

## **Influence of Ultra Injection Pressure with Dynamic Injection Timing on CRDI Engine Performance Using Simarouba Biodiesel Blends**

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### **ABSTRACT**

This paper presents an experimental investigation carried out on a “single cylinder diesel engine upgraded with a common rail direct injection (CRDI) system. Tests were conducted by fuelling high-speed diesel (HSD) and Simarouba biodiesel (SOME) blends to study the influence of injection pressure (IPR) and injection timing (ITG) on the performance and emissions. Four unique IPR of 400 bar, 600 bar, 800 bar and 1000 bar with four different ITG of 10°, 13°, 15° and 18° before top dead center (bTDC) combinations were taken for study with the engine loading varied from 25% to full load. Critical performance parameter like brake thermal efficiency (BTE) and brake specific fuel consumption (BSFC) were calculated, while, the primary emission parameters of the diesel engine, the NO<sub>x</sub> and smoke opacity were recorded. From the results it is concluded that the given engine recorded favourable results at IPR- ITG combination of 800 bar and 13° bTDC for all fuels tested at higher load conditions specifically at 75% load to full load. Among the different fuels investigated SOME30 yielded the best performance and moderate emission at this combination of IPR- ITG.

**Keywords:** Biodiesel; performance; emission; common rail direct injection (CRDI), engine; injection pressure and timing.

### **INTRODUCTION**

Alternative fuels are seriously examined for replacement of the diesel fuel. Use of biodiesel produced using renewable sources, which is an eco-friendly and safe fuel with low emission values with ecological benefits in CI engines, is regarded as an alternative way to decrease the pollutant level and the potential or probable carcinogenic level [1]. Biodiesel is gaining importance as an alternative to conventional fuels because of their useful properties and compatibility with the petroleum-based diesel fuel. They also offer promise on the long-term fuel-source sustainability and minimum environmental ill-effects after combustion [2]. Biodiesel– fuelled engines give a large opportunity to cope with the fundamental problems facing society, specifically increased energy utilization and global warming. The use of biodiesel with technologically advanced injection strategy has shown a significant impact on diesel engine emissions [3]. Biodiesel is non-

flammable, non-explosive in contrast to diesel fuel [4]. Direct injection diesel engine (DIDE) can be operated with up to 20% of biodiesel blending with diesel without any requirement of enormous alterations in any diesel engine [5].

Research work carried out on diesel engines fueled with biodiesel, with no change in the existing engine test rig, has shown that the engine can produce equal power output, BTE and slightly increase in emissions as compared to diesel. However, the study indicated that the blending of biodiesel with the diesel could be done only up to 20%. It is also advised that the increased percentage of mixing is conceivable in a high-pressure fuel injection system (HPFIS) [5]. The increased fuel injection pressure (FIP) causes the reduction in the size of the injected fuel droplets resulting in better atomization, and faster evaporation of the fuel particles. This will result in a more complete combustion of the fuel leading to improved thermal efficiency and increased power output. Also, the combustion delay time is reduced with increased IPR. Due to this, the mixture is formed in a shorter time, the amount of the nitric oxide (NO<sub>x</sub>) formed reduced considerably due to the ignition time delay [6-8]. Increasing IPR will remove the accumulation of particles, which results in a significant decrease in particle total mass concentration and reduces soot formation [9]. Advanced ITG produces lower smoke compared with retarded ITG [10]. The NO<sub>x</sub> emission is minimized by retarding the ITG [11-13]. With retarded ITG the cylinder pressure and heat release rates are improved [14]. The combined effect of ITG advance and increased IPR has increased brake thermal efficiency [15, 16]. Thus, it can be concluded that a proper combination of IPR and ITG will help in improved combustion resulting in improved performance and emission parameters of a diesel engine. A suitable blend of IPR and ITG will lead to enhanced spray characteristics with better atomization promoting a total fuel-air mixing, which is the basis for the enhanced combustion process [8]. A glance, on the few surveys of the investigations carried out by various researchers on diesel engine fuelled with biodiesel at different IPR and ITG, is discussed underneath:

T. Balusamy et al. studied the effect of IPR and ITG on a DIDE [15]. They observed the gain in the BTE and further noticed a reduction in CO (by 25 %), HC (from 9.5 to 7.7 ppm), smoke (from 48% to 35%) for increased IPR with advanced ITG. Venkatraman et al. [17] studied Pungam biodiesel blends with diesel and observed that an increased compression ratio (CR), IPR and ITG results in improved the BTE, reduced the BSFC and emissions. Metin Gumus et al. [18] have concluded that BSFC and smoke opacity decreased with an increase in the biodiesel amount in diesel along with the increased IPR. G.R. Kannan et al. [19] in their study on a DI engine at varying IPR and IGT, have found the higher BTE for 240 bar and 25.5° bTDC. Extensive research was done by Cenk Sayin et al. [20] on the DI engine to find the FIP effect using canola oil biodiesel blends. They emphasized that to achieve higher BTE and decreased BSFC, high IPR is necessary. G.R. Kannan et al. [21] have found that the collective effect of high IPR and an advanced ITG brings out in improved BTE, cylinder gas pressure (CGP), Heat Release Rate (HRR) and reduced NO<sub>x</sub> and Particulate matter from Waste Cooking oil biodiesel. Venkanna Krishnamurthy Belagur et al. [22] conducted an experimental study using Honne Oil Methyl Ester (HOME) with diesel. From their research, they reported that the increased ITG had improved combustion parameters leading to increasing BTE and reduction in emissions. S. Jaichandar et al. [23] in their study have revealed an increase in BTE (34.31%), reduced SFC (0.243 kg/kW-hr), CO, UHC and smoke intensity. The NO<sub>x</sub> emission was increased at high IPR of 220 bar. Avinash Kumar Agarwal et al. [24] in their investigative work on a CRDI engine used Karanja biodiesel blends, have observed improved BTE with reduced the emissions. Deepesh Sonar et al.

[25] used diesel-Mahua oil blends in their study on an engine operated at different IPR. Their study revealed an improvement in BTE and BSFC at IPR of 226 bar and also the drastic reduction in CO, UHC emission and a marginal increase in The NO<sub>x</sub> emissions. Atul Dhar et al. [26] used Karanja biodiesel blends for their study and observed an increase in BSFC and BTE for Karanja biodiesel blends than diesel. Srinath Pai et al. [5] have in their investigation of the higher Fuel IPR effect on biodiesel blends, have concluded that the high IPR increases the atomization, evaporation, and penetration of the denser biodiesel blend. R. Senthil et al. [27] have observed the increase in the NO<sub>x</sub> emission and decrease in CO and HC at advanced ITG.

The author would like to bring to the notice of the readers that, a previous experimental investigation carried out revealed the combination of IPR of 800 bar and IT of 18° bTDC has proved to be the best combination for improved performance of the CRDI engine [8]. In which the investigation was carried out for a combination of IPR of 600, 800 and 1000 bar with ITG of 10°, 18°, 23° and 28° bTDC combinations [8]. Further, owing to curiosity, a continuation of the investigation was carried at advance injection timing of 10°, 13°, and 15° bTDC for the above combination of pressures on the same engine set up. The results of this work are presented in this paper. The discussion is mainly focused on the engine performance at higher loads specifically at 75% and 100% because this is the ideal operating load in any IC engine. CRDI engine under study has performed better in the load range from 75% to 100% with an improving trend in performance from 75 to 100%. In this paper, the analysis at 75% load is only discussed and similar results are also obtained at 100% load.

## EXPERIMENTAL SETUP

### Design of Experiment

The study aims to find out the IPR and ITG influence on a C.I engine performance and emissions for HSD and Simarouba biodiesel (SOME) blends. A single-cylinder diesel engine upgraded with CRDI system was used for the investigation. The properties of the fuels used in this study are given in Table 1. Specifications of the 5 Gas Analyzer are mentioned in Table 2. Specifications of the smoke meter are provided in Table 3.

Table 1. HSD and SOME properties.

Properties	Test method	HSD	SOME 100	SOME20	SOME30
Relative density at 15°C (g/mL)	ASTMD-1298	0.840	0.868	0.838	0.846
Cetane number	ASTMD-4737	48	52	49	50
Calorific value MJ/kg	ASTMD-4868	44.8	39.8	43.8	43.3
Flash point (°C)	ASTMD-93	55	165	79	88
Kinematic viscosity at 40°C (cSt)	ASTMD-445	2.35	4.8	3.1	3.5

Table 2. Specifications of the INDUS PEA 205, 5 gas analyser.

Type of gas	Measurement range	Data resolution	Instrument accuracy
CO	0 to 15 %	0.001 %	±0.06 %
CO <sub>2</sub>	0 to 20 %	0.01 %,	±0.05 %
O <sub>2</sub>	0 to 25 %	0.01 %,	± 0.1 %
HC	0 to 30000 ppm	1 ppm	± 12 ppm
NO <sub>x</sub>	0 to 5000 ppm	1 ppm	≤500 ppm: ± 50 ppm. ≥ 500 ppm: ± 20 ppm

Table 3. Specifications of AVL 437 smoke meter.

Measuring range	0 to 100 HSU (Hatridge smoke units)
Smoke Temperature	250°C (Maximum at the entrance)
Ambient temperature	0 to 50°C humidity 90% at 50 °C (Non-conditioning)
Power Supply	205 A, 11.5 -36V DC
Principle	light absorption principle

### Experimental Procedure

The experiments were conducted for four different loads of 25%, 50%, 75% and 100% loading, with constant engine speed of 1500 rpm and compression ratio of 16.5. FIP was varied from 400 bar to 1000 bar in steps of 200 bar. For each IPR, ITG is varied in steps of 10°, 13°, 15° and 18° bTDC. Experiments were conducted for all combinations of IPRs, ITGs at each of the load combinations using HSD, SOME20 and SOME30 as fuels. The effect of IPRs and ITGs on BTE, BSFC, The NO<sub>x</sub> and Smoke opacity are analyzed.

Figure 1 and Figure 2 are the photographic views of the fuel injector and engine respectively. The engine specifications of the fuel injector and engine with details are given in Table 4 and Table 5 respectively. The existing engine had necessary the arrangements to measure the load, fuel consumption, air consumption, temperatures at salient points. High accuracy piezoelectric sensors were utilized to measure the gas, combustion and fuel injection pressure. For the crank angle record, an encoder setup was used. During the experiments, compression ratio and engine speed were kept on constant for 16.5 and 1500 rpm, respectively.



Figure 1. Fuel injector.

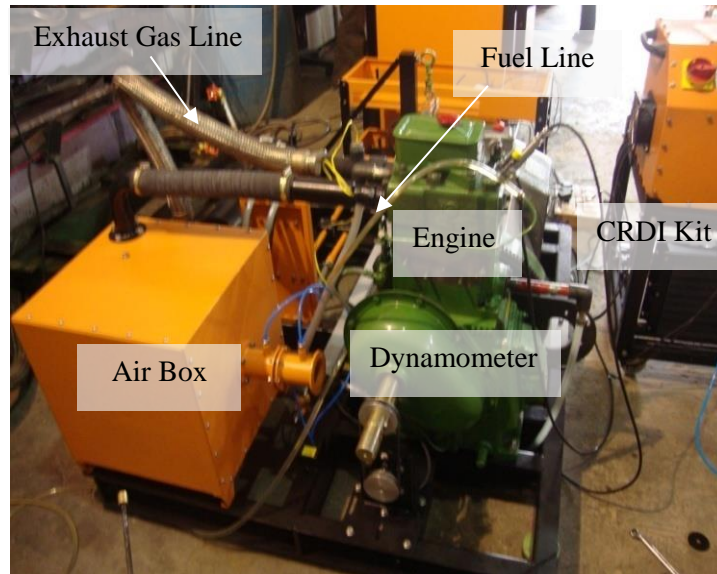


Figure 2. Photographic view of the engine setup.

Table 4. Specification of the injector.

Sl. No.	Parameter	Specifications
1	Injector	Delphi –TVS
2	Holes in the nozzle	1
3	Nozzle diameter	0.19mm
4	Injector operating pressure	2000 bar
5	Injection Pressure used	1000 bar

Table 5. Engine specifications.

Sl.No.	Parameter	Specifications
1	Engine Type	AV1
2	No of cylinders	Single
3	Rated power	5 HP (3.7 kW) @1500 RPM
4	No of strokes	Four-stroke
5	Nozzle opening pressure	200 bar
6	Start of injection (SOI) timing	23° bTDC
7	Cylinder diameter (Bore)	0.0875 metre
8	Stroke length	0.11 m
9	Compression ratio	16.5: 1
10	Specified Fuel	H. S. Diesel

## RESULTS AND DISCUSSION

### Influence of Injection Pressure and Injection Timing on Performance

#### Brake thermal efficiency

Figure 3 analyses the results obtained from the influence of IPR and ITG on BTE for 75% loading with HSD and SOME blends (SOME20 and SOME30). It is noted that BTE for SOME blends was higher than HSD at all combinations of IPR and IRG. Similar results were by Avinash Kumar Agarwal [24] in his experimental investigation. The primary cause for BTE improvement of SOME blends is the more oxygen content of biodiesel. Hence, the blended fuel helps to improve the combustion and results in better BTE [2]. The maximum BTE has observed for SOME30 at all the IPR- ITG combinations. V.K Shahir has also obtained the best BTE for B30 [28]. At 400 bar with 75% loading, maximum BTE obtained for SOME30 is about 27.92% at 18° bTDC. Similarly, for SOME30 at the same load, at 600 bar and 15° bTDC, at 800 bar and 13° bTDC and 1000 bar and 10° bTDC, the BTE values recorded were 28.87%, 31.29% and 29.11% respectively. The highest BTE observed for SOME30 is at IPR 800 bar with ITG 13° bTDC combination. At 100% load for the same combination of IPR and ITG, maximum BTE of 35.80% is noticed for SOME30. This is due to the better atomization and better combustion at the proper combination of higher IPR [20, 21, 23] and ITG [24]. Increasing IPR decreases the injection span, prompting the finest spray droplets, which enhances the fuel-air mixing, subsequently expanding the pre-mixed heat release. Retarding ITG causes an increase in thermal efficiency [12].

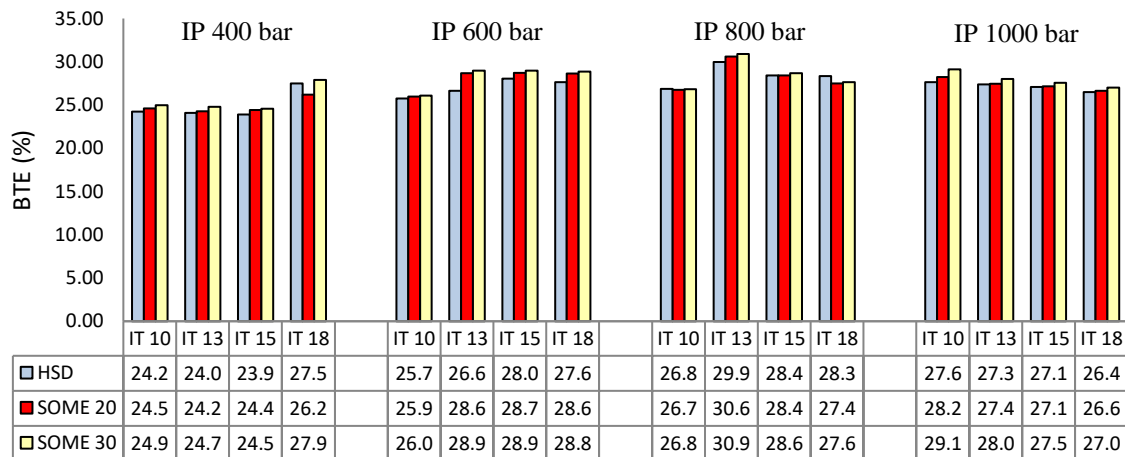


Figure 3: IPR-ITG V/S BTE.

#### Specific fuel consumption

The variations of the BSFC, for 75% load for SOME20, SOME30 and HSD are shown in Figure 4. The BSFC has less value for HSD with at each of the IPR- ITG combinations. Among the all the fuels, the lowest value of BSFC found is 0.2657 kg/kW-hr at IPR of 800 bar at 13° bTDC for SOME30. At the same combination at 100% load, BSFC (0.23224 kg/kW-hr) has recorded the minimum for SOME30. This may be due to higher oxygen and higher IPR, which contributes to better combustion. Similar results and

reasons were reported by V.K Shahir [28]. Regardless of the type of fuel tested, the BSFC was increased with advancing ITG, and it was observed that the BSFC reduced with an increase in the IPR. Lower combustion is attributed to low IPR where there is oxygen starvation due to the least penetration, less dispersion of the fuel and improper air mixing [23]. A similar study by Avinash Kumar Agarwal et al. [24] had concluded that at higher IPRs, fuel energy was most effectively changed over into useful power when SOI timing was closer to TDC. The minimum BSFC has been observed for increased IPR with dynamic ITG near to TDC, hence obtained results are justifiable.

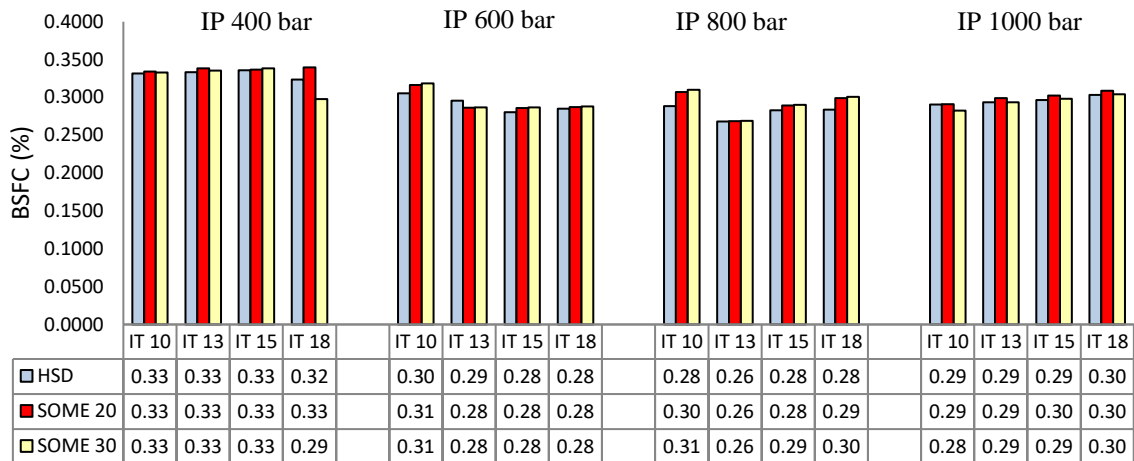


Figure 4: Influence of IP - IT on BSFC at 75% load

### **Influence of Injection Pressure and Injection Timing on Emissions**

#### *Nitrogen oxides (NOx) emission*

Influences of IPR and ITG on the NO<sub>x</sub> for 75% load for SOME20, SOME30 and HSD fuel are plotted in Figure 5. It is apparent that the NO<sub>x</sub> emission increased with an increment in IPRs for all the fuel utilised and decreased with retarding ITG. Similar results were obtained by Peng Ye [3] in his research. It is also observed that the NO<sub>x</sub> emission increased with an increase in SOME blending percentage, this is due to the increase in the amount of oxygen in the blend, which in turn enhances peak cylinder temperatures, and hence the NO<sub>x</sub> formation [29, 30]. Similar outcomes were obtained by the other researchers [2, 24, 28, 29]. It is also believed that the formation of the NO<sub>x</sub> in the CI engines depends on the element concentration within the flammable mixture, a peak cylinder temperature of the composting mixture at [24, 31]. Generally, the NO<sub>x</sub> increases with an IPR for all test fuel. The reason for this could be the highest average gas temperature and residence time at higher IPR.

Among 75% loading results, the NO<sub>x</sub> value is the maximum (928 ppm) for SOME30 at 1000 bar and 10° bTDC combination and minimum (502 ppm) for HSD at IPR 400 bar 18° bTDC combination. Whereas, the minimum box of 450 ppm is obtained for HSD at IPR-ITG combination of 800 bar-13° bTDC at 100% load. The reason is at higher IPRs; the delayed ITG caused accelerated amounts of fuel to start combustion after top dead centre (TDC), leading to lower cylinder pressure peak values and reduced cylinder temperatures. As a result, the NO<sub>x</sub> emission concentration gradually decreases. The reduced NO<sub>x</sub> emissions for SOME biodiesel are the cause of the long chain lengths, higher (CN) and higher degrees of saturation[32]. The NO<sub>x</sub> emissions were reduced by



retarding the ITG [24]. Ultra IPR, with dynamic ITG, will help to cut down the NOx [33]. Numerous studies have reported that the NOx emissions from biodiesel usage depend upon the kind of engine used and furthermore engine working conditions [24].

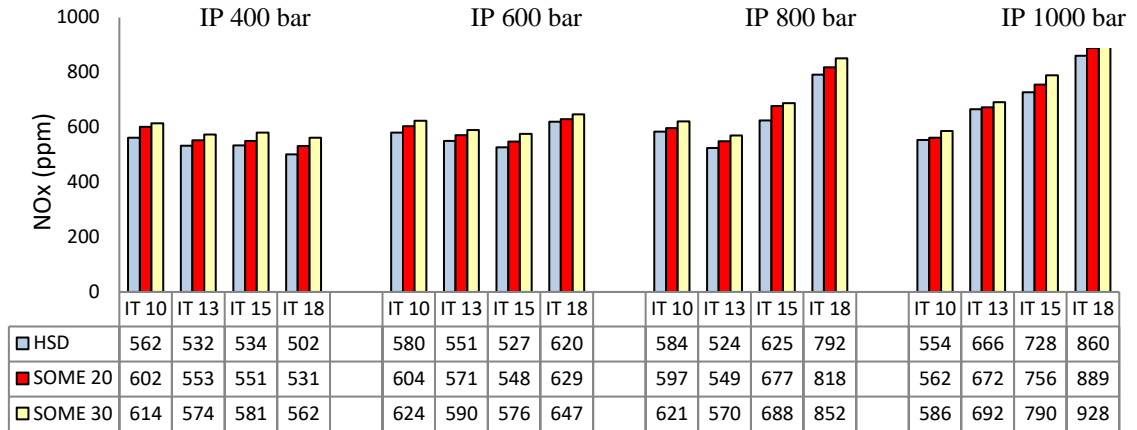


Figure 5: Influence of IP - IT on NOx for 75% load

*Smoke opacity*

The variations of the Smoke opacity with IPRs and ITGs for 75% load with SOME20, SOME30 and HSD fuel are plotted shown in Figure 6. From the figure, it is clear that as the IPR increases smoke emission decreases for the test fuel (HSD and SOME), and similar results were observed in the literature [18]. Ultra-high injection pressures lead to the reduction of soot emissions mainly attributed to better spray atomization and air entrainment [13, 23]. Increase in IPR decreases the smoke emission [18-20]. It is clear from the outcome that the smoke emission level further decreased with SOME biodiesel usage when compared to diesel fuel for each test. This is mainly due to the high oxygen content and low carbon (C) to hydrogen (H) ratio and the absence of aromatics in biodiesel [21]. A similar trend has been observed in the literature [29]. It is evident from Figure 6 that ITG also plays an important role in smoke opacity formation. Advancing ITG reduces the smoke formation while retarding ITG increases the same. Similar results are obtained in the literature [29].

At 75% load condition, the smoke emissions of SOME blends were less than that of diesel. The minimum smoke emission was found to be 29 HSU at IPR 1000 bar for ITG 18° bTDC for SOME30. While smoke of 24 HSU was given by SOME30 for full load at 800 bar-13° ITG combination, here the combustion being helped by the closeness of the fuel bound oxygen of the biodiesel in SOME blends. Moreover, the combined effect of a proper ITG and higher IPR promote a longer duration and higher temperatures throughout the expansion stroke where oxidation of the soot particles happens [21].



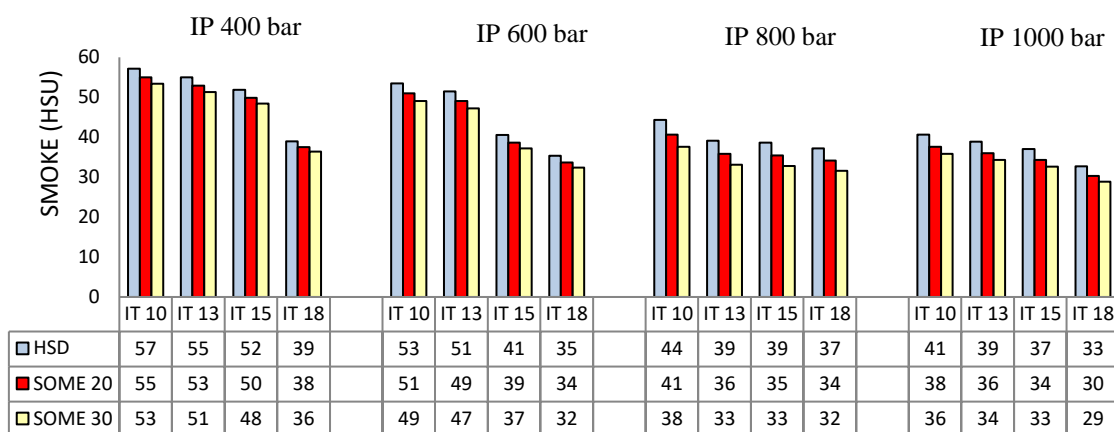


Figure 6: Influence of IP - IT on smoke opacity for 75% load.

## CONCLUSION

This paper attempts to study the influence of IPR, and ITG on the performance and emission characteristics of the CRDI engine fueled with Diesel and SOME blends, and by the outcome, the following conclusions are made.

For the given engine at 75% and full load condition, the IPR of 800 bar and ITG of 13° bTDC combination has recorded the favourable results for all fuels tested. The highest BTE with a minimum BSFC found in IPR 800 and ITG 13° bTDC combination. The NO<sub>x</sub> emission from the HSD is less than SOME blends and is found minimum at the all combinations of IPR-ITG. The smoke emissions of SOME blends are less than that of diesel for all IPRs and further decreased with increase in IPR and also with retarded ITG. A higher values of BTE obtained when BSFC was low. Further, retarding ITG decreases the NO<sub>x</sub> and increases the Smoke opacity. Hence, suitable ITG should be chosen to maintain a proper trade-off between the NO<sub>x</sub> and the Smoke opacity.

To conclude this study has shown that a proper IPR and dynamic ITG would change any engine performance and emissions. From the experimental investigation, it can be concluded that the higher IPR with the perfect ITG would enhance the biodiesel blending percentage and helps to improve the performance, and also to overcome the environmental issues with depletion problem of diesel.

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