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Reduction of NOx and Noise Emissions by Pilot Injection Strategy in CRDI Diesel Engine with the use of Central Composite Design (CCD)

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Abstract— *In this study, two factor central composite face centered design was employed to study and optimize the process variables on pilot injection strategy in common rail direct injection diesel engine. The effect of process variables such as pilot injection quantity (5-25%) and pilot injection angle (5-30º before main injection) is studied. The effect of pilot injection on NOx, noise emission and performance of a single cylinder direct injection diesel engine is investigated. By advancing the timing and quantity of pilot injection decreases the NOx and noise emissions. Pilot injection at advanced injection angles serves to decrease the NOx and noise while suppressing the increase of HC and fuel consumption. These effects due to the reduced amount of adhering fuel to the cylinder wall.*

***Keywords*— Common rail direct injection (CRDI), Central composite design (CCD), Pilot injection, Performance, Emissions.**

I. INTRODUCTION

The major pollutants from diesel engines is NOx. It has been judged to pose a lung cancer hazard for humans as well as increasing the risk of non-cancer respiratory ailments [1-2]. NOx react in the atmosphere in the presence of sunlight to form the ground-level ozone. Ground-level ozone is a major part of smog in cities and as well as in many rural areas. In addition, NOx reacts with oxygen, water and oxidants in the atmosphere to form acid rain [3]. Stringent exhaust emission standards necessitate the reduction of NOx for diesel engines, however, it seems to be very difficult to reduce NOx emission without enhancing soot emission by injection timing [4]. The reason is that there has always been a contradiction between NOx and soot emissions when the injection timing is retarded or advanced. Split injection has been shown to be a powerful tool to reduce NOx and noise emissions from the DI engine simultaneously when the injection timing is optimized [5, 6]. It is defined as splitting the main single injection profile in two or more injection pulses with definite delay dwell between the injections [7]. In the Common Rail system, the solenoid valve, used to control the injector, can be energized several times during one working cycle of the engine: in this way multiple injection, pilot injection and post injection are feasible [8-10]. In the present study, the influences of main injection quantity, pilot injection quantity and timing, on engine performance, emission and noise, were evaluated. Experimental results were elaborated using a CCD (central composite design) technique, to evaluate the influence of the control parameters.

II. EXPERIMENTAL DESIGN

The Central composite design (CCD), is an experimental design used to achieve maximal information about a process from a minimal number of experiments [11]. In the central composite design, face centered (CCFC) experimental design was used in this study to determine the optimal conditions and study the effect of two variables (pilot injection quantity (5-25%), pilot injection angle (5-30º before main injection) on four responses (fuel consumption (gm/kw.h), NOx, HC and noise emissions) of single cylinder direct injection diesel engine. From the preliminary experimental results, process variables and their ranges (pilot injection quantity (5-25%), pilot injection angle (5-30º before main injection)) were determined. After selection of independent variables and their ranges, experiments were established based on a CCFC design with two factors and each independent variable was coded at three levels between -1, 0 and +1. In this study, the total number of 13 experiments (in order to allow the estimation of pure error) was carried out and the total number experiments were calculated from the following equation [12]:

$$N = 2^n + 2n + n_c$$

Where N is the total number of experiments required; n is the number of factors; and c is the number of centre points. The experimental progression was randomized with the intention of minimize the effects of unpredicted variability in the responses due to extraneous factors. A

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second-order polynomial equation was used with the intention of develop a experimental model which correlated the responses to the independent variables. The general form of second order polynomial equation is

$$Y = \beta_0 + \sum_{j=1}^{k} \beta_j \ X_j + \sum_{j=1}^{k} \beta_{jj} X_j^2 + \sum_{i} \sum_{<j=2}^{k} \beta_{ij} X_i X_j + e_i$$

Where Y is the response; Xi and Xj are variables (i and j range from 1 to k); b0 is the model intercept coefficient; bj, bjj and bij are interaction coefficients of linear, quadratic and the secondorder terms, respectively; k is the number of independent parameters (k= 4 in this study); and ei is the error [13].

III. EFFECTS OF PROCESS VARIABLES

In the present study, two factors at three level central composite, face centered (CCFC) design used to study the influence of process variables such as pilot injection timing and pilot injection quantity in CRDI system assisted diesel engine. The three dimensional response surface wAS constructed from the developed models. Response surface plots are graphical representations of a regression equation that illustrate the main and interactive effects of independent variables on a response variable. These graphs are simple to understand and symbolize the interactions between pairs of independent variables on the responses and also accustomed to locate their optimal levels.

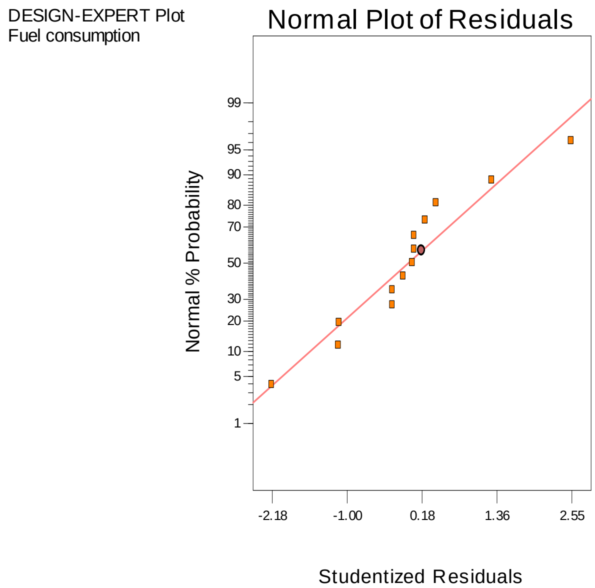

Fig. 1. Plot of residuals for fuel consumption

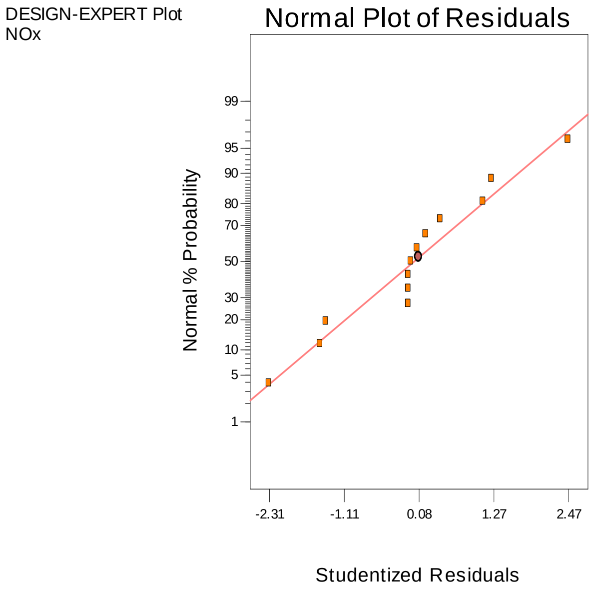

Fig. 2. Plot of residuals for NOx emission

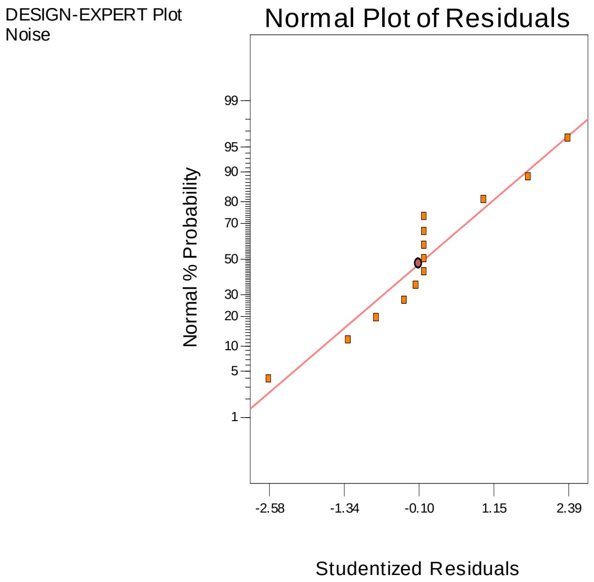

Fig. 3. Plot of residuals for noise emission

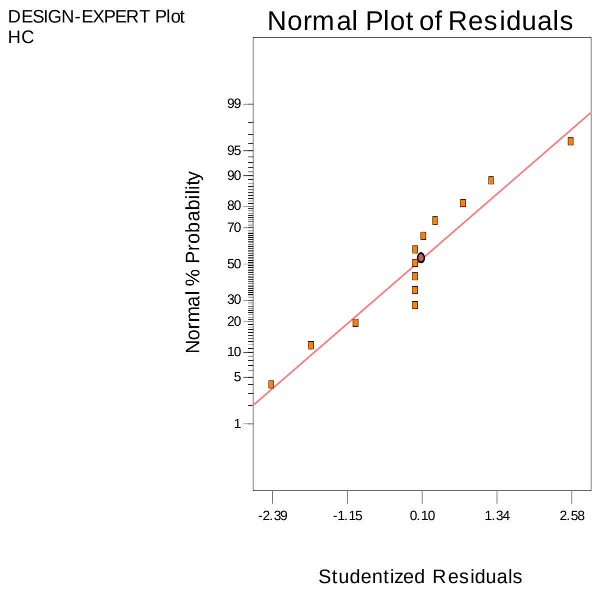

Fig. 4. Plot of residuals for HC emission

IV. EXPERIMENTAL SETUP AND TEST PROCEDURE

Experiments were conducted on Kirloskar AV1, four stroke, single cylinder and air cooled diesel engine assisted by common rail direct injection system. The rated power of the engine was 3.7 kW. The engine was operated at a constant speed of 1500 rpm with varying injection pressure from 250-500 bar to maintain the speed. Details of the engine specification are given in Table 2 and injector specification given in table 3. Thermocouple and a digital display were used to note the exhaust gas temperature. The Hartridge smoke meter was used for measuring of smoke density. NOx, HC and CO emissions were measured by AVL five gas analyzer. Readings were taken when the engine was operated at a constant speed of 1500 rpm for all loads. Parameters such as engine speed, fuel flow, and emission characteristics such as NOx, noise, HC were recorded. The performance of the engine was evaluated in terms of brake power, and specific fuel consumption from the above parameters.

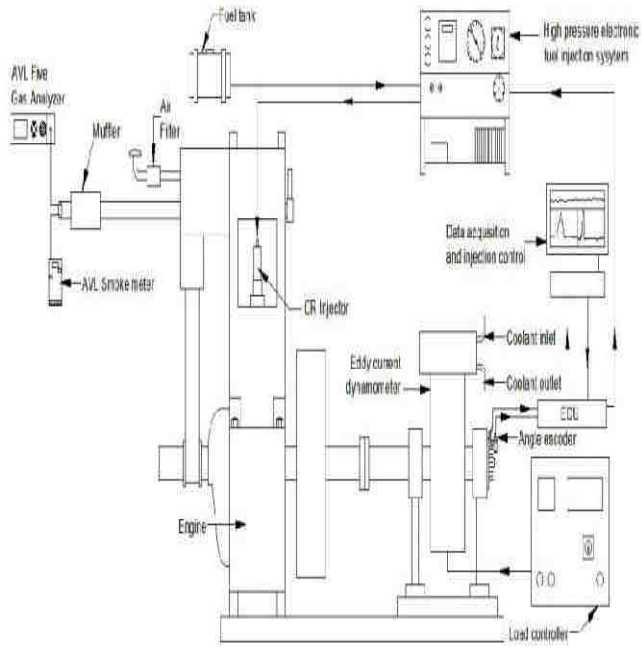

Fig. 5. Engine setup with common rail fuel injection system

Table 1. Engine specification

Type	:	Vertical, water cooled, four stroke
Number of cylinders	:	One
Bore	:	87.5 mm
Stroke	:	110 mm
Compression ratio	:	17.5:1
Maximum power	:	3.7 kW
Speed	:	1500 rev/min
Dynamometer	:	Eddy current
Injection timing	:	23° (before TDC)
Injection pressure	:	250-500 kgf/cm^2

Table 2. Injector fuel system specifications

Fuel fed	**Units**	**Common rail**
Injection pressure	MPa	250-600 MPa
Number of nozzle holes	-	3
Nozzle hole diameter	mm	0.518
Start of injection	-	23^o Before top dead center (BTDC)

Injection duration	µsec	750
Fuel injected	g/cycle	0.168 (at full load)

V. RESULT AND DISCUSSION

The operation of the engine was found to be very smooth through the rated load, without any operational problems for the pilot injection strategy.

Fuel consumption

The specific fuel consumption with respect to pilot injection quantity and timing using central composite design was shown in Figure 3. SFC of the pilot injection strategy was relatively increased compared to single injection because early injection is influenced on the insufficient combustion in the initial combustion duration [15]. From the figure, fuel consumption was increased when the quantity of pilot injection increased also SFC relatively increased with the advances with the pilot injection timing.

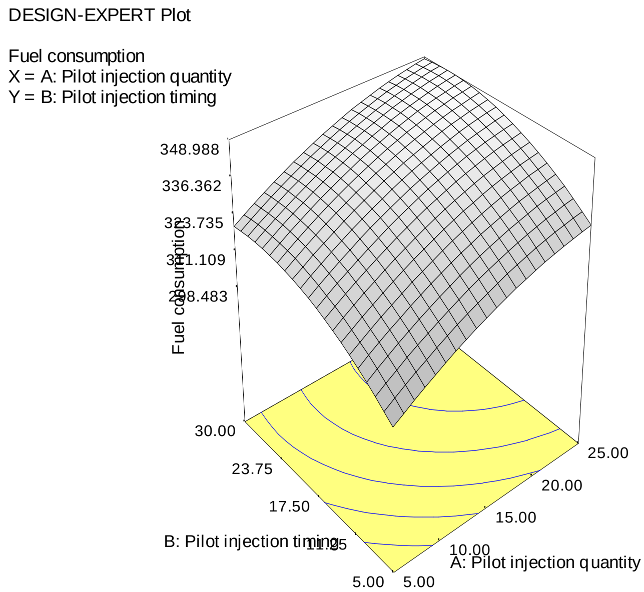

Fig. 6. Three dimensional response surface for Fuel consumption

NOx emissions

The NOx emissions with respect to pilot injection quantity and timing was shown in Figure 3. Introduction of pilot injection, the flame temperature when the combustion of fuel has been reduced. Due reduction of flame temperature, the amount of NOx emission also reduced. The effect of the injection pause becomes more significant in the reduction of NOx when 30-17.5-70 case. It delays the main part of the combustion and reduces the NOx formation rate significantly compared with the single injection case. Comparing the 30-17.5-70 case with the single injection case in which the injection timing is retarded 17.5 degrees BTDC due to its injection timing, combustion of the fuel in the second pulse is delayed by the injection pause.

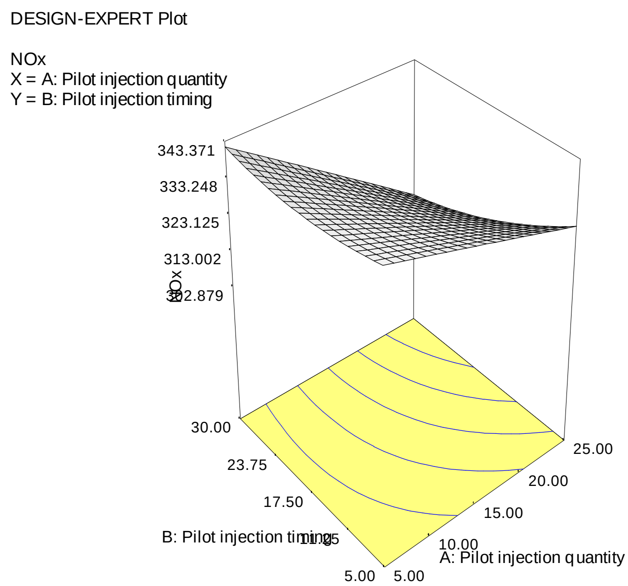

Fig. 7. Three dimensional response surface for NOx emission

Noise emission

The noise emission with respect to pilot injection quantity and timing using central composite design was shown in Figure 3. In IC engines, combustion noise is the major part of noise pollution. By introduction of pilot injection, peak pressure, flame temperature and as well as combustion noise also reduced [16]. From the figure, it is clear that the noise emission has reduced when pilot injection quantity increased. Noise emission has been reduced upto 3db when the injection quantity of pilot injection will be increased.

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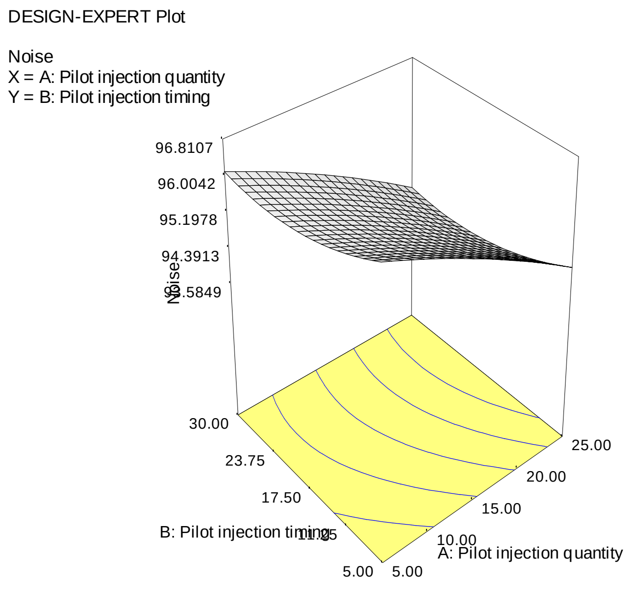

Fig. 8. Three dimensional response surface for Noise emission

HC emissions

The HC emission with respect to pilot injection quantity and timing using central composite design was shown in Figure 3. HC emissions are increased when pilot injection timing is advanced. In particular, HC emissions are rapidly increasing at pilot injection timing is advanced from 38° BTDC. This reason is that insufficient combustion is made due to the wall-wetting consequence of the fuel spay in the engine cylinder wall beyond the injection timing of 35° BTDC [17].

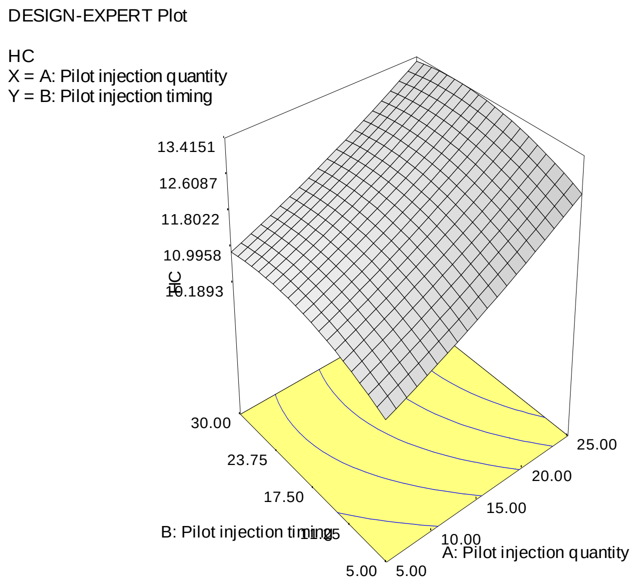

Fig.9. Three dimensional response surface for HC emission

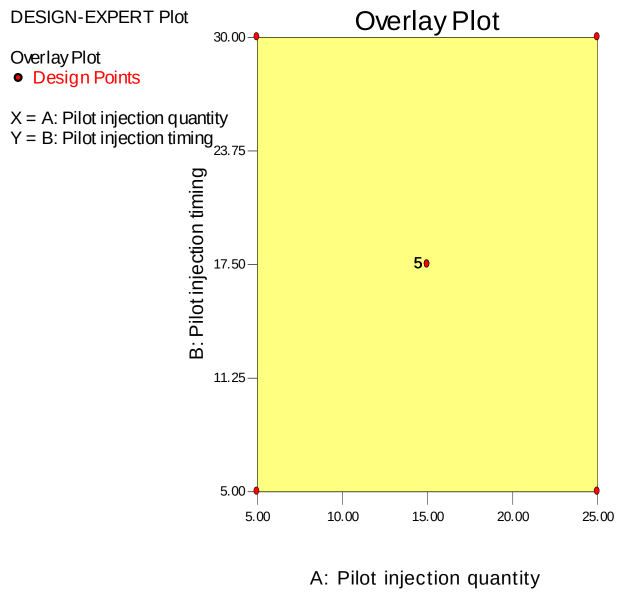

Fig. 10. Three dimensional response surface for Overlay plot

VI. CONCLUSION

The performance, emission, and combustion of CRDI diesel engine using biodiesel (ZJME25) and modified biodiesel (AONP25 and AONP50) were analysed. Based on the investigation, the following conclusions are drawn.

- The specific fuel consumption is slightly higher for pilot injection of fuel when compared to normal injection at at the maximum load.
- The NOx emission is lower for introduction of pilot injection than the single injection. The NOx emission was found to be decreased with the increasing of quantity of fuel in pilot injection and injection angle.
- The amount of noise emission is the lower when introduction of pilot injection than the single injection. The noise emission emission has reduced up to 3 db when 25% fuel injected as pilot injection at 25° before the main injection of fuel.
- The introduction of pilot injection increases the HC emissions when comparing with single injection.

Overall, it is clear that the introduction of pilot injection enhances the performance and reduces the emission of the diesel engine. From the central composite design the optimum pilot injection timing is 17.5 and optimum injection quantity is 15%. In these optimum pilot injection quantity and timing, the NOx and noise emission was minimized, and HC emission also nominal when compared with other cases.

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