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Injection Timing Variation and its Influence on the Performance and Combustion Characteristics on a Direct Injection CI Engine

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ABSTRACT:

The present experimental investigation aims at improving the combustion and performance parameters by varying the injection timing. A 3.5 kW single cylinder stationary CI engine equipped with eddy current dynamometer is used in this investigation. The static injection timing is varied using spill method by an advancement and retirement of 2 CAD with respect to standard injection timing of 23° BTDC. On comparison with the standard injection timing, the brake thermal efficiency, cylinder pressure, rate of heat release, mean gas temperature and rate of pressure rise are found to increase along with a significant decrease in brake specific fuel consumption for an advanced injection timing of 21° BTDC. Negative improvement is observed with respect to retarded injection timing of 25° BTDC. Optimum parameters for enhanced engine performance is found to be 21° BTDC injection timing with a 200 bar injection pressure at rated speed.

KEYWORDS:

Injection timing variation; In-cylinder pressure; Net heat release; Mean gas temperature

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1. Introduction

Better thermodynamic effectiveness, durability and higher fuel economy favoured the use of compression ignition engine in the transportation, aviation, construction and agricultural sector to a great extent. In spite of these benefits, diesel engine are greatly responsible for causing environmental hazards through pollution. The need to improve the atmospheric air quality necessitated the government to implement Bharath stage VI norms by 2019. This led the engine manufacturing companies and OEM's suppliers of automobile vehicle sector to make engine modifications and implement after treatment to reduce the exhaust emissions. Among the diesel engine exhaust emissions, NO_x is more vulnerable. Several attempts have been made by researchers to reduce this formation using EGR and thereby, increasing the engine performance also. Reduction in combustion peak temperature reduces the formation of NO_x but it influences by producing more particulate matter in the exhaust.

Particulate matter emission from CI engine along with the reduction in oxides of nitrogen is a difficult phenomenon as a trade-off relation exists between them. Several researchers through their studies have contributed largely to the increase in the engine performance and reduction in emission reduction by varying the in-cylinder parameters like injection timing, injection pressure, compression ratio, combustion chamber modification and others [1-2]. Studies were carried out to analyse the effect of injection timing and pressure of 500 and 1000 bar on the performance and combustion parameters at constant speed of 2500rpm. Lower injection pressure had a positive effect on the heat release rate and in-cylinder pressure. Advancing of injection timing showed an enhanced performance with a significant reduction in the exhaust gas temperature and brake specific fuel consumption [3]. Variation in injection pressure was demonstrated by Kato et al [4]. High injection pressure reduced the PM emission without altering the NO_x emission.

Many studies revealed that the varying injection timing improves the fuel-air atomization and mixing and enhanced the combustion with reduced pollutants. Ganapathy et al [5] varied the injection timing using full factorial design and analysed its effect on engine parameters when Jatropha biodiesel was used as fuel. Advancement of injection timing lowered the HC, CO, smoke and fuel consumption along with the increase in thermal efficiency, rate of heat release and NO_x emission. It was concluded that an optimum injection timing of 340 CAD yielded better performance. Saravanan [6] introduced the EGR along with the advancing of injection timing in CI engine at various loads. Higher peak pressure, longer ignition delay, higher heat release rate with reduced combustion duration was noticed advancing the injection timing. EGR further increased the peak pressure and ignition delay thereby influencing better combustion.

Advancement and retirement of the injection timing generally deviates the piston position, in-cylinder pressure and fuel injection temperature.

This influenced the ignition delay period, fuel atomization and fuel spray pattern thereby, effectively optimizing the engine performance favouring low temperature reactions [7]. Several studies were also reported on the effect of injection timing detailing the particle size distribution of a compression ignition engine in the presence of EGR. The low temperature reaction resulted in the reduction of NO_x and soot emission in the presence of the EGR [8, 11]. Based on the literature review, it is understood that variations in injection timing may lead to improvement in the performance and combustion characteristics of a CI engine. In the present experimental investigation, the performance and combustion characteristics of the CI engine is analysed by varying the static injection timing. 23 CAD being the standard injection timing, advancement and retirement of injection is carried out with 2 crank angle degree namely 21 CAD and 25 CAD. Engine speed, injection timing, torque, and load are the input parameters. The output parameters investigated are cumulative heat release, rate of heat release, cylinder pressure, brake thermal efficiency, brake specific fuel consumption, rate of pressure rise and mean gas temperature. The effect of static injection timing (SIT) on the output parameters are compared and studied.

2. Experimental setup

2.1. Test engine

The experimental study is performed on a vertically mounted air cooled, single cylinder four stroke direct injection CI engine of 240 PE Kirloskar make. The bore and stroke length is 87.5mm and 110mm with a rated power of 3.5 kW at 1500rpm as shown in Fig. 1. The factory set standard injection timing is found to be 23° BTDC with an injection pressure between 200 and 210 bar. SAJ make eddy current dynamometer is used for loading the test engine.

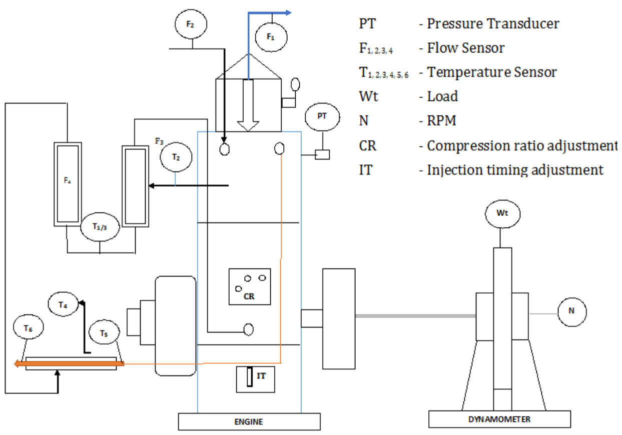

Fig. 1: Experimental setup - schematic diagram

Orifice fitted with a manometer is used for measuring the mass flow rate of the air intake which incorporates a surge tank to ensure steady air flow through the intake manifold. The combustion analysis is carried out using MIII A22 pressure transducer of PCB piezoelectric make having sensitivity of 1 mV/psi. It has a range of 0-350 bar. The cooling of engine is accomplished through a Rotameter setup having a range of 40 to 400 litre per hour. The inlet and outlet water temperature, exhaust gas temperature (EGT) is measured using PT100, RTD and K type thermocouple located in appropriate places. The consumption of diesel fuel is measured using fuel measuring unit of FFO.012 apex glass apex make. An inductive speed pickup was employed to measure the speed of the engine. AX 409 Candra make piezo electric amplifier power unit installed with signal conditioning system along with kubler make crank angle encoder is used to amplify the signal before entering the digital data acquisition system. The detailed test engine specification is given in Table 1.

Table 1: Specifications of test engine and combustion analyser

Specification of test engine	
Model and make	240 PE / Kirloskar
Stroke	110mm
Bore	87.5mm
Injection pressure (opening)	200-210 bar
Compression ratio	17.5 : 1
Rated speed	1500rpm
Rated power	3.5 kW
Injection timing (standard)	23° BTDC
Loading	Eddy current dynamometer
Dynamometer arm length	185mm
Swept volume	661.45cc
Combustion analyser specification	
Model and make	M III A22, PCB Pizeotronics
Range	0-5000 psi (0-350 bar)
Acceleration (sensitivity)	0.002 psi/g
Sensitivity	1 mV / psi
Linearity	2%
Operating temperature range	-100°F to + 275°F (-73°C to + 135°C)

2.2. Test procedure

Commercial diesel fuel having a cetane number between 48 and 50 is used as the fuel in this experimental investigation as given in Table 2. The test engine is made to run at the rated speed of 1500rpm throughout the experimentation. The lower and upper limit of the engine load is designated as 1kg and 12kg depending on its dynamic stability. The standard factory set injection timing of 23° BTDC with 200 bar injection pressure is set initially during the engine warm up for 20min and studied for its comparability and repeatability. Engine load, speed and static injection timing are the input variables during the experimental study. Spill method is adopted for changing the static injection timing. Generally, the fuel injection timing is identified by placing a semi-circular protractor fitted to the engine shaft pulley. Standard injection timing contained three shims of 0.25mm thickness. Addition of these shims by two numbers in the fuel injector retarded the fuel injection timing by 2 CAD whereas removal of shims advanced the injection timing by same 2 CAD [5]. An average of hundred successive cycle is recorded to eliminate in-consistency and changeability during the combustion and performance analysis.

Table 2: Properties of diesel fuel

Diesel fuel properties	
Viscosity @ 40°C (mm^2/S)	3.8
Calorific value (kJ/kg)	43450
Specific gravity	0.834
Flash point (°C)	57
Fire point (°C)	65
Cetane number	48-50
Auto ignition temperature (°C)	310-330

Engine performance analysis is carried out by analysing the brake thermal efficiency and brake specific fuel consumption through fuel consumption, engine load and speed data. Combustion study is carried out by analysing the mean gas temperature, rate of pressure rise, cumulative heat release, rate of heat release and cylinder pressure. Uncertainties and ambiguities in the experimental investigation may have arisen due to the errors in observation, calibration, selection of tools and instruments, environmental condition and planning. It is very important and necessary to prove that the experiment is error free and accurate. Root mean square method is adopted to prove the accuracy of this experimental investigation. Table 3 illustrates the percentage of errors of various parameters used in this study [12, 14].

Table 3: Uncertainties and ambiguities

Parameter	Percentage of uncertainty (%)
Load	± 0.6
Speed	± 1.1
Time	± 0.5
Temperature	± 1.1
In-cylinder pressure	± 0.7
Fuel line pressure	± 0.6

$$Uncertainty\ \% = Square\ root\ of\ [(Uncertainty\ of\ load)^2 + (Uncertainty\ of\ speed)^2 + (Uncertainty\ of\ time)^2 + (Uncertainty\ of\ temperature)^2 + (Uncertainty\ of\ in\_cylinder\ pressure)^2 + (Uncertainty\ of\ fuel\ line\ pressure)^2]$$

$$= Square\ root\ of\ [(\pm 0.6)^2 + (\pm 1.1)^2 + (\pm 0.5)^2 + (\pm 1.1)^2 + (\pm 0.7)^2 + (\pm 0.6)^2] = \pm \mathbf{1.969}\%$$

3. Results and discussion

3.1. Performance analysis

The effect of advancing and retarding the injection timing (IT) on BSFC for the diesel fuelled engine is plotted in Fig. 2. It can be noticed that, generally BSFC decreases with the escalation in load across at all injection timings. Standard injection timing of 23° BTDC exhibited 0.79kg/kWhr at low load. The BSFC is found to decrease gradually up to 0.30kg/kWhr at full load condition. Injection timing advancement up to 21° BTDC by 2 CAD showed a slight increase in the BSFC by up to 0.97kg/kWhr at low load which is 18.55% higher than the standard injection timing. But with increase in the load, the BSFC decreased and found comparable with the standard injection timing at part loading condition. Further reduction in BSFC by up to 0.523kg/kWhr is noticed for an advanced injection timing (21 CAD) at full load condition which is the least value attained when advancing the injection timing as reported in the literature review. This may be due to the improved combustion of hydrocarbon fuel particles admitted within the combustion chamber along with improved combustion efficiency. Higher BSFC is observed throughout the entire loading condition when engine is operated at a retarded injection timing of 25 CAD.

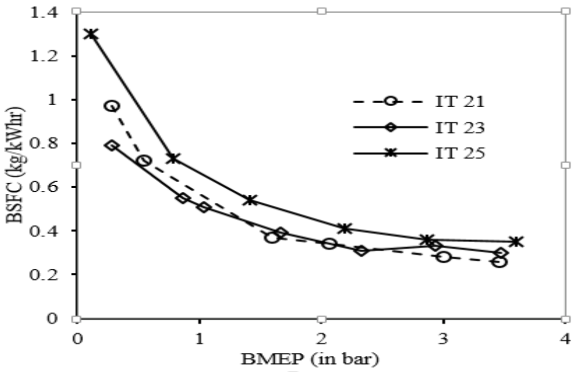

Fig. 2: Effect of IT on BSFC

Fig. 3 depicts the variation of BTE at advanced, standard and retarded injection timing at all loading conditions. In general, the BTE increases with rise in load across all injection timings. From the Fig., it can be observed that the retarded injection timing (25 CAD) showed a BTE of 11.41%, 20.63% and 26.13% at low, part and full load which is the lowest on comparison with standard and advanced injection timing. This may be resulted due to the prolonged ignition delay and poor mixing of the fuel and air particle. Standard injection timing showed higher BTE at low load which gradually reduced on comparison with advanced injection timing as the load is increased. The maximum BTE at 23° BTDC injection timing is found to be 28.12% as shown in the Fig. The engine proved to have a better brake thermal efficiency at an advanced injection timing of 21° BTDC across all loading condition which may be due to the early combustion and better atomization of the fuel. At advanced injection timing, maximum brake thermal efficiency is found to be 31.52% which correlated with the findings of Celikten [9].

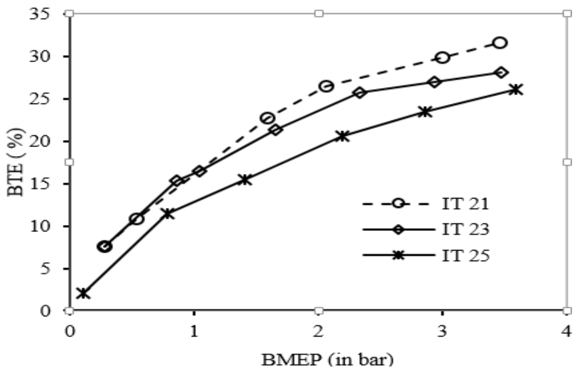

Fig. 3: Effect of IT on BTE

4. Combustion analysis

4.1. In-cylinder pressure

Fig. 4 illustrates the effect of injection timings on in-cylinder pressure at no load and full load condition with diesel as the fuel. It can be understood that the SOC (start of combustion) is greatly affected by altering the injection timing. From the Fig., it can be noticed that the advancement of injection timing by up to 21 CAD resulted higher in-cylinder pressure by up to 46.12 bar at no load and 60.57 bar at full load condition. This may be due to the enhanced premixed combustion period. It can also be noticed from the in-cylinder curves that the earlier start of the combustion is also attributed by the prolonged delay period. Retirement of injection timing resulted in reduced premixed combustion phase due to lower in-cylinder pressure. At retarded injection timing (25° BTDC), the maximum in-cylinder pressure is observed to be 42.16 bar at no load and 56.43 bar at full load condition. This reduction in cylinder pressure is due to smaller ignition delay, especially the physical delay which caused the admittance of fuel even after the start of combustion leading to vaporization heat losses. However, standard injection timing exhibited an in-cylinder pressure of 43.16 bar at no load and 58.05 bar at full load which is significantly lower than the advanced injection timing. These findings correlated well that of Mani and Nagarajan [10].

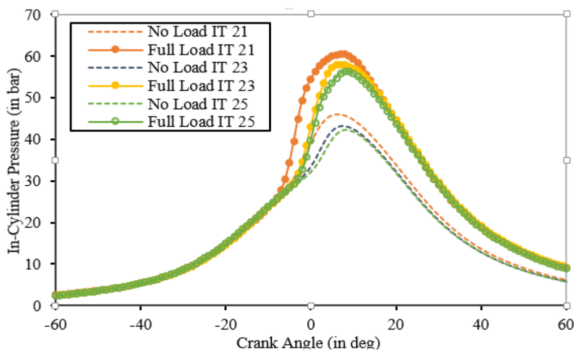

Fig. 4: Effect of IT on in-cylinder pressure

4.2. Net heat release

Fig. 5 depicts the comparison of net rate of heat release at advanced (21 CAD), standard (23 CAD) and retarded (25 CAD) injection timing at no load and full load condition. Net rate of heat release (NHR) curve represents the quantum of useful work which could be extracted from the available heat energy produced during the burning of the fuel. Generally, it can be noticed that the NHR during advanced fuel injection is 11.21% higher than that of standard injection timing and 24.72% higher than the retarded injection timing. Advanced fuel injection initiates earlier combustion compared to standard fuel injection and in-turn results in higher rate of heat release due to early compression of the burnt gases in the combustion chamber. It can be seen that, the net heat release rate at advanced injection timing is greater than the retarded and standard injection timing. At 21° BTDC (advanced injection timing), the NHR was noticed to be 20.58 J/deg at no load and 49.77 J/deg at full load condition. This may be due to the prolonged ignition delay period leading to the accumulation of fuel within the combustion chamber resulting in maximum rate of heat release. Lesser intensity of NHR is observed at retarded injection timing of 25° BTDC. At 25° BTDC (retarded injection timing), the NHR is observed to be 20.45% J/deg at no load and 39.90 J/deg at full load. This drastic decrease in NHR may be due to the shorter ignition delay thereby leading to poor atomisation along with an improper mixing of air and fuel resulting in a less significant premixed combustion period. At 23° BTDC (standard injection timing), the net heat release is noticed as 20.52 J/deg and 44.75 J/deg at no load and full load respectively. This finding are compared with Gumus [13] and there is a good agreement with the finding of this present study.

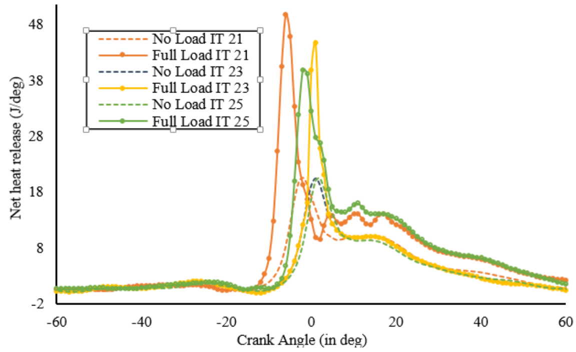

Fig. 5: Effect of IT on NHR

4.3. Rate of pressure rise

The variation in rate of pressure rise (ROPR) at advanced, retarded and standard injection timing at no load and full load condition is plotted in the Fig. 6. It can be noticed that there is a continuous increase in the ROPR with the increase in engine load. Standard injection timing at 23° BTDC showed 2.01 bar rise in pressure during the combustion process at no load whereas, at full load condition, it exhibited 4.56 bar of pressure rise as shown in Fig. 6.

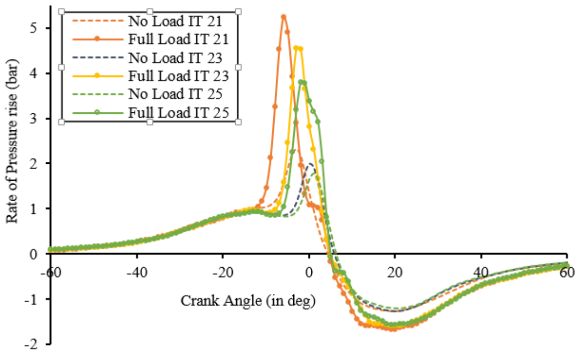

Fig. 6: Effect of IT on ROPR

Advancing the injection timing up to 21° BTDC showed 2.31 bar and 5.24 bar rise in pressure at no load and full load respectively. This significant increase in rate of pressure rise may be due to the early commencement of the combustion process after a prolonged ignition delay period. Since the temperature and pressure are directly proportional to each other, more fuel which is accumulated within the combustion chamber during this delay period is combusted thereby leading to a higher latent heat of vaporization. This enhances the premixed combustion phase. Retarded injection timing at 25° BTDC exhibited a lower ROPR than the standard injection timing by 19.68% which is unfavourable. This may be due to poor combustion efficiency and reduced ignition delay period [15, 16].

4.4. Cumulative heat release

The aggregate summation of instantaneous heat release till the start of expansion process from the end of the compression stroke is termed as cumulative heat release. Fig. 7 depicts the variation in cumulative heat release (CHR) at various fuel injection timing for full load and no load conditions. It can be clearly seen that there is an exponential increase in the rate of heat release for a specified duration after which it decreases gradually. Generally, CHR at advanced injection timing is found to be greater than the standard and retarded injection timing. Advanced injection timing showed a maximum heat release of 0.98 kJ and 0.64 kJ at full load and no load condition between 65 and 72 CAD after top dead centre. The heat release at standard injection timing is lesser with advanced injection timing by 7.6%. At retarded injection timing, the CHR is observed to be 0.56 kJ and 0.92 at no load and full load condition respectively.

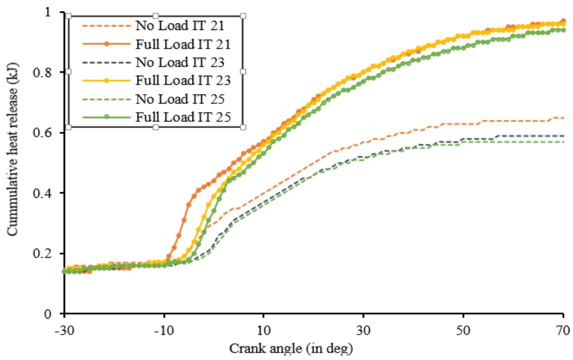

Fig. 7: Effect of IT on CHR

4.5. Mean gas temperature

Mean gas temperature (MGT) is the temperature between end of compression process and start of expansion process of air-fuel mixture inside the combustion chamber. The variation of MGT at no load and full load condition for advance, standard and retarded injection timing plotted against various crank angle is shown in Fig. 8. It can be noticed that advancing the injection timing produced higher MGT at all loads compared to standard and retarded injection timing. The occurrence of peak MGT at advanced injection timing is also seen shifting itself towards the top dead centre. This may be due to the early combustion influenced by premixed combustion period. Advanced injection timing at 21° BTDC showed a peak MGT of 1187.88°C and 884.33°C at full load and no load respectively whereas, standard injection timing showed a peak MGT of 1177.44°C and 856.98°C.

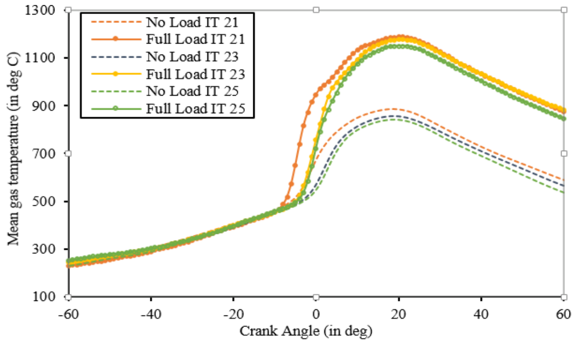

Fig. 8: Effect of IT on MGT

5. Conclusion

The experiments are conducted at advanced (21° BTDC), standard (23° BTDC) and retarded (25° BTDC) injection timings at rated load and speed. The variation in fuel injection timing significantly affected the performance characteristics and its combustion parameters of a stationary CI engine and the following conclusions are drawn.

- The test engine is able to run smoothly at all the injection timings at rated speed and load.
- At low load, the BSFC of advanced injection timing is found to be 0.97kg/kWhr which is reduced up to 0.523kg/kWhr at full load condition. Standard and retarded injection timing are noticed to have a higher BSFC than the advanced injection timing.
- Enhanced engine performance with the maximum BTE of 31.52% is noticed for advanced injection timing of 21° BTDC.
- Early starting and rapid combustion is seen by advancing the injection timing. This resulted with a higher cylinder pressure and maximum heat release rate during the combustion process.
- The cumulative heat release showed a marginal variation with the advancement of injection timing.
- Advanced injection timing accumulated more quantity of fuel within the combustion chamber due to prolonged ignition delay thereby increasing the rate of pressure rise significantly.
- Mean gas temperature also showed an incremental values with the advanced injection timing on comparison with standard and retarded timings.

Finally, the optimal parameters for enhanced engine performance is found to be 21° BTDC injection timing with a 200 bar injection pressure at rated speed.

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