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EXPERIMENTAL STUDIES ON PREMIXED CHARGE COMPRESSION IGNITION (PCCI) ENGINE USING PORT INJECTION OF HEATED DIESEL

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Abstract

Port fuel injection is a proven technique in gasoline engine for its simplicity and cost effectiveness. This technique is a remarkable successor to conventional carburetors in reducing emission and improving transient performance. Nowadays, port injection technique is widely researched in Homogenous Charge Compression Ignition (HCCI), Premixed Charge Compression Ignition (PCCI) and Reactivity Controlled Compression Ignition (RCCI) systems, which reduce NOx and soot emission significantly. However, usage of high viscous fuels like diesel in the above techniques has to overcome various challenges like improper vaporization, wall wetting and poor atomization. This article aims to identify the way to obtain a typical diesel spray similar to that of gasoline spray in port injection by elevating the fuel temperature and injection pressure. The results show that the diesel spray at an elevated temperature of 80°C and an injection pressure of 4 bar looked similar to that of gasoline spray (at 33°C and 3 bar). Further experimental studies on engine was performed in Diesel - PCCI mode to study the influence of heated diesel over unheated diesel spray on engine performance and emissions.

Keywords: Diesel spray, Gasoline spray, HCCI, PCCI, Heated diesel, Injection pressure.

1. Introduction

Port injection technique is widely used in gasoline engines due to its simplicity, low cost and good transient response. Only fuels having low viscosity and high volatility like gasoline can atomize and vaporize easily at low injection pressures (2 to 6 bar) of port fuel injectors [1, 2]. However, in diesel engines an in-cylinder injection pressure of about 100 to 200 MPa is used due to high viscosity of diesel and less time for fuel vaporization [3, 4].

Stringent emission norms forces the automotive manufactures to focus on new combustion techniques which can optimise engine performance as well as emissions simultaneously. At present, HCCI engine is gaining attention for its CI engine like efficiency and SI engine like emissions. Here, the port injected fuel is compressed and ignited which results in a LTC [5-7]. Being highly viscous and less volatile, diesel has become insignificant for HCCI operation [7].

Port injection follows closed valve injection strategy and has sufficient time to obtain a uniform air/fuel mixture. Generally, fuel is targeted on backside of the intake valve for better vaporization [8]. This uniform distribution reduces the formation of fuel rich regions, which reduces peak in cylinder pressure, and heat release rate that initiates NOx formation. It overcomes the usage of after treatment methods (Catalytic converter) to avoid NOx emissions in SI engines [9].

However, use of high viscous, less volatile and low saturated vapour pressure fuel (diesel) in port injection will lead to cylinder wall impingement (wall wetting) which results in poor combustion efficiency [10, 11]. An efficient fuel spray through port injection can be obtained by varying any of the spray influencing parameters like spray angle, fuel temperature and fuel injection pressure [12].

Methods like vaporizing diesel (diesel vaporizer) and NVO injection were reported in literatures for diesel port injection [13, 14]. Results obtained in the literature by using a diesel vaporizer along with EGR showed a sensible reduction in peak pressures and heat release rates [13]. NVO (early closing of the exhaust valve and late opening of the intake valve) injection of diesel showed a knocking combustion at increased load, speed and internal EGR (part of exhaust gas, which was made to stay in the cylinder due to early closing of the exhaust valve) proportions. However, use of increased external EGR proportions (part of gas extracted from the exhaust, which was cooled and supplied back to the engine along with the intake air) reported a knocking less combustion [14]. Fuel heating is also one among the technique for obtaining an efficient fuel spray. When the fuel temperature is increased, sauter mean diameter of the droplets was reported to be decreased [15]. This will improve the fuel vaporization.

This research work aims in obtaining a good fuel spray with high viscous diesel fuel in a typical port injector by heating the diesel to higher temperatures (40, 60 and 80°C). The spray images obtained during heated diesel spray were finally compared with gasoline spray since gasoline is a prominent fuel for port injection. Finally, the influence of heated diesel on engine performance was tested in Diesel -PCCI mode. PCCI is similar to HCCI where a part of charge is premixed and the rest is direct injected to achieve less NOx and soot emissions [16]. Generally, this mode of operation is limited to part loads [17]. PCCI operation at high loads will lead to knocking.

This research work on PCCI mode was performed at two loads (8 and 14Nm) and two fuel ratios of direct injected diesel to port injected diesel (65:35 and 50:50).

This fuel proportion was selected based on the inputs from previous literature. In literature, most of the combined PI-DI studies were conducted at 30 to 50% port injection proportion by mass. The influence of heated diesel port injection on performance and emissions was discussed in this article. This work will be a knowledge base for further investigations in diesel port injection with PCCI mode.

2. Spray Atomization

Spray atomization is a process of obtaining fine fuel droplets during injection. Fuel evaporation enhances with the decrease in droplet size. When the number of fuel droplets increases the surface area of the droplets decreases, which results in a better evaporation. Generally, fuel spray emerges as a sheet and separates into ligaments [18]. The separated ligament gets ruptured further into small and fine droplets as shown in Fig. 1. Atomization can be characterised by the number of droplets formed. Effective atomization will enhance the fuel evaporation, which in turn reduces the wall wetting and hydrocarbon emission [9].

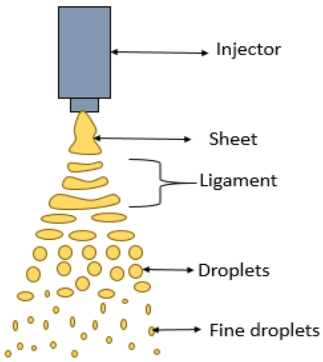

Fig. 1. Spray atomization process.

3. Experimental Setup

Experimental setup used for the spray test is as shown in Fig. 2. The spray test was performed using a Maruti Suzuki's 4 hole port fuel injector. The injector was placed vertically downwards. A pulsed fuel spray was achieved using a micro controller. The micro controller was made using an ATMEGA8L - 8PU microprocessor. To avoid direct heating of diesel, a water bath with an immersion heater was used. A fuel pump immersed in diesel was used to pump the fuel into fuel lines. Excess fuel, which escapes from injection, was taken back to the fuel tank using a fuel return line. A pressure gauge and flow control valve was placed on the fuel return line to monitor and control the fuel injection pressure. Injection pressure was varied to 3 and 4 bars using this flow control valve placed right behind the pressure gauge. A pair of power supply with 12V needed for the controller and the fuel pump was taken from a regulated power supply (RPS 32V, 6A). To obtain a clear image, the fuel spray was illuminated using a high power LED lamp. A black screen was placed behind the setup to avoid unwanted light reflections. A high-resolution camera (24.78 mega pixel) was used to capture the video of illuminated fuel spray. Finally, the video was separated to various individual frames using the frame splitter.

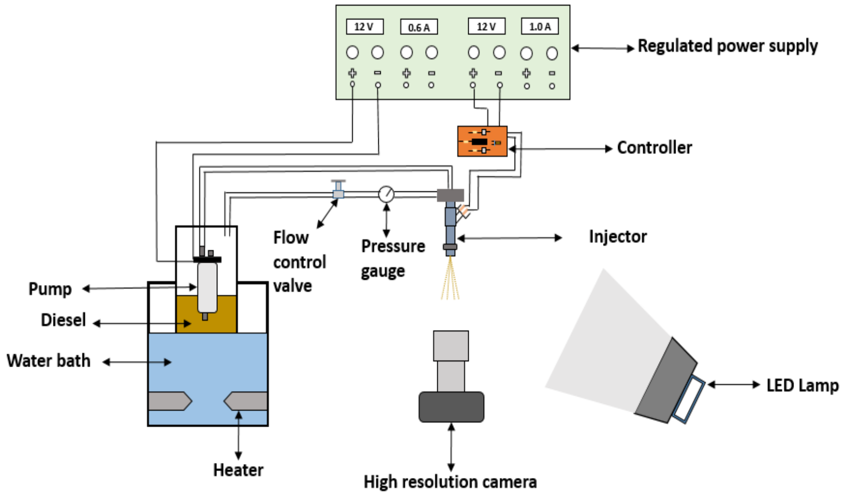

Fig. 2. Spray experimental setup.

4. Results and Discussion

4.1. Viscosity test

Viscosity test for diesel was performed to know the varying trend of diesel viscosity with temperature. At the same time, viscosity of gasoline at atmospheric temperature (33°C) was also measured for comparison. The test was performed using a redwood viscometer at five different temperatures (40, 50, 60, 70 and 80°C). Time taken (t) for collecting 50 ml diesel at different temperatures was noted. Kinematic viscosity at different temperature was then calculated using the following formula, where A and B are the redwood constants (A=0.0026 cm^2/sec^2, B=1.72 cm^2).

Kinematic viscosity = At - (B/t)

When the diesel was heated from 40 to 80°C, its viscosity was found to be decreased. This is due to decrease in intermolecular force at high temperatures, which resulted in random molecular movements. Figure 3 shows the decreasing trend of viscosity with increase in temperature.

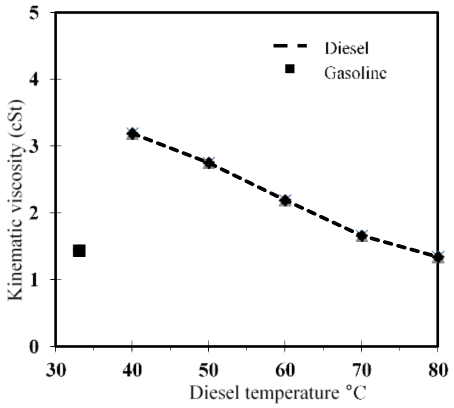

Fig. 3. Variation of diesel viscosity with fuel temperature.

4.2. Gasoline spray at 3 and 4 bar

Gasoline has a good atomization and vaporization characteristics due to its less viscosity and low flash point (-43°C). Hence the gasoline spray test was conducted without preheating. Figure 4 shows the spray images of gasoline at 3 and 4 bar injection pressures. Increase in injection pressure does not show any remarkable change. The spray was found to be well atomized with very less plumes. A similar study was reported in literature for gasoline with a 2 hole port injector at 3 bar injection pressure. The spray appeared to be well atomized and no sheets were formed during the test [2].

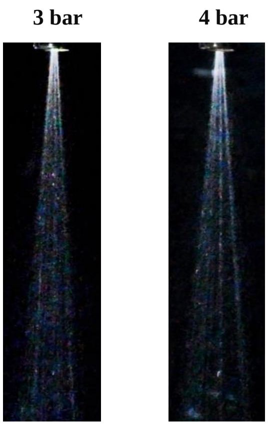

Fig. 4. Spray images of gasoline at 3 and 4 bar.

4.3. Diesel spray at 3 and 4 bar

Diesel is tested initially without any preheating to compare with normal gasoline spray. The spray through each injector hole was observed to be detached with very poor atomization and plumes. Figure 5 shows the spray images of diesel captured at 3 and 4 bar injection pressure and at atmospheric temperature. The spray had a wide spray angle, which is 4.5 to 6.5° greater, when compared with gasoline. This kind of spray will result in cylinder wall impingement and poor combustion efficiency. Increasing the injection pressure form 3 to 4 bar resulted in a slightly improved atomization at the spray tip.

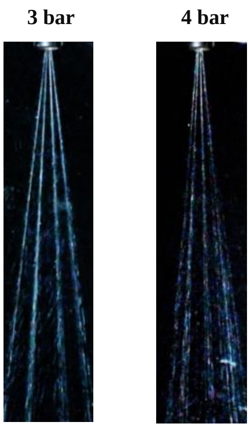

Fig. 5. Spray images at of diesel at 3 and 4 bar.

4.4. Heated diesel spray

At 40°C, diesel spray appeared to be similar with the spray obtained at atmospheric temperature, but the spray cone angle was decreased by 1°. Increase in injection pressure from 3 to 4 bar showed a slightly improved atomization at the spray tip as shown in Fig. 6(a).

At 60°C the spray looked little feeble than the spray obtained at 40°C. Increase in injection pressure from 3 to 4 bar does not show any remarkable improvement. When compared with gasoline, this spray had poor atomization. Figure 6(b) shows the spray images obtained at 60°C.

Diesel spray at 80°C showed a better atomization than any other diesel sprays. At 4 bar the spray looked almost similar to that of gasoline spray at 3 bar. Spray angle obtained at 3 and 4 bar injection pressure remained same and 1° greater than that of gasoline spray. This spray could improve the combustion efficiency of port injected HCCI diesel engine by reducing cylinder wall impingement. Figure 6(c) shows the spray images obtained at 80°C.

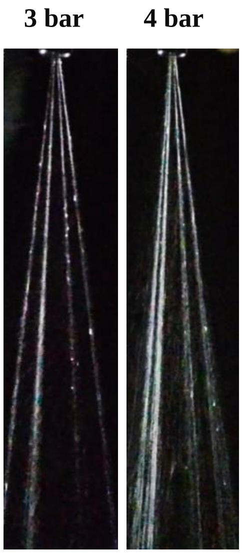

Fig 6(a). Spray image of gasoline at 40°C.

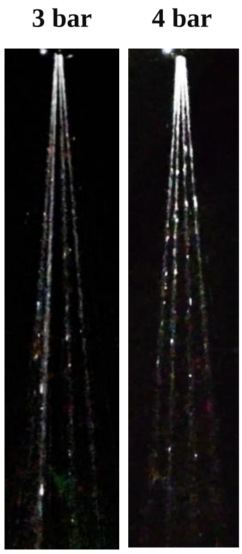

Fig 6(b). Spray image of gasoline at 60°C.

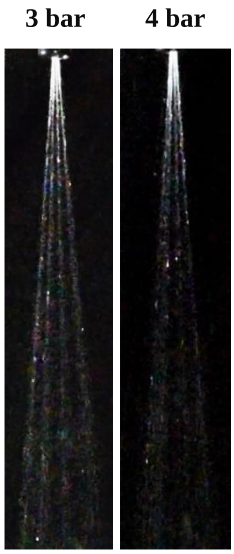

Fig 6(c). Spray image of gasoline at 80°C.

4.5. Diesel spray cone angle variation with temperature, viscosity and injection pressure

Spray cone angle is measured in between the two straight lines formed from the nozzle tip on the outer surface of the spray [19]. Spray cone angle and injection pressure has an inverse relation with drop size. In case of diesel, viscosity played major role in diesel atomization than injection pressure and spray angle. Here, increase in injection pressure has decreased the spray cone angle and larger spray cone angles showed poor atomization. Table 1 shows the spray cone angle obtained for diesel and gasoline at different conditions.

Table 1. Variation of spray cone angle at different fuel temperature and injection pressure.

Fuel	Temperature	Pressure	Spray cone angle
Gasoline	Atmospheric temp (33°C)	3 bar	7.5°
		4 bar	7.5°
Diesel	Atmospheric temp (33°C)	3 bar	14°
		4 bar	12°
	40°C	3 bar	13°
		4 bar	11°
	60°C	3 bar	8°
		4 bar	7°
	80°C	3 bar	8.5°
		4 bar	8.5°

Normally, when injection pressure increases the spray angle increases [1, 2]. In the above case, the spray angle was found to decrease with increase in injection pressure. This trend continued until the diesel temperature was 60°C. When the diesel temperature was 80°C the angle remained same for both 3 and 4 bar. Figure 7 shows the variation of spray cone angle at different temperatures and pressures.

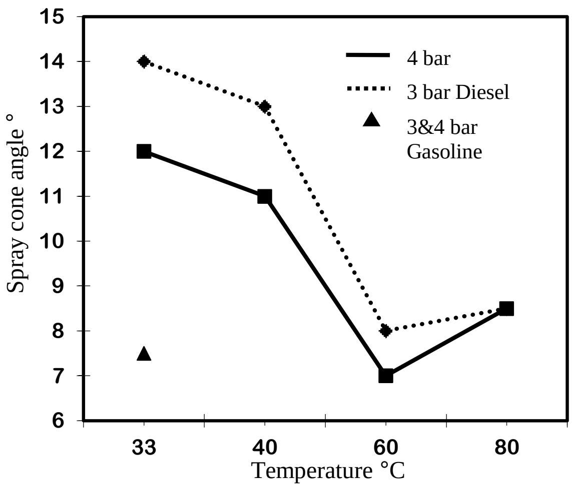

Fig. 7. Variation of spray cone angle with fuel temperature.

The trend of increasing spray angle with an increase in injection pressure does not work out for high viscous fluids at low temperatures. When diesel temperature was increased to 80°C, the spray angle shows an increasing trend with an increase in injection pressure.

This trend of increasing spray angle with the decrease in diesel viscosity showed good atomization and vaporisation by resembling similar to the gasoline spray. This sign of improved diesel spray in a typical port injector adds advantage to further investigations on diesel port injection.

4.6. Experiments in CI engine with PCCI mode

The results obtained in the spray test was used as a base for conducting experiments in the engine. A single cylinder direct injected diesel engine was chosen for the test. The specifications of the engine are given in Table 2.

Table 2. Engine specifications.

Engine Parameter	Description
Bore * Stroke	87.5 * 80mm
Volume	500cc
Compression ratio	17 :1
Brake horse power	8 hp
Rated speed	2200 rpm

The existing engine cylinder head was modified by placing a port injector at the intake port for the experimental analysis as shown in Fig. 8. The injector was kept inclined at 60º to the horizontal surface to target the backside of intake valve. An ATmega328 microcontroller was used to obtain different port injected fuel proportion by controlling the pulse width of the port injector. The Hall Effect sensor mounted at the camshaft was used to trigger the injector to spray the fuel. A water bath heating technique was used to heat the fuel to required temperatures.

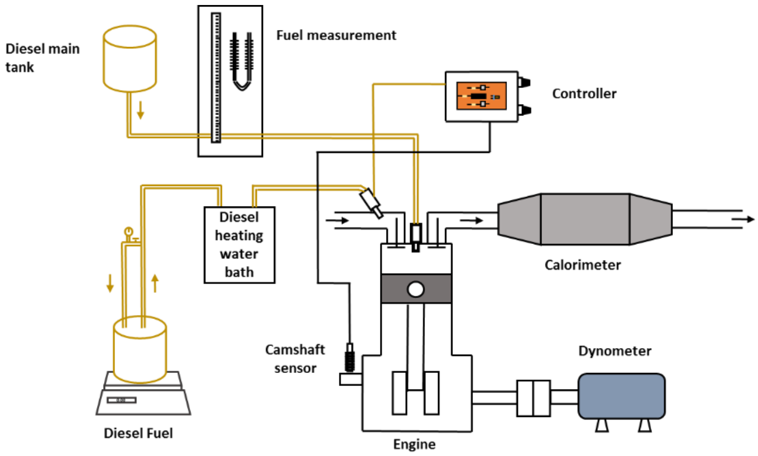

Fig. 8. Engine experimental setup.

The test was conducted for two different load cases. In the first case, the load was kept constant at 8 Nm and the port injected fuel proportion was retained at 35% and 50%. In the second case the load was kept at 14 Nm and port injected fuel proportion was retained at 35% and 50%. In both cases, the port injected diesel was heated to 40, 60 and 80°C to determine the effect of heating the diesel. The engine speed was kept at 1900 rpm throughout the test. The intake air temperature was kept at the atmospheric temperature. The injection timing and injection pulse width of diesel was determined using Hall Effect sensor and the controller (ATmega328). It was programmed to actuate the injector when the inlet valve remains open. The diesel port injection proportion was controlled using the potentiometer in the circuit, which varies the injection pulse width with the change in resistance. The circuit was programmed to increase or decrease the injection pulse width using the potentiometer manually to keep the port injected fuel proportion constant in 35% and 50% at different loads.

4.6.1. Thermal efficiency

Thermal efficiency is an output parameter that relates to the performance of an engine and defines how effectively the input fuel energy was converted to work. Increasing the temperature of diesel showed slight improvements in thermal efficiency when compared to the diesel at room temperature. Figures 9(a) and (b) show the variation of thermal efficiency with respect to diesel temperature taken at loads 8 and 14 Nm respectively.

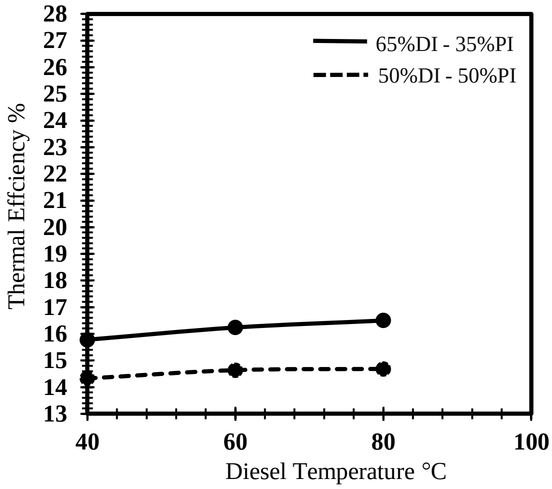

Fig. 9(a). Variation of thermal efficiency with diesel temperature at 8 Nm load.

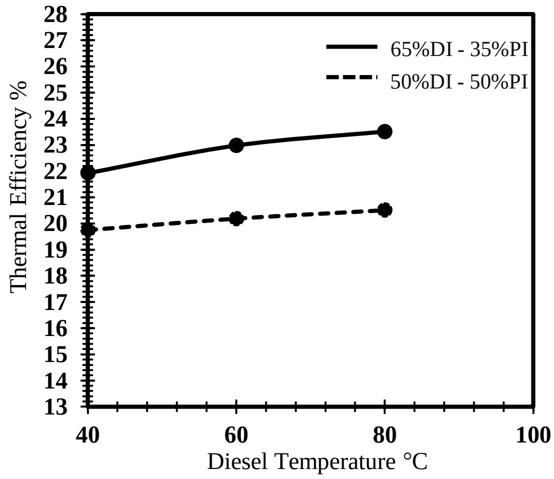

Fig. 9(b). Variation of thermal efficiency with diesel temperature at 14 Nm load.

Increase in thermal efficiency by heating diesel from 40 to 80ºC at 8 Nm and 35% diesel port injection was comparable. However, the increase in thermal efficiency by heating diesel from 40 to 80°C at 14 Nm was about 1.58% absolute. This value was beyond the uncertainty range of thermal efficiency, which is ±0.87%. It can be concluded that at high loads heated diesel with 35% proportion injected through port is beneficial in improving efficiency when compared to diesel at room temperature. No major significant improvements in efficiency were observed with 50% port injection with heated diesel and diesel without heating.

4.6.2. NOx emission

NOx emissions are formed as a result of high in cylinder temperature in CI engines [20]. Figures 10(a) and (b) show the variation of NOx emissions with diesel temperature. Increasing the diesel temperature increases NOx formation. This is due to better atomization and vaporisation of diesel, which results in a better combustion. This facilitates high NOx formation at elevated fuel temperatures. The increase in NOx emission was significant only when the diesel temperature is increased from 40 to 60ºC. The increase was found to be 70 - 90 ppm in case of 8 Nm load and around 190 ppm in case of 14 Nm load. Increase in diesel temperature from 60 to 80°C does not show any significant difference in NOx emissions.

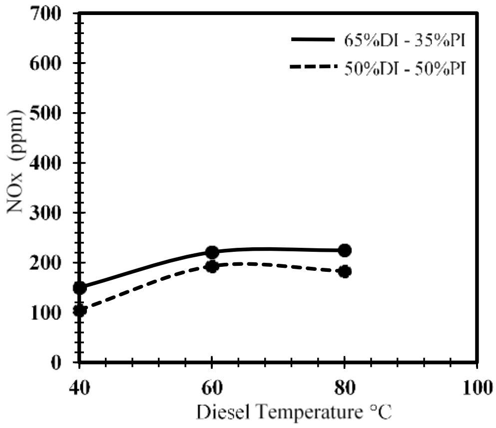

Fig. 10(a). Variation of NOx with diesel temperature at 8 Nm load.

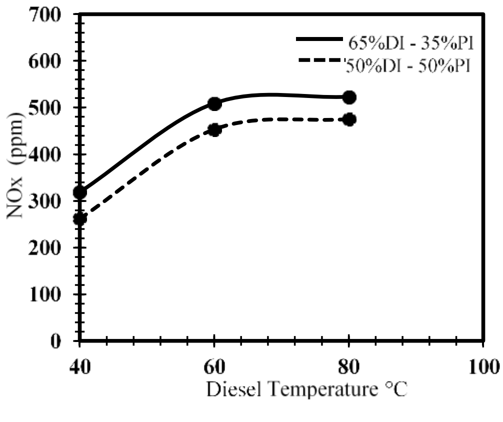

Fig. 10(b). Variation of NOx with diesel temperature at 14 Nm load.

Changing the port injected fuel proportion showed significant difference NOx emissions. Increasing the port injected fuel proportion from 35 to 50% resulted in a decrease in NOx around 30 to 50 ppm at 8 Nm load and around 45 to 60 ppm at 14 Nm load.

Varying the engine load have also resulted a significant difference in NOx emissions. NOx emissions are found to be high at 14 Nm when compared to 8 Nm. Generally, when load increases brake thermal efficiency increases in case of CI engines. Increase in thermal efficiency at 14 Nm results in an increase in in-cylinder temperature, which increases the NOx formation.

4.6.3. HC emission

Generally, HC emissions are produced as a result of in incomplete combustion. When diesel is heated from 40 to 80ºC the HC emissions showed a decreasing trend. This may be due to the better atomization and evaporation of diesel by heating the diesel. Better evaporation helps to enhance combustion, which results in low HC emissions. Figures 11(a) and (b) shows the variation of HC emissions with diesel temperature at 8 and 14 Nm respectively.

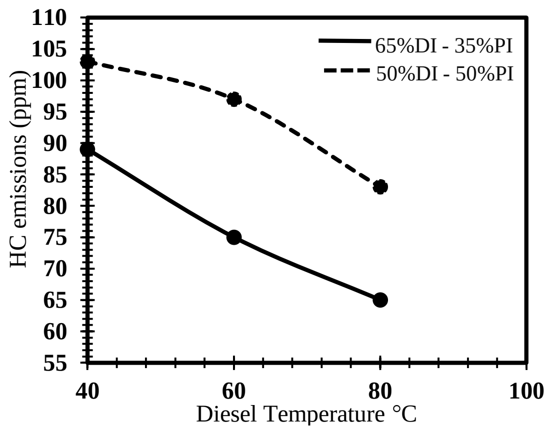

Fig. 11(a). Variation of HC emissions with diesel temperature at 8 Nm load.

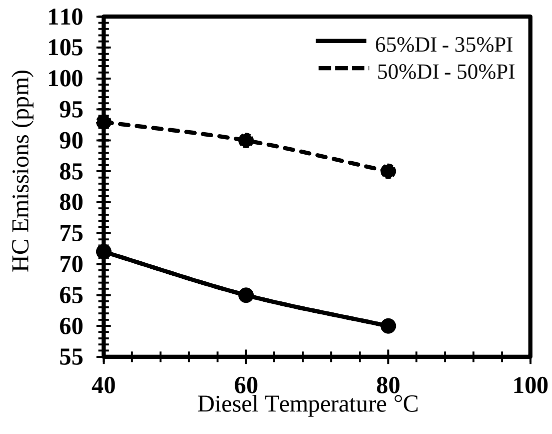

Fig. 11(b). Variation of HC emissions with diesel temperature at 14 Nm load.

The HC emission was found to be decreased around 20 ppm when diesel is heated from 40 to 80ºC at 8 Nm load. However, increasing the port injected fuel proportion from 35% to 50% showed an increase in HC emissions around 15 to 25 ppm. Generally, when the charge is premixed it results in an LTC. Increasing the port injection proportion promotes LTC, which results in high HC emissions at increased diesel port injection [13].

In case of 14 Nm load the decrease in HC emission by heating diesel was around 8 - 12 ppm. This decrease in HC was less when compared to the decrease at 8 Nm load. Increasing the port injected fuel proportion from 35% to 50% increased the HC emissions around 20 to 25 ppm.

4.6.4. CO emission

Carbon monoxide (CO) is a by-product of partial combustion. CO emissions are formed when the intake charge becomes rich (λ <1) [6]. Generally, the diesel engines have lean air-fuel mixture, which means the air/fuel ratio (λ) will be greater than 1. In the present study, the port injection of diesel causes the air/fuel ratio (λ) to decrease which results in high CO emissions. However, heating of port injected diesel to high temperatures has caused the CO emissions to decrease when compared to unheated diesel. Figures 12(a) and (b) show the variation of CO emissions with diesel temperature at 8 and 14 Nm respectively.

Increasing diesel temperature from 40 to 80°C has decreased the CO emissions around 0.04 to 0.07% at 8 Nm load. The CO emission in case of 50 % diesel port injection was found to be high when compared to 35% diesel port injection. This is because increasing port injected fuel proportion makes the intake charge even richer, which increases the CO emissions.

In case of 14 Nm load the CO emissions was comparable for all the diesel temperatures. The increase in diesel temperature did not influence the CO emissions much at high load.

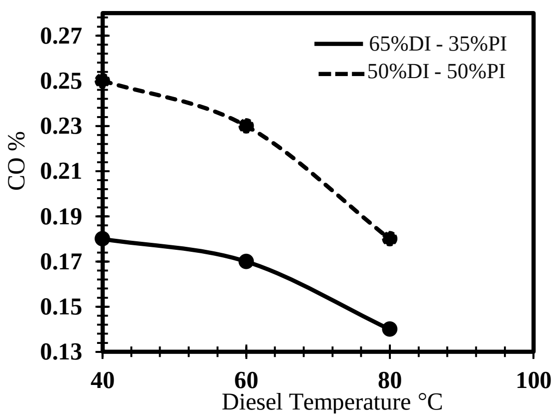

Fig. 12(a). Variation of CO emissions with diesel temperature at 8 Nm load.

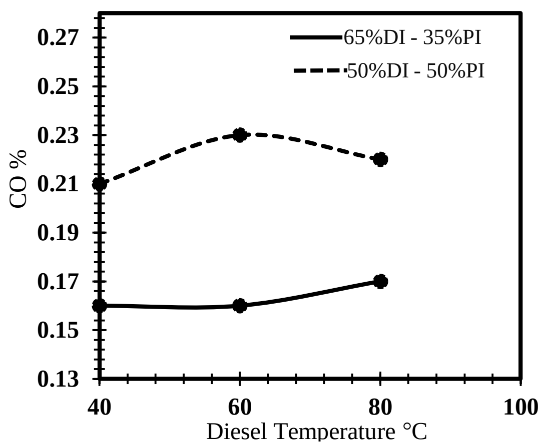

Fig. 12(b). Variation of CO emissions with diesel temperature at 14 Nm load.

4.6.5. CO_2 emission

Carbon dioxide is a by-product of complete combustion. A slight increase in the CO_2 emission was observed with the increase in diesel temperature. An increase in diesel temperature will improve the atomisation and vaporisation of port injected diesel that results in an increase in CO_2 emissions. Figure 13 shows the variation of CO_2 emissions with diesel temperature at 8 and 14 Nm respectively.

A slight increase in CO_2 emissions was observed when the diesel temperature is increased from 40 to 80ºC at 8 Nm load. The increase was around 0.3 to 0.5% for both the port injected diesel proportions.

In case of 14 Nm load the CO_2 emissions were found to be high when compared to 8 Nm load. This could be due to the increased thermal efficiency at 14 Nm load which increases the CO_2 emissions The increase in diesel temperature showed similar CO_2 emissions for 35 % port injected diesel. In case 50% port injected diesel the CO_2 emissions was increased around 0.45% with increase in diesel temperature.

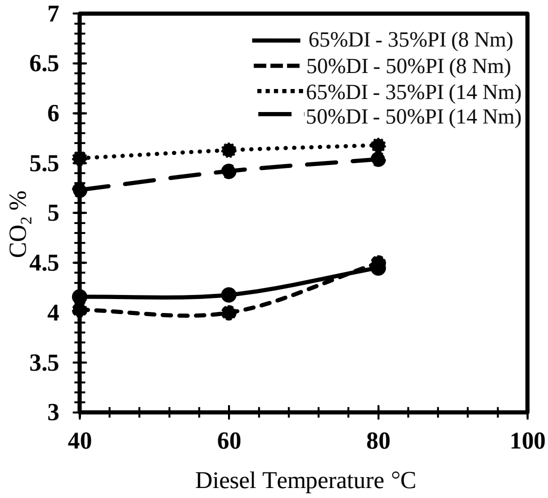

Fig. 13. Variation of CO_2 emissions with diesel temperature at 8 Nm and 14 Nm load.

5. Conclusions and Future work

This research work on diesel heating with PCCI mode has resulted significant results in performance and emission. Following conclusions were obtained from this work.

- Increasing the fuel temperature to 80°C, reduced the diesel viscosity below 1.5 cSt. Spray cone angle of diesel spray decreases with increase in injection pressure from 3 to 4 bar at low temperatures (40 and 60°C).
- It is confirmed by visualisation of diesel spray, increasing the injection pressure from 3 to 4 bar effectively improved the spray atomization at elevated temperatures of diesel.
- A better diesel spray resembling the gasoline spray was obtained at a fuel temperature of 80°C and an injection pressure of 4 bar.
- Significant improvement in thermal efficiency was observed at high loads with 35% proportion of diesel injected through port using PCCI mode.
- HC and CO emissions showed a significant decrease with increase in port injected diesel temperature.
- NOx emission showed an increasing trend with increase in diesel temperature form 40 to 60°C.

Overall, simultaneously increasing the injection pressure and diesel temperature could lead to better spray formation in a port injector, which resembles to gasoline spray. Increasing port injected diesel temperature at PCCI mode showed improvements in thermal efficiency, decrease in CO and HC emissions and increase in NOx emission.

This work can be further extended to conduct Diesel PCCI and HCCI studies in CI engine. It can also be used to conduct RCCI studies that requires port injection of high reactive fuels like diesel.

Abbreviations

CI	Compression Ignition.
DI	Direct Injection
EGR	Exhaust Gas Recirculation.
HCCI	Homogeneous Charge Compression Ignition
LTC	Low Temperature Combustion
NVO	Negative Valve Overlap
PCCI	Pre mixed Charge Compression Ignition
RCCI	Reactivity Controlled Compression Ignition
PI	Port Injection
RPS	Regulated Power Supply
SI	Spark Ignition

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