Utilization of DOE and ANOVA method for analysing the effect of Interaction factor on emission and performance of a turbocharged CRDi equipped diesel engine: A Review

Shubham Sharma1[a*], Dr. Madhu Murthy K2[b], Vinod Babu M3c

Department of Mechanical Engineering, National Institute of Technology, Warangal (NITW), 506004 Warangal,Telangana, India
Email:-Shubhamsharma585@gmail.com

1. Abstract:-

The accomplishment of the common rail direct injection diesel engine is a function injection strategy which depends upon several variables, for instance, fuel injection's pressure (FIP), Main injection's timing (MIT), Pilot injection's timing (PIT), Pilot injection's quantity (PIQ), Boost pressure from Turbocharger. These variables are also known as controllable variables. Combustion of the engine is analyzed by emissions (such as NOx, CO, UHC, and Particulate Matter) from engine and increment or decrement in the rate of pressure rise and Rate of Heat Release. These variables are also known as Response variables. Each variable mentioned above as controlled variable has its own effect on combustion and performance of the engine. On occurs a slight change in one controlled variable every response variable changes. Every controlled variable is interlinked to each other so by changing only one controlled variable one cannot predict actual behavior of combustion parameters. Hence For the study of optimized behavior of combustion every parameter has to be altered at the same time so their Interaction factor can be analyzed in an effective way. Interaction effect helps to analyze the actual effect of the individual parameter with respect to others. This interaction factor could be obtained by various designs of experiments (DOE) (E.g. Factorial design, Taguchi method and Response surface methodology) and ANOVA technique and can give optimized result for CRDi Diesel engine to increase performance.

Keywords: Common rail direct injection engine, FIP, MIT, Optimization methods

2. Introduction:-

Today more than 95 percent of all large heavy-duty vehicles are using diesel as an origin of Energy. Now a day's diesel is easily available fuel but there is another aspect emission is also needs to be considered because of increasing pollution in the environment. Diesel engines produce higher levels of particulates these can infiltrate into the lungs that become the reason of irritation and asthma attacks in human. Diesel also produces nitrogen oxides or NOx. Long term exposure to nitrogen dioxide in particular person can improper lung function and may increase the risk of respiratory conditions and worsen allergic reactions. PM is one of the major pollutants from diesel engine. Drastic Increment in vehicles and added combustion processes has resulted in a notable increment in ambient PM over the past twenty years. Due to bad combustion of diesel; CO and UHC also obtains through tailpipe with ideal products. CO has tendency to mix with haemoglobin in blood and reduces the oxygen carried by blood. Pollutants through tailpipe include NO_x, UHC, CO, and PM mostly. UHC in the exhaust of combustion has an origin from fuel and there weight in exhaust depends on engine performance. At the time of combustion thermal cracking takes place in the chamber and due to thermal cracking HC converts in CO_2, H_2O ideally. UHC like Benzene can disrupt the cell growths in humans and also causes cancer so controlling of UHC is essential. These all emissions in tail pipe are function of various combustion characteristics, which controls combustion (for ex. FIP, MIT, PIQ, PIT, Boost pressure from turbocharger). However, more research still needs to be done for a wider analysis. In present era, it's very important to research continuously to reduce emissions because still, we are very far away from zero emissions. That is why to achieve sustainability in a diesel engine, performance has to be improved so that emission parameter's quantity can be reduced to meet the new global standards[1].

3. Objectives:-

In most of the research on CRDi engine analysis remains limited to only a few variables like fuel injection pressure and main injection timing but for more insight of CRDi engine and to increase its performance it's very important to highlight the Interaction factor among all important parameters. Purpose of this paper is to present the latest researches which have been done in the CRDi engine. This paper summarizes the individual behavior of different primary factors on emissions, combustion characteristics of the engine. This paper also highlights some studies on DOE methods which are useful to analyze such type of interaction parameters so that new dimensions of research can be opened. It also presents importance of the ANOVA method in the optimization of primary variables viz. FIP, MIT, PIT, PIQ and Boost pressure so emissions of CRDi engine can be reduced more and performance can be increased to the next level.

4. Effect of controlling parameters on Emissions/Response parameters

Studies mentioned below have been done by various researcher and scientists that shows, emission from engine, the power output of engine and performance of the engine is highly dependent on some primary factors and these factors are Fuel Injection Pressure, Main Injection Timing, Pilot Injection Timing, Pilot Injection Quantity and Boost Pressure created from the turbocharger.

4.1 Effect of variation of fuel injection pressure (FIP)

The optimum value of Fuel injection pressure is very necessary for both high performances as well as lower emissions. Very high FIP creates a high peak in-cylinder pressure and high heat release rate which leads to knocking so heat loss from cylinder walls also takes place which gives inferior engine performance. The optimum level of FIP is required for better combustion because it helps to atomize the liquid fuel into very small diameter droplets, which shortens the physical delay of combustion. Due to minimization of physical delay, accumulation of fuel do not takes place and uniform combustion occurs. Too high a fuel injection pressure causes shorter ignition delay, which leads to in-homogeneity in fuel-air mixture, resulting in relatively lower combustion efficiency[2]. Vinod bau et al. performed experiment on Kirloskar single cylinder diesel engine equipped with CRDi technology at constant rpm of 1500. He analyzed the performance of the engine at three FIP (300 bar, 400 bar, and 500 bar). And found that at 500 bar FIP, rate of heat release increases considerably for 19^{o} bTDC compared to 7^{o} bTDC [3]. A.K. Agarwal et al. performed an experiment on CRDi engine and on analyzing spray characteristics of the same engine he found that high FIP atomized the fuel at the time of injection and vaporized it uniformly in the cylinder that leads to better air-fuel mixing. The increment in FIP causes the fuel-air mixing in the combustion chamber more favourable, so the unburnt hydrocarbon emission obtains less compared to the emission of less FIP[2]. HC, CO, NOx and PM emissions are highly dependent on FIP so it is an important factor needs to be optimized for higher performance and less pollution. Improved air-fuel mixing reduces CO emission and smoke formation. It has been also observed that CO, UHC and smoke emissions are reduced and NOx emissions increases on increasing the FIP[4]. High FIP increases pre mixed combustion's duration and reduce overall combustion duration due to this soot oxidation could not complete and reduction in both soot formation and heat loss can be seen[2].

4.2 Effect of variation of Pilot injection timing (PIT)

Pilot injection timing is a very important factor of the CRDi engine. Thus analysis of PIT is very significant to understand the behavior of emissions and performance. Advanced PIT and retarded PIT both may be proved harmful until the position of PIT does not optimize. Advancing PIT increases in-cylinder temperature and in-cylinder pressure before the injection of major fuel. Knocking is a factor which limits the advancement of PIT and represents maximum pressure rise[5]. It has been found that to reduce the rate of heat release with smooth pressure, PIT has a significant role and Advanced PIT increases brake mean effective pressure in engine[6]. It has been also seen that emissions of NOx and soot particle from pilot injected compressed ignition engine is higher than spark ignited the engine[7]. Advancing PIT reduces HC and CO emissions because of more oxidation but same time NOx emission increases. After a limit advancing PIT creates very high combustion noise[8,9]. Retardation of PIT lowers the fuel consumption and reduces NOx emission.

Effect of PIT becomes more visible at low load conditions. Advanced PIT also reduces particulate matter whereas retarded timing reduces the formation of NOx emission in the chamber [10]. Peak in-cylinder temperature and in-cylinder pressure are a function of PIT and due to this NOx also becomes dependent on PIT. Early PIT creates a delay in the main injection so reaction between air and fuel gets more time and complete combustion occurs. Late PIT reduces the time of reaction between fuel and air combustion efficiency decreases and smoke increases in the exhaust that is why early PIT reduces smoke formation. Early PIT increases cylinder pressure and cylinder temperature which results in increased NOx emission. So by these study, it can be concluded that early PIT reduces the soot formation [11].

4.3 Effect of variation of Pilot injection quantity (PIQ)

Indicated mean effective pressure significantly increases with increment in injected fuel quantity at all selected fuel injection pressure's[2]. Pilot injected quantity prepares the suitable environment for fuel of the second injection so ignition delay and sudden heat release can be reduced. Multiple injections used to reduce the temperature inside of combustion chamber and due to this NOx level could be controlled but low temperature can create a problem of oxidation and it increases CO emission. While multiple injections reduce HC emission because of enhancement in the combustion process[10,7]. Sindhu at el. performed an experiment on a single cylinder Kirloskar engine and compared the effect of two split injections with a single injection. she used two strategies of pilot injection with 8^{o} dwell period and starting of injection at 16^{o} bTDC. In the first strategy ratio of pilot injection and main injection kept 25 % and 75% while in the second strategy this ratio kept as 75% and 25%. Minimum NOx has been seen for 1^{st} strategy (25% pilot injection) and with minimization of NOx, UHC and CO increases. While minimum soot formation observed in second strategies compared to single injection and first strategy. Primary purpose to launch pilot injection is to reduce the RHR and limit the NOx emission by injecting a small quantity of fuel before the main injection of fuel[9].

4.4 Effect of variation of Main injection timing (MIT)

MIT represents injection timing of foremost fuel in degree with respects to top dead center. R. Sindhu performed simulation and experiment on single cylinder Kirloskar engine and summarized that Advancing MIT increases peak in-cylinder pressure which increases heat transfer so combustion characteristics get affected. While retarded injection timing reduces the rate of heat release thus low temperature obtained. As the injection timing delayed, the fuel mixture favoured better vaporization which limits the creation of unburned hydrocarbons. On advancing the MIT, BTE and BMEP increase but BSFC decreases. Due to the early injection of fuel, peak in-cylinder pressure rises which also helps to get maximum power. Early injection is also helpful for fuel with less quality because bad quality fuels take more time to ignite. Different strategies can be made to inject fuel in the combustion chamber to get better performance and fewer emissions[9]. According to Jain A. starting time of the main injection and pilot injection improve combustion but after a limit more advanced main injection timing resulted in a slightly bad performance and bad emissions characteristic. It has been also concluded that the use of early injection provides lower soot and higher NO_x emissions than the late injection. That is why on advancing MIT NOx emission also increases and CO_2, UHC decreases[12]. Pandian at el. also used RSM technique and ANOVA technique for design of experiment on twin cylinder CI engine and concluded that advancing the MIT from 18^{o} bTDC to 30^{o} bTDC, CO, HC and smoke emissions reduces while NOx emission increases. They also admitted the interaction factor of MIT with FIP and nozzle tip protrusion [13]. Tao et al. performed experiments on diesel engine using the retarded MIT and seen reduction in Nox emission. diminishes CO2 emission and drastically increase UHC, CO emissions whereas Advanced injection timing allows more time to mix fuel and air so oxidation process improves hence less CO occurs[14].

4.5 Effect of variation in Boost pressure

It has been found that an increase in boost pressure or pressure of intake air has a significant role in increasing the power and efficiency of the engine. Boost pressure of air can be created by turbocharger or supercharger. Boost pressure is kept in between 0.2 to 0.5 bar generally on basis of geometry and strength of combustion cylinder. Increasing Boost pressure allow more air molecules to enter in the chamber due to this oxidation of fuel particles increases and due to lean mixture engine's efficiency also increases but these all depends on intake pressure of air whereas Excess boost pressure can create considerable noise and stresses in engine body. Optimized boost pressure is very necessary because at very high intake pressure it increases emissions also and becomes a threat for engines body by increased vibration and Knocking. Fluctuations in response variables are due to the nature of the highly complexed swirl dynamics of intake created by boost pressure hence BP is also a factor which affects combustion and emissions of engine. Turbocharger allows more oxygen in the cylinder by means of more air (10 to 20% more) so it can react with more fuel and increased power can be achieved. It's is not only reduced smoke level but also gives increased torque by 45% more than those do not use it at low speed [15]. It also reduces fuel consumptions by reducing pumping loss during intake of fresh air. Reduced fuel consumption can be seen on high speed also due to decrement in pumping loss by utilization of flue gasses' energy [16].

5. Approach useful for optimizing diesel engine performance and emissions:

From above literature it has been found that CRDi engine's performance, combustion characteristics and emissions from exhaust are functions of several variables such as FIP, MIT, PIT, PIQ and Boost pressure. All these variables have an adverse effect at both maximum and minimum range and their range is generally observed by a misfire and knocking conditions. Every parameter described above has a specific value at which it gives optimum result if other parameters remain constant. Here optimum result describes minimization of emissions. For actual optimization analysis of all control variables simultaneously is necessary. There is an Interaction factor exists among all variables because their combination strategy decides emission level. This type of problem can be handled by the design of the experiment in several ways with different designs. The application of design of experiment requires careful planning, the sagacioust layout of the experiment, and rigorous analysis of the result. Mostly studies for achieving optimization has been done using Factorial design, Response surface methodology and Taguchi method. To analyze the data of various DOE methods, ANOVA technique can be used which is a statistical tool used in DOE for data analysis. ANOVA (analysis of variance) method evaluates the contributions of the every controlled factor in terms of the percentage[17]. Z Win at el. investigated a four stroke diesel engine of 3.5 kW and optimized 7 responses namely engine and combustion noise, smoke opacity, BSFC and three emissions (UHC, NOx and CO). In this experiment they selected eight factors as controlled factors with two levels each (namely: MIT, nozzle opening pressure, nozzle tip's protrusion, holes in nozzle, nozzle hole diameter, diameter of plunger, load, and speed of engine). They concluded that Taguchi method is very effective in optimization of injection and operating parameters. For finding importance of every controlled factor in percentage they used ANOVA technique and stated that Taguchi is robust and more cost effective than full factorial design [18]. Abhishek at el. performed an experiment on Kirlosker diesel engine and worked on FIP, MIT and Load torque with four levels of every factor to optimize BTE. In that research, they employed Taguchi's L16 orthogonal array and S/N ratio which gave optimum grouping and maximum BTE with minimum NOx. They found best two strategies as follows: - for minimum NOx, FIP: MIT: Load are 200 bar, 17.14^{o} bTDC, 2.56kW while for maximum BTE, FIP: MIT: Load is 200 bar, 12.38^{o} bTDC, and 4.84 kW. They also concluded that the Taguchi method is a suitable method to estimate the response in extreme conditions[19].

6. Conclusion

Conclusions of above literature is that FIP, MIT, PIT, PIQ and Boost pressure are independent parameters of CRDi engine which controls NOx, CO, UHC and PM emissions and combustion characteristics. On changing the value of one independent controlled factor, range of other control factor also get affected, this proves the interaction effect among all controlled parameters. For effective optimization, and better performance the study of all controlling parameters needs to be done all together. By various researches on application of DOE it has been found that Taguchi and RSM both methods can be used for finding interaction effect in various primary input variables. Whereas ANOVA method can be used to decide quality of response variable by analysis of variance and can present significance of every controlled parameter to generation of emission and power output.

Reference

1. Li, Z. *et al.* E ff ects of the variation in diesel fuel components on the particulate matter and unregulated gaseous emissions from a common rail diesel engine. *Fuel* **232,** 279–289 (2018).
2. Agarwal, A. K. *et al.* Combustion characteristics of a common rail direct injection engine using different fuel injection strategies. *Int. J. Therm. Sci.* **134,** 475–484 (2018).
3. Marri, V. B. *et al.* Experimental investigations on the influence of higher injection pressures and retarded injection timings on a single cylinder CRDi diesel engine Experimental investigations on the influence of higher injection pressures and. *Int. J. Ambient Energy* **0,** 1–14 (2018).
4. Aalam, C. S. & Saravanan, C. G. Effects of Fuel Injection Pressure on CRDI Diesel Engine Performance and Emissions using CCD. 1411–1416 (2015).
5. Yang, B., Wang, L., Ning, L. & Zeng, K. Effects of pilot injection timing on the combustion noise and particle emissions of a diesel / natural gas dual-fuel engine at low load Phone number : + 8613609198531. *Appl. Therm. Eng.* (2016). doi:10.1016/j.applthermaleng.2016.03.126
6. Jeong, J. H., Jung, D. W., Lim, O. T., Pyo, Y. D. & Lee, Y. J. INFLUENCE OF PILOT INJECTION ON COMBUSTION CHARACTERISTICS AND EMISSIONS IN A DI DIESEL ENGINE FUELED WITH DIESEL AND DME. **15,** 861–869 (2014).
7. Li, M., Zhang, Q., Liu, X., Ma, Y. & Zheng, Q. SC. *Energy* (2018). doi:10.1016/j.energy.2018.08.102
8. Dhar, A. Effect of Multiple Injections on Particulate Size- Number Distributions in a Common Rail Direct Injection Engine Fueled with Karanja Biodiesel Blends. (2018). doi:10.4271/2013-01-1554
9. Sindhu, R., Rao, G. A. P. & Murthy, K. M. Effective reduction of NOx emissions from diesel engine using split injections. *Alexandria Eng. J.* **57,** 1379–1392 (2018).
10. Ishida, M., Chen, Z., Luo, G. & Ueki, H. The Effect of Pilot Injection on Combustion in a Turbocharged D . I . Diesel Engine. (2018).
11. Nik Rosli Abdullah, Rizalman Mamat, Miroslaw L, A. T. Effects of pilot injection timing and EGR on a modern V6 common rail direct injection diesel engine Effects of pilot injection timing and EGR on a modern V6 common rail direct injection diesel engine. doi:10.1088/1757-899X/50/1/012008
12. Sayin, C., Uslu, K. & Canakci, M. Influence of injection timing on the exhaust emissions of a dual-fuel CI engine. **33,** 1314–1323 (2008).
13. Pandian, M., Sivapirakasam, S. P. & Udayakumar, M. Investigation on the effect of injection system parameters on performance and emission characteristics of a twin cylinder *.Appl. Energy* **88,** 2663–2676 (2011).
14. Tao, F. *et al.* Modeling the Effects of EGR and Injection Pressure on Soot Formation in a High-Speed Direct-Injection (HSDI) Diesel Engine Using a Multi-Step Phenomenological Soot Model. **2005,** (2018).
15. Muqeem, M., Ahmad, M. & Sherwani, A. F. Turbocharging of Diesel Engine for Improving Performance and Exhaust Emissions : A Review. **12,** 22–29 (2015).
16. Feneley, A. J., Pesiridis, A. & Mahmoudzadeh, A. Variable Geometry Turbocharger Technologies for Exhaust Energy Recovery and Boosting - A Review. *Renew. Sustain. Energy Rev.* 1–17 (2016). doi:10.1016/j.rser.2016.12.125
17. Armstrong, R. A., Eperjesi, F. & Gilmartin, B. The application of analysis of variance (ANOVA) to different experimental designs in optometry. 248–256 (2002).
18. Win, Z., Gakkhar, R. P., Jain, S. C. & Bhattacharya, M. Investigation of diesel engine operating and injection system parameters for low noise , emissions , and fuel consumption using Taguchi methods. **219,** 1237–1251 (2005).
19. Ahamad, N., Sharma, A. & Singh, Y. Performance and emission analysis of a diesel engine implementing polanga biodiesel and optimization using Taguchi method. *Process Saf. Environ. Prot.* **120,** 146–154 (2018).