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Effect of Hydrogen Flow Rates on the Performance of CNG-Biodiesel Fueled Dual Fuel Engines

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Abstract
Experimental investigations were conducted on a single-cylinder four-stroke water cooled direct injection (DI) compression ignition (CI) engine operating in dual fuel mode using diesel/Honge oil methyl ester (HOME) as injected fuels and varying hydrogen percentage in CNG gas combinations. Percentage of hydrogen in CNG was varied from 5 to 20% in steps of 5% and the resulting mixture was inducted into the engine manifold through a mixing device suitably developed in-house. Results showed a considerable improvement in brake thermal efficiency with reduced smoke, hydrocarbon (HC), carbon monoxide (CO) emissions and marginally increased nitric oxide (NOx) emission levels with increased hydrogen flow rates. Furthermore, the ignition delay, combustion duration, pressure-crank angle and heat release rate were analyzed and compared with base data. Combustion analysis showed that the rapid rate of burning of CNG-air mixture with the increased addition of hydrogen resulted in higher cylinder pressure and energy release rates. Hydrogen blended with CNG enabled leaner operation and showed an improvement in overall performance and environmental benefit.

Key Word and Phrases
Honge Oil Methyl Ester (HOME), Compressed Natural Gas (CNG), Hydrogen, Emissions, Carburetor.

1. Introduction

Diesel engines are becoming more and more popular because of their higher brake thermal efficiency, power, reliability, and durability. Hence, diesel engine technology plays a vital role in transport, agricultural and power generation applications. By the present energy scenario, life of conventional fossil fuels has become limited, while the demand for energy is growing at a faster rate. Due to rapid depletion of conventional fuels, increasing prices of crude petroleum and stringent environmental legislations, use of environment friendly fuels (biofuels) in partial or complete replacement for diesel engine applications is the need of the hour. The fossil fuels reserve depletion times for oil, coal and gas will be there for maximum of 35, 107 and 37 years, respectively [1]. In this regard, India and rest of the world have recommended many energy policies for their control and restriction. Therefore, energy conservation with high efficiency and low emission are important research topics for engine design and development. Some cities in India and various parts of the world are reaching epidemically poor air quality limits and need an immediate remedy to environment destruction caused by burning of fuels.

Biofuels provides both an environmental benefit and, in most markets a cheaper fuel than refined petroleum products. This compensates economically over the vehicle’s lifetime for the additional cost of the equipment. In view of this, several researchers have made an attempt to utilize different biofuels and gaseous fuels such as compressed natural gas (CNG), liquefied petroleum gas (LPG), hydrogen. They reported that use of these biofuels resulted in low, same or high performance compared to diesel operation. Biofuels are becoming more and more important in the present energy scenario since they have numerous advantages compared to fossil fuels as they are renewable and biodegradable besides providing energy security and foreign exchange saving, addressing environmental concerns, and socio-economic issues as well. Therefore renewable fuels are sustainable in nature and can be predominantly used as fuel for transportation and power generation applications [2]. Many investigators have studied the effect of various engine and operating parameters on the performance and emission characteristics of diesel engine operating in single fuel mode using biodiesels of different origin. Increased compression ratio and advancing the injection timing resulted in better engine performance. Several researchers have been directed towards the development of alternative fueled engines to achieve specific goals [3], [4], [5], [6].

Biodiesel improves fuel lubricity and raises the cetane number of the fuel. Such liquid fuels can also be used as injected fuels in diesel engines operating in dual fuel mode. Shifting from single fuel mode of operation to dual fuel mode is one way to reduce the liquid fuel usage. Employing biodiesel and CNG in dual fuel mode is an attractive option for India as our country is basically agriculture based and therefore, biodiesel can be used conveniently in a dual fuel technology and can ease the burden on the economy by curtailing the crude petroleum imports. However, dual fuel engines suffers from lower volumetric efficiency and increased ignition delay, hence the use of biodiesel as injected fuel, lowers the drawbacks of the use of gaseous fuel in dual fuel mode. In this context, clean burning and carbon free gaseous fuel, has attracted great interest and has huge potential. CNG as a fuel has been considered as a proven alternative to the conventional fuelled engines. It is most widely used in dual fuel applications. In diesel engines, use of CNG in dual fuel mode results in higher HC/CO emissions with lower power output compared to diesel operation. This problem can be improved by Hydrogen addition to CNG called HCNG, which burns cooler than CNG resulting in higher power and lower exhaust gas temperatures (EGT) depending on the mixture ratio. Fundamental studies suggest that non-premixed flame stability is enhanced and improved by mixing with hydrogen addition [1].

However, Natural gas has a slow flame speed, and can be improved by hydrogen addition. CNG and H_2 cannot be directly used alone in diesel engines because of their lower cetane number and higher self-ignition temperature (858 K), but can be used in the dual fuel mode [7], [8]. The burning velocity of hydrogen is being six times higher than gasoline favours faster combustion [9]. The high flammability range of hydrogen ($0.1<Ø<7.1$), shows that engines run on hydrogen can operate stably under highly dilute conditions, allowing better performance with reduced emission levels and fuel consumption. Recent studies show that desirable combustion properties of blend of CNG and hydrogen or alone make it most likely candidate to eventually replace petroleum fuels. It has been observed from published literatures that CNG blended with hydrogen (H_2-CNG), leads to improved performance. Hydrogen is an excellent additive in relatively small concentrations, to some common fuels such as methane. Hydrogen has long been recognized as a fuel having some unique and highly desirable properties for application to engines [9], [10]. The concept of using hydrogen as an alternative fuel for diesel engines is recent. H_2 can be supplied in the engine by carburetion, manifold or port injection or by cylinder injection [11], [12]. However, the injection of H_2 in the intake manifold or port requires a minor modification in the engine and offers a better power output than carburetion.

Several researchers have carried out experiments on continuous carburetion, continuous manifold injection, timed manifold injection and low pressure direct cylinder injection [8], [11], [12], [13]. The maximum brake thermal efficiency of 31.32% was obtained at 2200 rpm with 13 Nm torque. In general, it is found that HC, CO_2, and CO emissions decreases with increasing volume of H_2, but oxides of nitrogen (NO_x) emissions generally increase. If a catalytic converter is used, NO_x emission values can be decreased to extremely low levels. Experiments on a diesel and natural gas fueled dual-fuel single-cylinder diesel engine, indicated that the ignition delay of diesel-NG dual-fuel operation was extended than normal diesel operation. The peak heat release rate and cylinder pressure decreased with the increase of NG addition at low to medium load but increased at higher load due to the fast burning rate of diesel-NG operated combustion. Drastically increase of CO/HC as well as decrease of particulate became the trade-off effect for diesel-NG dual-fuel engine [14]. Hydrogen addition reduces the equivalence ratio at lean limit of combustion of natural gas without increasing combustion duration, which results in higher brake thermal efficiencies and lower emission levels. Moreover, hydrogen addition shows some improvement in BMEP [10]. Besides reducing green house gases and atmospheric pollutants, hydrogen enrichment of natural gas also enhances combustion characteristics of the engine [6], [7], [10]. With a lesser pilot quantity of diesel, hydrogen-enriched engines give higher brake thermal efficiency with smoother combustion than a diesel engine. Increasing hydrogen beyond a certain quantity results in knocking; at the highest diesel flow rate, brake thermal efficiency is found to be the same as that of diesel engines. Hence, the overall behavior of the engine is similar to that of a diesel engine. Hydrogen is a useful additive for natural gas that enables leaner operation under part load conditions and improves BMEP at wide open throttle near the lean limit. Moreover, NOx values were reduced; if normal hydrocarbon emissions or fuel consumption observed with natural gas are not exceeded[33]. Fuel efficiency of the H-CNG fueled engine is about 20 to 25% higher than that of CNG engine [15]. Hydrogen has higher flame speed than natural gas; therefore, the equivalence ratio is much higher than the stoichiometric condition, the combustion of methane is not as stable as with a blend of H_2-CNG [15].

The liquid fuel-CNG-hydrogen dual-fuel combustion process in a diesel engine was investigated by [11], [12], [16], [17]. Literatures were stated that brake thermal efficiency of intake port injection is clearly higher than in-cylinder injection at all equivalence ratios [14]. Improved efficiency has been reported with intake port injection compared to in-cylinder injection at different equivalence ratios [18] [19] showed highest brake thermal efficiency of 30% at a compression ratio of 24.5. Dual fuelengine using Hydrogen along with diesel injection to study performance of dual injection hydrogen fueled engine by using solenoid in-cylinder injection and external fuel injection technique has been reported [20]. An increase in brake thermal efficiency by about 22% was noted for dual injection at low loads and 5% at high loads compared to direct injection. Researchers suggested that in dual injection, the stability and maximum power could be obtained by direct injection of hydrogen. However the maximum efficiency could be obtained by the external mixture formation in hydrogen engine. Literatures on hydrogen fueled engine showed that, H_2 -diesel dual fuel mode with 90% enriched H_2 gives higher efficiency, but cannot complete the load range beyond that due to knocking problems [20]. However, drop in brake thermal efficiency was reported when the amount of H_2 is less than or equal to 5%. It could be attributed to reduced flame propagation [21]. In gasoline fueled engines, knock limits associated with mixtures containing different percentages of H_2 and CH_4 was investigated by [29], [30]. Experimental studies using 100/0, 90/10, 80/20, 70/30, 60/40, 50/50, 40/60, 30/70 and 20/80 CH_4-H_2 proportions by varying equivalence ratios was investigated by [22], [23]. They investigated initiation speed (m/s), power output difference, indicated output efficiency, ignition lag, combustion duration (◦CA), maximum cylinder pressure, knocking regions in different proportions of H_2 and CH_4 percentage, at different equivalence ratios and different injection timings (10◦; 20◦; 30◦ bTDC).

Increased power output has been reported with increasing concentration of hydrogen in the engine at 20°bTDC and with the increasing concentration of hydrogen in the engine, at 30◦bTDC, power output decreased. If some amount of hydrogen was added to the methane as a fuel for the SI engine, performance characteristics of the engine increased drastically. Effect of various engine speeds and equivalence ratios on combustion of a hydrogen blended gasoline engine and found that the combustion duration decreased with the increase of hydrogen blending fraction.[24]. Hydrogen addition during combustion reduces cyclic variation [25]. Some investigators have reported that introduction of hydrogen into the diesel engine causes the energy release rate to increase at the early stages of combustion, which increases the indicated efficiency. This is also the reason for the lowered exhaust temperature. According to them, for fixed H_2 supply at 50%, 75% and 100% load, H_2 replaces 13.4%, 10.1% and 8.4% energy respectively with high diffusive speed and high energy release rate[26]. Further study on hydrogen fueled engine has been carried out by [27]. Combustion efficiency and power output was dependent on engine load and amount of hydrogen addition. They have reported that peak cylinder pressure was higher when the engine load was above 70% and this effect should be limited for safety due to knocking tendency of engine. However, it was mentioned that combustion efficiency of hydrogen was lower when small amount of hydrogen was inducted.

In this context, experiments were conducted on a single-cylinder four-stroke water-cooled DI diesel engine operated in dual-fuel mode with Honge oil methyl ester (HOME) and blends of CNG/H_2 induction at optimized engine parameters, and the results were analyzed and compared with base line data.

2. Fuel Properties

The properties of Honge oil and HOME were determined and are summarized in Table 1. Table 2 presents the properties of the gaseous fuels, namely CNG and HCNG, respectively.

Table 1 Properties of Fuels Used

Sl. No.	Properties	Diesel	Honge oil	HOME
1	Chemical Formula	$C_{13}H_{24}$	----	----
2	Density (kg/m^3)	840	915	880
3	Calorific value (kJ/kg)	43,000	35800	36,010
4	Viscosity at 40^{o}C (cSt*)	2-5	44.85	5.5
5	Flashpoint (^{o}C)	75	210	167
6	Cetane Number	45-55	40	45
7	Carbon Residue (%)	0.1	0.66	----
8	Cloud point	-2	----	7
9	Pour point	-5	----	4
10	Carbon residue	0.13	0.55	0.01
11	Molecular weight	181		227
12	Auto ignition temperature (^{o}C)	260		470
13	Ash content % by mass	0.57		0.01
14	Oxidation stability	High	Low	Low
15	Sulphur Content	High	No	No

(*Centistokes)

Table 2 Properties of CNG, and HCNG

Sl. No	Properties	CNG	HCNG
1	Density of Liquid at 15^{o}C, kg/ m^3	0.77	---
3	Boiling Point, K	147 K	---
4	Lower calorific value, kJ/kg	48000	47170
5	Limits of Flammability in air, vol. %	5-15	5 - 35
6	Auto Ignition Temp, K	813	825
7	Theoretical Max flame Temp, K	2148	2210
8	Flash point ^{0}C	124	---
9	Octane number	130	---
10	Burning velocity, cm/sec	45	110
11	Stoichiometric A/F, kg of air/kg of fuel	17:1	----
12	Flame temperature, ^{0}C	---	1927
13	Equivalence ratio	0.7-4 0	0.5 - 5.4

3. Experimental Set-up

The experimental set-up used for CNG and HCNG-operated dual-fuel engines is shown in Figure 1. Engine tests were conducted on a four-stroke single cylinder water-cooled DI compression ignition engine with a displacement volume of 662 cc, compression ratio of 17.5:1 and developing power of 5.2 kW at 1500 rev/min. The engine was always operated at a rated speed of 1500 rev/min. This engine had a conventional fuel injection system. The injector opening pressure and the static injection timing as specified by the manufacturer were 205 bar and 23^o before Top Dead Centre (BTDC), respectively. The engine is provided with a governor and it maintains a constant engine speed at all the loads on the engine. The governor of the engine was used to control the engine speed. The engine was provided with a hemispherical combustion chamber with overhead valves operated through push rods. Cooling of the engine was accomplished by circulating water through the jackets on the engine block and cylinder head. A piezoelectric pressure transducer was mounted on the cylinder head surface to measure the cylinder pressure. Table 3 shows the specification of the engine used for the study. Exhaust gas analyzer and Hartridge smoke meter were used to measure HC, CO, NO_x and smoke emissions.

Fig.1 Experimantal set-up

Table 3 Specifications of the CI engine.

Sl No	Parameters	Specification
2	Type	TV1 (Kirlosker make)
3	Software used	Engine soft
4	Nozzle opening pressure	200 to 225 bar
5	Governor type	Mechanical centrifugal type
6	No of cylinders	Single cylinder
7	No of strokes	Four stroke
8	Fuel	H. S. Diesel
9	Rated power	5.2 kW (7 HP at 1500 RPM)
10	Cylinder diameter (Bore)	0.0875 m
11	Stroke length	0.11 m
12	Compression ratio	17.5 : 1
Air Measurement Manometer:		
13	Made	MX 201
14	Type	U- Type
15	Range	100 – 0 – 100 mm
Eddy current dynamometer:		
16	Model	AG – 10
17	Type	Eddy current
18	Maximum	7.5 (kW at 1500 to 3000 RPM)
19	Flow	Water must flow through Dynamometer during the use
20	Dynamometer arm length	0.180 m
21	Fuel measuring unit – Range	0 to 50 ml

4. Results and Discussions

This section presents the results of experimental investigations carried out on a diesel engine suitably modified to operate in dual fuel mode. During the complete experimentation, the gas flow rate was maintained constant and engine speed was maintained at 1500 rpm. Two carburetors were developed with 12 holes having 3 and 6 mm orifices to ensure stoichiometric air-gas mixture to be supplied to the engine. The carburetor with 6 mm orifice ensured near static stoichiometric air-gas mixture and is used for the study presented. The flow rates of both CNG and HCNG were varied from 0.25 -0.75 kg/hr in steps of 0.25 kg/h in order compare their performance in dual fuel engine. The liquid fuel of HOME/JOME was used as injected fuels.

4.1 Effect of Hydrogen/CNG Flow Rates on the Performance of Dual Fuel Engine

4.1.1 Performance Characteristics

The variation of brake thermal efficiency (BTE) with different flow rate of CNG and HCNG for dual fuel combinations is shown in Figure 2. Increasing the CNG and HCNG flow rates resulted into decreased BTE and this could be due to availability of stronger ignition source and also due to increased temperature, which reduces substantially gaseous fuel escaping combustion. As the gas flow rates increased from 0.25 to 0.75 kg/h, the BTE decreased at higher loads as the addition of CNG, HCNG to the intake air reduces the volumetric efficiency. At higher liquid fuel pilot quantities CNG fuel utilization improves. The BTE for Diesel/biodiesel-HCNG combination resulted in higher BTE compared to CNG operation. This could be due to higher calorific value of HCNG and flame velocity compared to CNG. The presence of hydrogen allows the lean burn limit to be influences the reduction in loss by high combustion temperature and heat transfer; hence, the brake thermal efficiency was improved. The fast burn rate of hydrogen causes the combustion duration to decrease while the heat release rate and exhaust NOx increase with an increase, percentage of hydrogen [28], [29]. The lower viscosity and higher calorific value of the diesel along with the two gaseous fuel combinations performed better compared to two injected biodiesels. For the two biodiesels considered HOME–HCNG combination resulted in slightly higher BTE compared to JOME-HCNG and HOME/JOME-CNG combinations. The reasons could be the lower fatty acid composition of HOME compared to JOME.

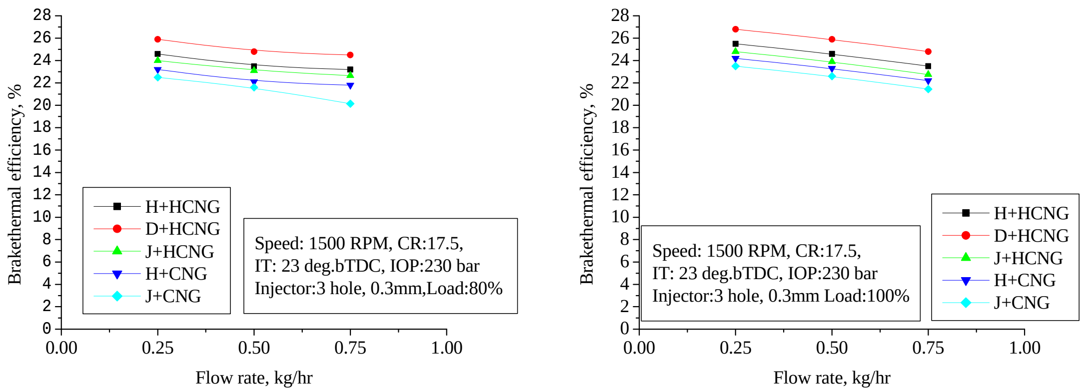

Fig. 2 Variation of brake thermal efficiency with flow rate

4.1.2 Emission Characteristics

The variations of smoke opacity for HOME/JOME–CNG and diesel/HOME/JOME–HCNG operation with respect to higher loads are presented in Figure 3. Increased gaseous flow rates decrease the smoke density and this could be due to better combustion of the fuel- air quantities. A decreased trend of smoke was observed with higher CNG and HCNG flow rates and this could be due to increased temperature of the gases inside the cylinder which favours the soot oxidation rate leading to a further decrease of soot. However smoke density marginally increases as the gaseous fuel flow rate is increased and the air inducted in to the cylinder at higher loads resulting into incomplete combustion. Gases of CNG and Hydrogen being common, properties of biodiesels injected resulted in higher smoke opacity compared to diesel. It is mainly due to heavier molecular structure and higher viscosity of the respective biodiesels which makes atomization difficult and leads to higher smoke emissions. The major advantage of dual fuel engine using hydrogen is that the smoke emissions were lowered compared to CNG operation. This may be due to less carbon content and faster burning rates associated with clean burning characteristics of hydrogen compared to CNG. The higher burning velocity and flame temperature of HCNG leads to more better burning compared to CNG during the dual fuel operation.

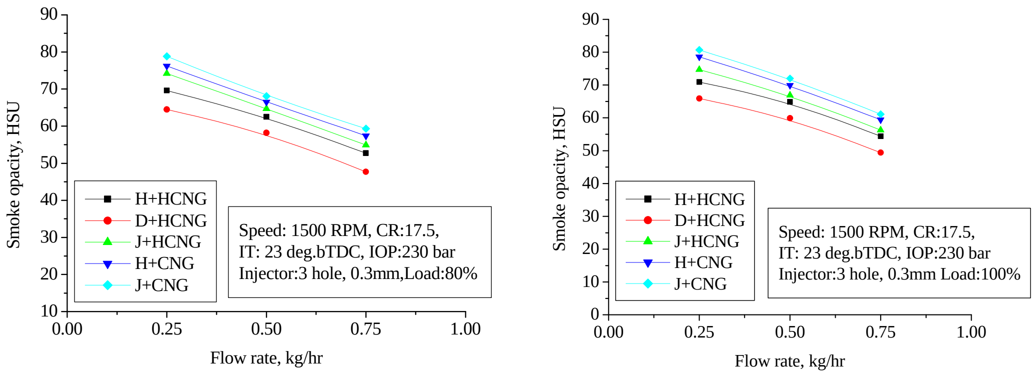

Fig. 3 Variation of Smoke opacity with flow rate

The variations of HC emission levels for Diesel/HOME/JOME-CNG and Diesel/HOME/JOME– HCNG operation for different gas flow rates at higher loads are presented in Figure 4. Hydro-carbon emissions with biodiesel in both versions of the gaseous fuel operation were higher compared to diesel. Relatively poor atomization and lower volatility of HOME/JOME compared to diesel is responsible for this trend. The lower brake thermal efficiency associated with biodiesel operation could also be responsible for this behavior.

Increased CNG flow rates resulted into higher HC emissions, while HCNG showed similar trends with marginally reduced HC emissions. The hydrocarbon emissions levels in the engine exhaust using DFC is higher due to the CNG charge, which causes lean, homogeneous, low-temperature combustion, resulting in less complete combustion. This is because small amount of pilot fuel cannot propagate longer distance inside the cylinder to burn the whole premixed fuel mixture. Though the oxidation of unburned hydrocarbons increased due to burnt gas temperature, the filling of unburned mixture in the crevice volumes with combustible mixture during the event of compression and ignition will become a main source of HC emissions .

HOME and JOME being common the properties of the two gases inducted results in the behaviour shown and accordingly HOME/JOME–HCNG operation results in lower HC emissions compared to HOME/JOME-CNG operation. The H_2 content in CNG gives a strong reduction of unburned hydrocarbon emission which results in more complete combustion [30]. In addition HCNG engine increases the H/C ratio of the fuel, which drastically reduces the carbon based emissions. The presence of hydrogen in CNG (HCNG) has higher flame velocity and flame temperature results in better combustion compared to CNG.

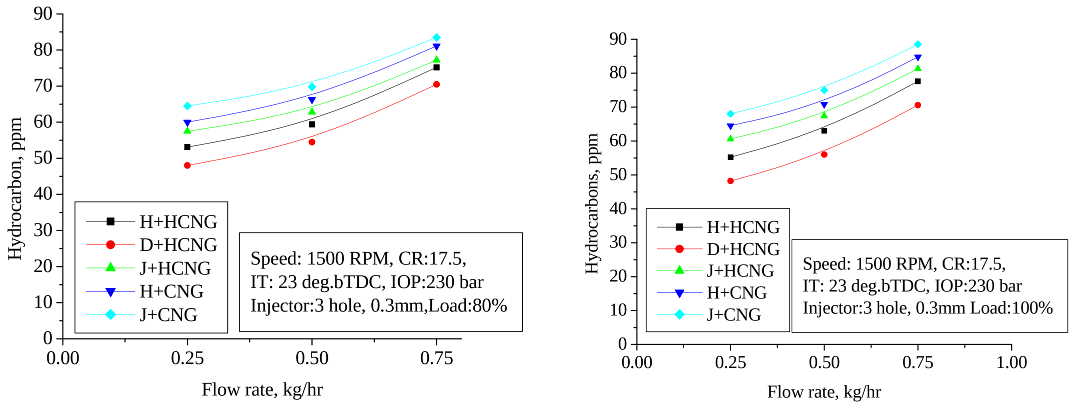

Fig. 4 Variation of HC with flow rate

The variations of CO emission levels for Diesel/HOME/JOME-CNG and Diesel/HOME/JOME– HCNG operation with respect to higher loads of engine operation are presented in Figure 5. The premixed combustion of biodiesel-HCNG results in more heat release rate leading to lower CO emissions compared to biodiesel-CNG. Moreover CO emissions mainly depend on stoichiometric air-fuel ratio and the rich mixture combustion leads to higher CO and emissions. Hence increased CNG and HCNG flow rate tends to improve combustion resulting in lower CO formations. The CO emissions further reduced with hydrogen addition with CNG. Some researchers reports lower CO emissions with lower CNG flow rates and increased CO levels with increase in CNG quantity for certain extent and later on, these begin to decrease. The increased gas flow rates of CNG and HCNG beyond 0.75 kg/h tends to cause engine knock leading to poor performance of the engine. Higher CO emission levels were observed for HOME/JOME-CNG combination compared to diesel/HOME/JOME-HCNG operation. This could be attributed to incomplete combustion of biodiesels injected due to their poor atomization and improper mixing of fuels. However lower CO emissions levels were observed for dual fuel operation with HCNG compared to CNG Moreover, the combustion temperatures are higher with HCNG fuel and the engine runs hotter thereby facilitating better combustion.

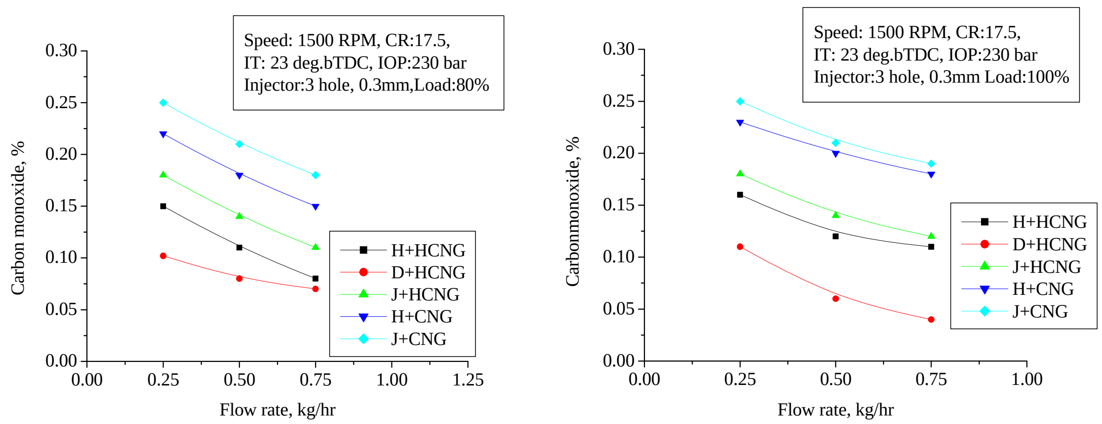

Fig. 5 Variation of CO with flow rate

The variations of NOx emission levels for Diesel/HOME/JOME-CNG and Diesel/HOME/JOME– HCNG operation with respect to higher loads are presented in Figure 6. As widely recognized, the formation of nitrogen oxides is favored by high oxygen concentration and higher charge temperature. Higher level of NO_x was observed for HCNG-biodiesel dual fuel operation and it could be due to higher premixed combustion phase observed compared to biodiesel-CNG (Fig.7.7). The injected biodiesels in CNG and HCNG dual fuel operation tends to lower NOx emissions and this may be due to their lower calorific value. The higher biodiesel consumption to develop same power output leading to delayed injection resulting in lower NOx emissions. The increased gas flow rate results in to higher NOx for all the fuel combinations. Compared to HOME/JOME- HCNG operation, it is observed that the HOME/JOME-CNG operation resulted in lower NOx emissions. It could be due to increased main combustion phase in the presence of hydrogen with elevated flame temperature which increases the NO_x emissions while reducing the HC emissions.

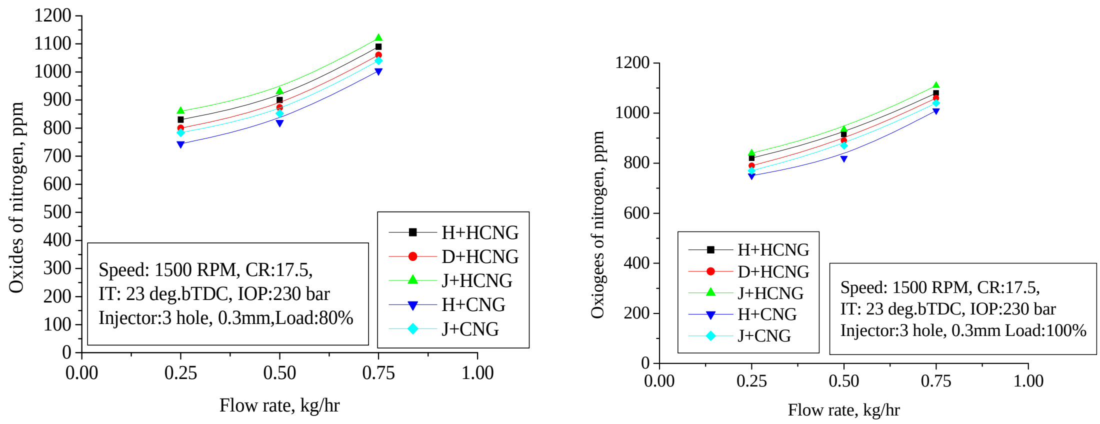

Fig. 6 Variation of NOx emission with flow rate

4.1.3 Combustion Characteristics

The combustion in a diesel engine differs when gaseous fuels are used and it depends on the engine operating conditions, engine design, fuel properties and air–fuel mixture quality. Different combustion characteristics were discussed as below:

The variations of ignition delay for Diesel/HOME/JOME-CNG and Diesel/HOME/JOME–HCNG operation with respect to higher loads are presented in Figure 7. The ignition delay is calculated based on the static injection timing using pressure crank angle history for 100 cycles. Ignition delay increased with increased gas flow rates due to the slow burning rates observed with gaseous fuels for both dual fuel operations. It may also be due to slow mixing rate with gaseous fuel operation as they have higher octane number and self ignition temperature. Burning velocity of HCNG being comparatively higher than CNG the delay period decreased marginally.

JOME resulted in slightly higher ignition delay compared to HOME with gases due to its comparatively higher viscosity. Biodiesel fuels showed lower premixed combustion heat release rate as more fuel burning takes place in the diffusion phase and the combustion starts later to diesel fuel.

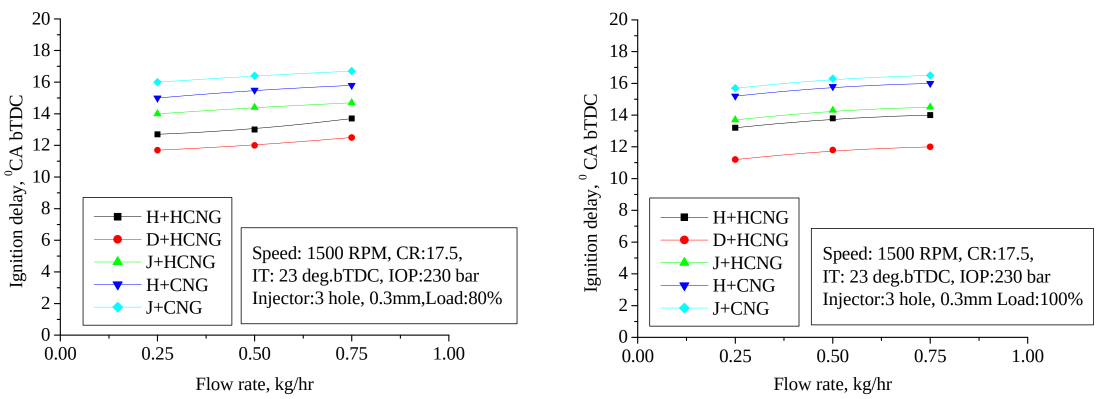

Fig. 7 Variation of ignition delay with flow rate

Combustion duration for Diesel/HOME/JOME-CNG and Diesel/HOME/JOME–HCNG operation with respect to higher loads is presented in Figure 8. The combustion duration was calculated based on the duration between the start of combustion and 90% cumulative heat release. The combustion duration increases with increase in the gaseous flow rates. This could be due to their slow mixing rate as they have higher octane number and self ignition temperature. Improper air–fuel mixing observed with biodiesels along with longer time for gas burning results in incomplete combustion. However, HCNG showed lower combustion duration as hydrogen present in CNG leads to faster combustion. Higher flame velocity, higher calorific value and fast burning rate of hydrogen in CNG (HCNG) causes the combustion duration to decrease while the heat release rate and exhaust NO_x increase with hydrogen addition [14].

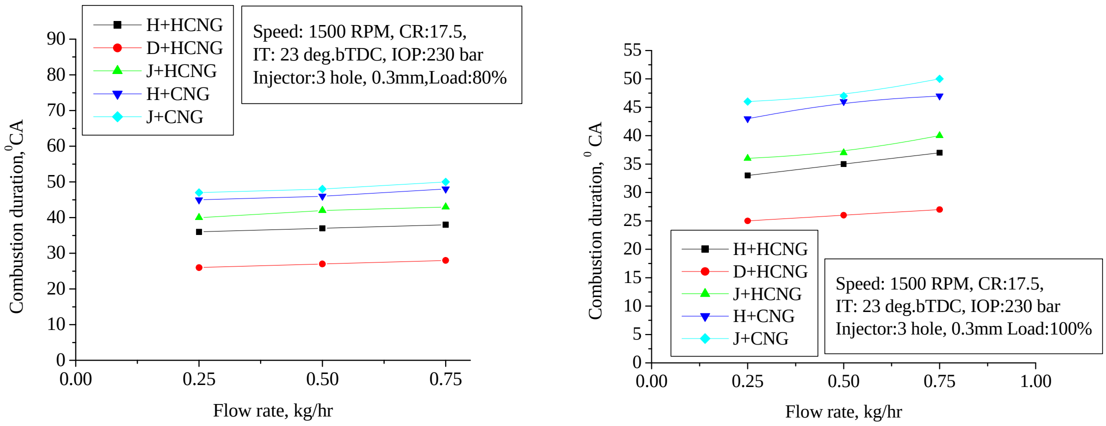

Fig. 8 Variation of combustion duration with flow rate

Figure 9 shows peak pressure variation with gas flow rate for Diesel/HOME/JOME-CNG and Diesel/HOME/JOME–HCNG operation at higher loads of engine operation. The peak pressure depends on the combustion rate and that how much fuel is taking part in rapid combustion period. The uncontrolled combustion phase is governed by the ignition delay period and by the mixture preparation. Higher cylinder pressure obtained with HCNG compared to CNG could be due to the higher heat release rate observed during rapid combustion phase. Lower cylinder pressure with increase in the mass flow rates of CNG /HCNG was observed. It could be attributed to an increase in the ignition delay period of pilot fuels injected. Hence, it is seen that ignition delay of the pilot fuel was significantly increased with an increase of gas flow rates. This increase in ignition delay period is mainly due to improper mixing of the fuel combination and lowering of compression temperature. However, a part of the air was replaced by gaseous fuels which in turn changes the charge mixture specific heat reduced the oxygen concentration in the fuel mixture and slower burning rate of CNG / HCNG also responsible for this trend. However, lower pressure was observed for biodiesel operation because of poor mixing with air due to their higher viscosity and lower volatility.

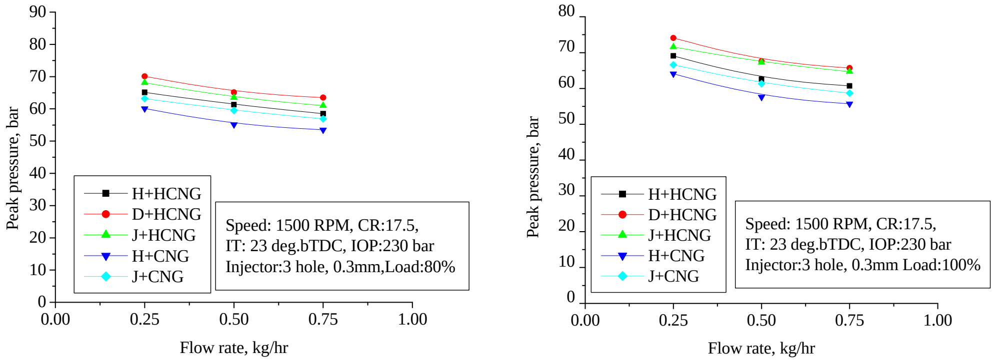

Fig. 9 Variation of peak pressure with flow rate

Combined effect of poor mixture preparation, longer ignition delay, lower calorific value and adiabatic flame temperature and slow burning nature of the HOME/JOME-CNG compared to HCNG resulted in lower peak pressure and maximum rate of pressure rise. However, the higher flame velocity, calorific value and slightly increased ignition delay of HCNG during dual fuel operation leads to increased combustion during rapid combustion phase. Hence it results in to higher peak pressure and maximum rate of pressure rise. Accordingly higher peak pressure and heat release rate were observed for HOME/JOME-HCNG operation due to the higher flame velocity and fast burning of hydrogen content in presence of CNG (Figure. 10).

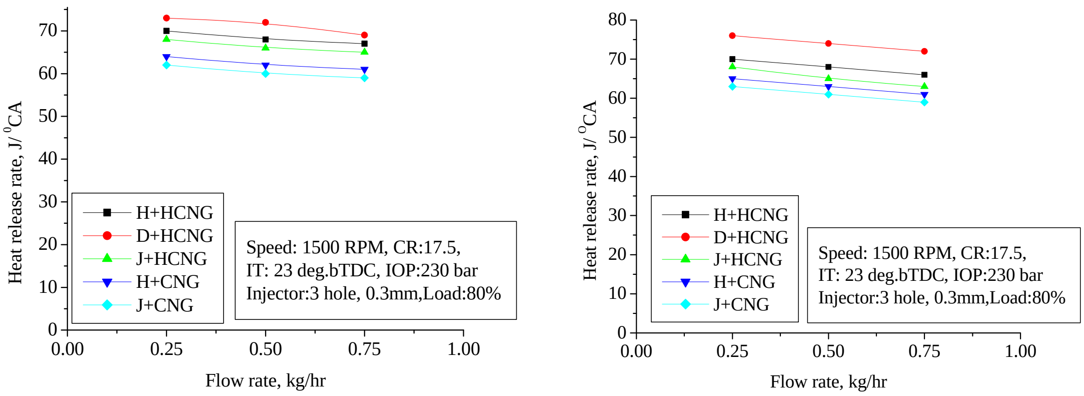

Fig. 10 Variation of heat release rate with flow rate

5. Conclusions

From the exhaustive study on th dual fuel engine using gaseous fuels of CNG and HCNG and biodiesels the following conclusions were made.

1. Dual fuel engines significantly reduce smoke, particulate and NOx emissions when compared to their counterpart diesel engines.
2. Biodiesels of HOME and JOME can provide partial substitution to diesel when used in dual fuel mode along with gaseous fuels.
3. CNG operated dual fuel engines besides using renewable fuels of HOME and JOME can provide partial substitution to renewable fuels and leads to higher emissions of HC and CO emissions.

4. Adding hydrogen to CNG significantly improves brake thermal efficiency and reduce emissions of smoke, HC, CO emissions except NO_x. HCNG makes it possible to run the engine leaner, resulting in lower emissions of HC and CO and higher NO_x emissions.
5. Increased gas flow rates of CNG, HCNG reduce smoke, HC and CO emissions. However the brake thermal efficiency reduces due to lowered volumetric efficiency.
6. Higher flame speed of hydrogen in HCNG results in reduced ignition delay, combustion duration while the peak pressure and heat release rates both increased.

On the closure it can be concluded that higher percentage of hydrogen in CNG can affect the engine performance favorably but limit the engine operation with severe knock especially at higher loads of engine operation. The problem of knocking can be effectively addressed by injecting HCNG into the intake manifold when the inlet valve opens to avoid pre-ignition. Advancing the injection timing of pilot biodiesel fuel and increased compression ratio can improve the performance of such dual fuel engines. The continued work on the use of hydrogen and HCNG fuels in biodiesel operated dual fuel engines will make use of port or manifold gas injection overcoming the drawbacks of the backfire and preignition which is prone to occur in carbureted engines and can be eliminated with proper gas injection timing using low pressure gas injector operated by a suitable Electronic Control Unit.

The present study reports on the CNG induction in a biodiesel fuelled diesel engines. The CNG engines on the road make use of solenoid operated low pressure gas injectors. The future work focuses on the use of CNG gas injectors along with biodiesel injection in modified diesel engines operated on dual fuel mode.

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