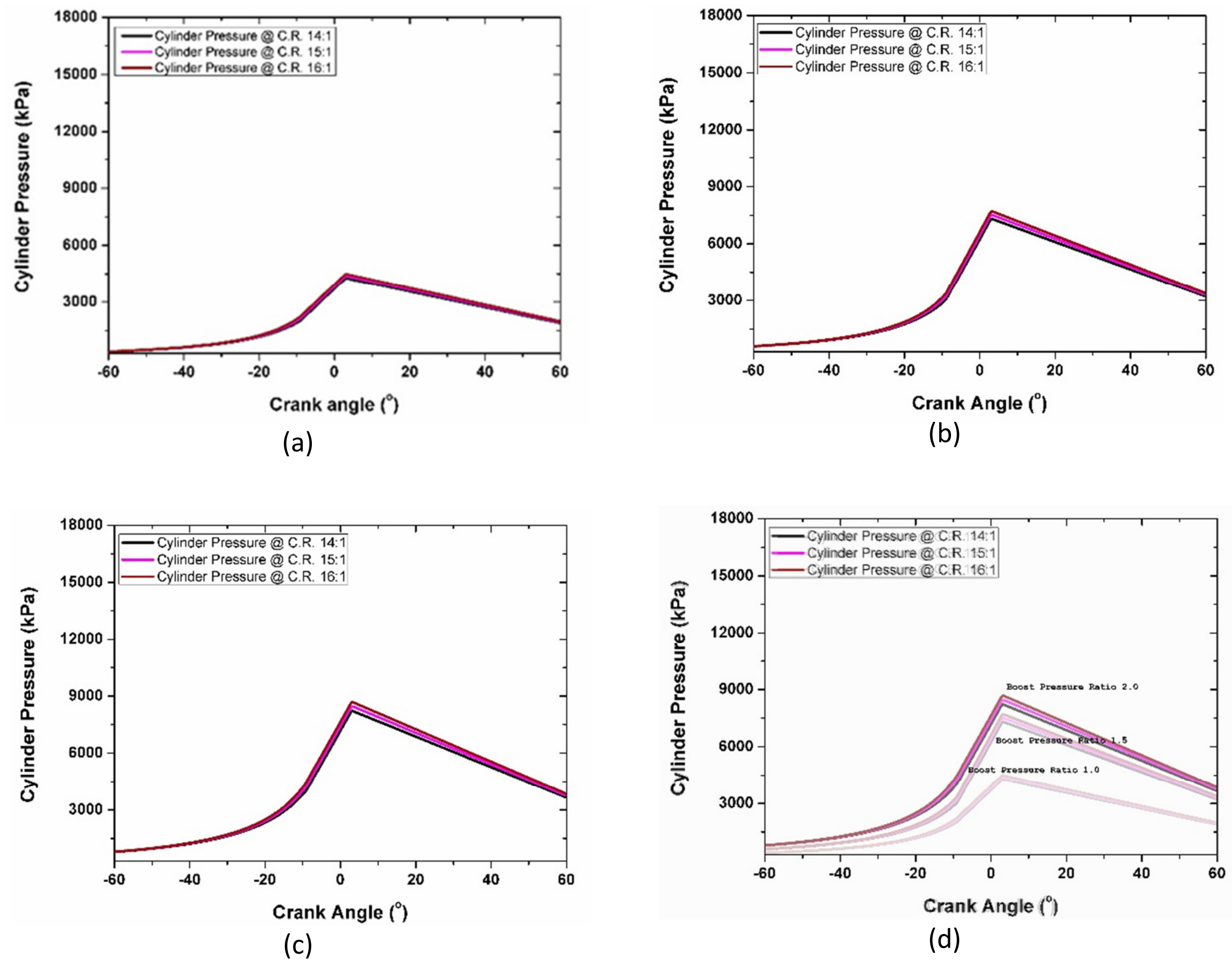
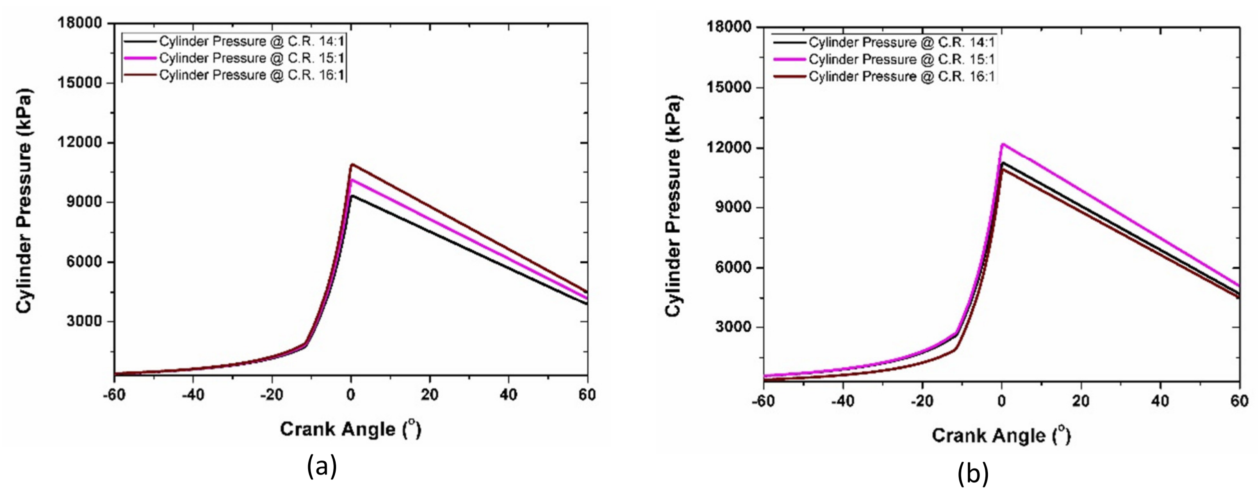
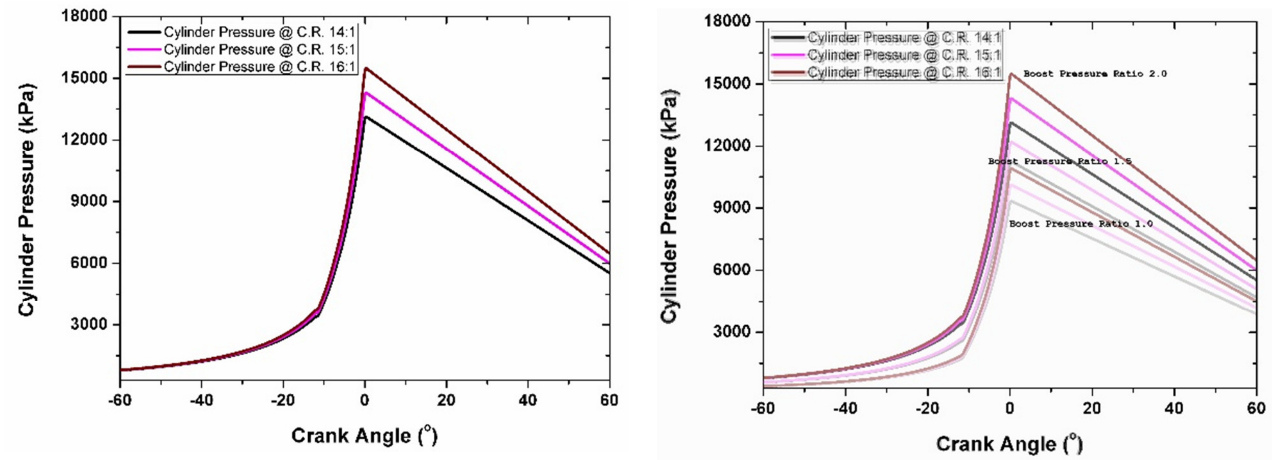


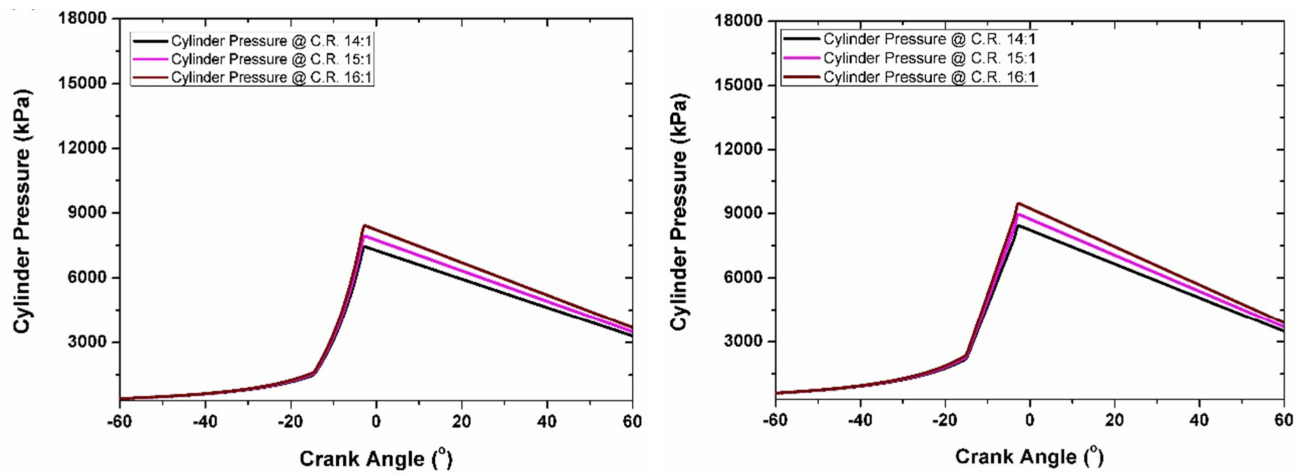
Fig. 1. *P*-θ plots for Injection timing 9° BTDC for boost pressure ratio (a) 1.0 (b) 1.5 (c) 2.0 (d) Combined



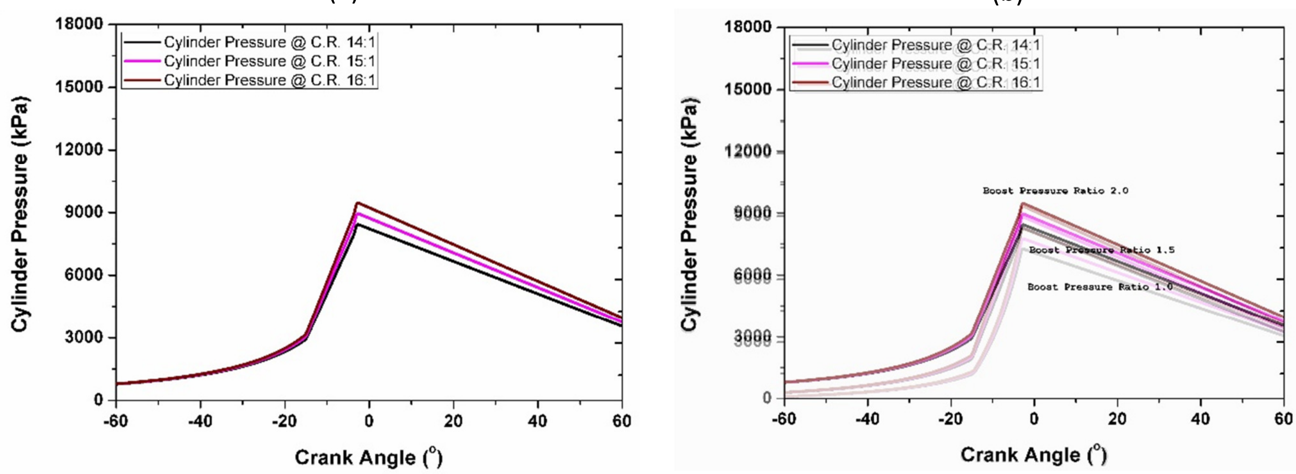


(c) (d)

Fig. 2. *P-θ* plots for Injection timing 12° BTDC for boost pressure ratio (a) 1.0 (b) 1.5 (c) 2.0 (d) Combined



(a) (b)



(c) (d)

Fig. 3. *P-θ* plots for Injection timing 15° BTDC for boost pressure ratio (a) 1.0 (b) 1.5 (c) 2.0 (d) Combined

Figure 4 shows the contour plot for $dp/d\theta$ for different values of the factors- Injection timing, boost pressure ratio and compression ratio. For the boost pressure ratios of 1.0 and 2.0, the maximum values of $dp/d\theta$ shifts towards higher compression ratio at 12° BTDC injection timing while at boost pressure ratio of 1.5, the peak values of $dp/d\theta$ were found to be concentrated at the mid-compression ratio of 15:1. 12° BTDC was found to be optimal timing for causing desired peaks in *dp/dθ*. Boosting the intake air in the vicinity of 1.5 bar would be beneficial since the peak pressure rise hovers around the compression ratio of 15:1 and an optimum injection timing of 12° BTDC.

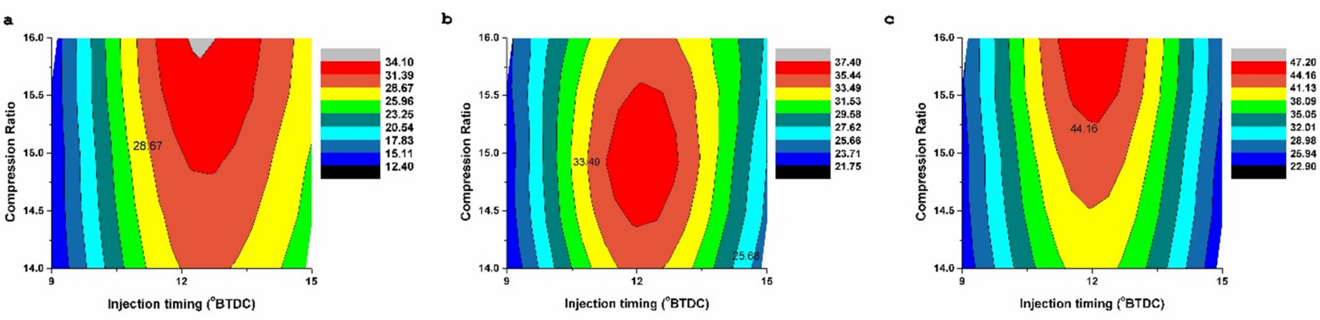


Fig. 4. Contour of '*dP/dθ*' at boost pressure ratio (a) 1.0 (b) 1.5 (c) 2.0

Taguchi analysis of the L_9 array showed that the injection timing was the most critical factor affecting the response of *dp/dθ* followed by the boost pressure and finally by the compression ratio. Table 2 shows the response for S/N ratios for the different factors. Figure 5 shows the variation of the mean S/N ratios with the engine operational parameters. Increase in the levels of the boost pressure and compression ratios elevated the S/N ratios while the maxima of S/N ratio was found for 12° BTDC injection timing. Table 2 shows the order of the engine operating variables affecting the pressure rise gradient w.r.t the crank angle. The injection timing registers a very high delta value since it causes a drastic variation in *dp/dθ* while transitioning between levels 1 to 2 and 2 to 3 respectively. Hence, this parameter has been ranked as the primary parameter affecting the S/N ratio and for achieving an optimum rate of pressure rise, selection of appropriate injection timing becomes the main task of the designer when choosing diesel-bio-diesel blends for combustion in compression ignition engines.

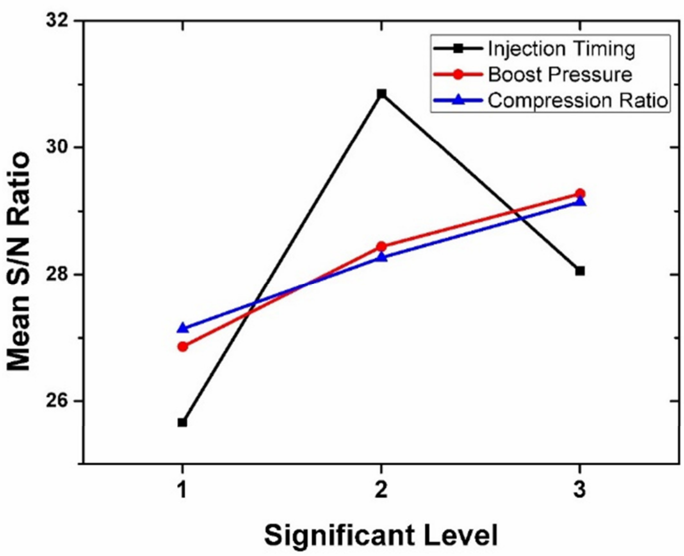


Fig. 5. Variation of Mean S/N ratios for the engine operational parameters

Table 2
S/N Ratios with delta values for the three engine operational parameters

Level	Injection Timing	Boost Pressure	Compression Ratio
1	25.66	26.86	27.14
2	30.85	28.44	28.27
3	28.06	29.27	29.14
Delta	5.19	2.14	2.00
Rank	1	2	3

4. Conclusions

Taguchi analysis of combustion of diesel/bio-diesel blend was successfully conducted using the Homogeneous Reactor model. The following conclusions were drawn:

- Injection timing emerged as the most critical factor affecting the pressure rise during the premixed combustion phase and the mixing controlled combustion phase followed by boost pressure ratio and compression ratio.
- Optimal conditions for maximizing the rise in the cylinder pressure obtained were noted- The injection timing of 12° BTDC, the compression ratio of 15:1 and the boost pressure of 1.5 bar resulted in the maximized peak pressure values.
- For ensuring the consistency of optimum pressure rise, the control of the boost pressure during engine operation ~ 1.5 bar through waste gating of turbocharges or speed control of superchargers would be beneficial.
- Higher compression ratio and boost pressures could augment the NO_x emission while reducing CO and UBHC emission. Hence from the standpoint of emission, a compromise has to be made between the rise in pressure, release of heat energy and the ensuing emission.

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