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Air Pollution Reduction and Environment Protection Using Methane Fuel for Turbocharged CI Engines

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ABSTRACT

The internal combustion engine is considered as one of the main sources for air pollution due to hydrocarbon fuel combustion. The increased land transport usage requires improvement of the engine efficiency and combustion process technology to reduce the engine emissions. A turbocharged engine and the gaseous fuel replacement are the green tools proposed by researchers to enhance fuel saving and emissions reduction. In this paper, both methods were investigated. The methane is a preferred gaseous fuel due to its lower carbon to hydrogen ratio, resulting in lesser HC and CO emissions. In this paper, a turbocharged compression ignition engine with methane/diesel dual fuel is simulated using professional GT-power code to investigate the effect of methane percentage in mixture on the engine performance and emissions. A turbocharged 6 cylinders compression ignition engine has been built and investigated. During the simulation, the methane/diesel ratios were varied from pure diesel with zero percent methane to 90% methane concentration by mass with 10% increment every run. The results show that the engine brake power and specific fuel consumption increased while the thermal efficiency decreased for lower CH_4 concentration. For higher CH_4 percentage, the brake power and thermal efficiency increased while specific fuel consumption decreased. Moreover, NO emission has 35% reduction compared to neat diesel fuel when 50% of methane was added to the mixture. Conversely, the CO and HC concentration increased when the methane ratio is less than 50% compared to neat diesel combustion. In general, the engine efficiency improved when methane was added to diesel fuel in compression ignition engine with turbocharger boost, resulting in lesser emissions and cleaner environment.

Keywords: air pollution, clean combustion, methane emissions, heavy-duty diesel engines

INTRODUCTION

One of the main challenges which faced by the automobile manufacturers is to reduce the engine emissions without serious modifications of engine systems in order to decrease the production cost and time. Many solutions were proposed by the researchers in the last decades to achieve green internal combustion engine. The use of gaseous fuel in compression ignition (CI) engine has received a great attention by researchers [Rakopoulos et al., 2001; Rakopoulos et al., 2006; Stone et al., 1991]. Several papers considered the performance of diesel engine operating on dual fuel mode [Ishida et al., 2000; Singh et al., 2004; Abd Alla et al., 2002; Lee et al., 2003]. Methane, as a second fuel in conventional compression ignition engine dual fuel (methane/diesel), is a promising gaseous fuel due to its clean combustion and low price compared with diesel fuel. In addition, many works reported that using methane/diesel mixture considerably improved the NOx-Soot trade off compared to neat diesel engine [Agarwal et al., 1998; Nwafor et al., 2000; Lee et al., 2003]. Moreover, methane has a high auto-ignition temperature, suitable for use in diesel engine with high compression ratio without the issue of knocking. The main drawbacks of using methane/diesel in dual fuel mode are the higher amounts of CO and HC emissions with lower engine efficiency compared to conventional diesel engine particularly at partial engine load, as reported by researchers [Krishnan et al., 2002; Ling et al., 2005; Shenghua et al., 2003, Nwafor et al., 2000]. Carlucci et al. [2004] reported that using a CH_4/diesel mixture in a compression engine at low load increases the HC and CO emission due to the lean methane/air mixture results in deficiency of combustion process. Korakianitis et al. [2011] observed that due do flame quenching caused by cylinder wall temperature, more methane is emitted to the atmosphere. Ansari et al. [2016] reported that the NG/diesel mixture extends the combustion duration and a decrease in the cylinder temperature results in lower NOx emission. The difference reactivity between NG and diesel decreases the flame temperature and, consequently, the NO formation [Nieman et al., 2012]. They confirmed that the multi-injection technique of DI diesel fuel increase the engine efficiency and decrease the emissions for different engine load. Zoldaket al. [2014] studied theoretically the effect of NG/diesel dual mode on the engine performance and emissions. The concluded that the cylinder pressure and pressure rate are increased compared to neat diesel fuel. Doosje et al. [2014] controlled the soot and NO_x emissions to match the Euro standards for NG/diesel engine operating at different load. Dahodwala et al. [2014] investigated the RCCI technique on CNG/Diesel engine. They concluded that the lower engine emissions can be achieved by higher CNG replacement at low load. Peykani et al. [2015] studied the effect of injection mode on the engine efficiency. They observed that the first and second start of injection timing and the amount of injected fuel have a major influence on the engine emissions. Another green technique to reduce the exhaust emissions and save fuel in a diesel engine is using turbocharge system to recover the waste heat from the exhaust gases [Rongchao et al. 2014]. The turbocharged compression ignition engine operating with methane fuel has a higher thermal efficiency and lesser emissions due to lean combustion characteristic [Sunyoup et al., 2014].

In this study, the effect of methane addition to turbocharged diesel engine on the performance and emission has been investigated using professional code GT-power. A six cylinder compression engine has been built and simulated. The methane/diesel ratio varied from (10–90%) by mass. Additionally, neat diesel was also combusted to compare with the CH_4/diesel mixture. The model has been validated using the available data from the literature and a good agreement was obtained. The engine output such as: brake power, thermal efficiency, fuel consumption, cylinder pressure and temperature, NO, HC and CO emissions were calculated and fully discussed.

SIMULATION MODEL

A six cylinder turbocharger with intercooler system for compression ignition engine has been built and simulated using professional code GT-power. The CH_4/diesel ratio varied from (0–90%) by mass. The methane was injected to the intake port with various mass flow rates to mix with air and create homogeneous charge. Liquid diesel fuel was injected directly to the combustion chamber with rail pressure = 2000 bar and the diesel fuel temperature equaled 330 K. The properties of methane and diesel are included in the software and are presented in Table 1. During the simulation, the total fuel mass (methane and diesel) was kept constant = 140 mg and the methane energy share was calculated using Eq. (1).

$$CH_4\; energy\; share = \frac{\dot{m}_{CH_4} \cdot LHV_{CH_4}}{\dot{m}_{CH4} \cdot LHV_{CH4} + \dot{m}_{diesel} \cdot LHV_{diesel}} \tag{1}$$

The turbocharger operating parameters such as speed, pressure ratio and mass flow rate are determined by a standard performance map specified by the user. The flow model required the solution of Naviera-Stokes equations. The conservation of momentum, energy and continuity are solved in one dimensional model with average values across the flow. Compressor and turbine are modeled using the map-based approach created by the user. The map describes the efficiency of the turbocharger system for each operating point. It should determine the operating conditions such as speed, mass flow rate and thermodynamics parameters for both turbine and compressor. The power consumed/produced by the turbomachinery can be calculated due to the enthalpy change. The program uses different heat transfer model. In this simulation, the WoschniGT model has been used to predict the heat transfer inside the cylinder. The program support dual fuel combustion. The combustion model used to predict the burn rate of direct injection diesel fuel is called DIPulse. The CH_4/air mixture burn rates were predict using EngCylCombSITurb and standard turbulent flame speed model. The system was equipped with throttle controller to control the throttle angle and the methane/air mixture flow rate and consequently the engine load. All the simulations were run with full engine load and without exhaust gases recirculation. The engine speed was kept constant for all the runs. The engine specifications and engine operation conditions are presented in Table 2 and 3. The model has been validated using available data from the literature. The results from this model compared with references [Saito et al., 2001; Zhou et al., 2014; Yu et al., 1986; Gatts et al., 2012]. The theoretical and experimental data showed a good agreement.

RESULTS AND DICSUSSION

The author investigated analytically the performance and emission characteristics of a turbocharged (DI) diesel engine operating on methane/diesel in dual fuel mode. The methane content varied from (10–90%) by mass. The neat diesel fuel was also calculated to compare with the dual mode to find out the effect of methane addition to diesel on the engine performance and emissions. Another technique used in the simulation to reduce emissions was by means of a turbocharger system. The engine ran at full load with constant lambda.

Table 1. Fuel properties

Properties	Units	Methane	Diesel
Carbon atoms per molecule	–	1	13.5
Hydrogen atoms per molecule	–	4	23.6
Oxygen atoms per molecule	–	0	0
Lower heating value	MJ/kg	50	43
Critical temperature]	K	190.4	569.4
Critical pressure	bar	46	24.6
Absolute entropy at 298k	J/kg-K	11618	3445.47
Laminar flame speed	m/s	0.38	0.3
Auto ignition temperature	k	813	530

Table 2. Engine geometry

Parameter	Unit	Value
Bore	mm	120
Stroke	mm	170
Conn. rod length	mm	290
Piston pin offset	mm	0
Displacement/cyl	L	1.9
Total displacement	L	11.4
Number of cylinders		6
Compression ratio		13.5
Bore/stroke		0.71
IVC, IVO	°CA	-122, 310
EVO, EVC	°CA	105, 390

Table 3. Engine operation conditions

Parameter	Unit	Value
Initial pressure	bar	1
Initial temperature	K	298
Speed	rpm	1800
Combustion start	°CA	-1.5
Injection start	°CA	-6
Vol. eff. ref. pressure	bar	1.7
Vol. eff. ref. temperature	K	315
Mean piston velocity	m/s	11

Combustion characteristics

Figure 1 shows the cylinder pressure as a function of methane percentage under full engine load. As shown in the figure, the cylinder pressure increased along with the CH_4 mass in the mixture. Moreover, the addition of 70% of CH_4 by mass increased the cylinder pressure up to 30% compared to neat diesel fuel. In turn, the addition of more than 80% methane results in a decrease of the cylinder pressure compared to diesel fuel. In addition, the ignition delay increased along with the methane fraction in the mixture due to the decrease in the oxygen concentration which affected the diesel combustion process [Saito et al., 2001]. The considerable increase of peak cylinder pressure caused by uncontrolled combustion of CH_4/diesel mixture compared with diesel fuel combustion was observed. This is due to high cylinder temperature resulting in multipoint methane combustion and consequently uncontrolled heat release rate. Moreover, the ignition delay increased when the methane ratio increased in the mixture due to the extended of premixed combustion period [Zhou et al., 2014]. Figure 2 shows the maximum in-cylinder temperature versus gas substitu-

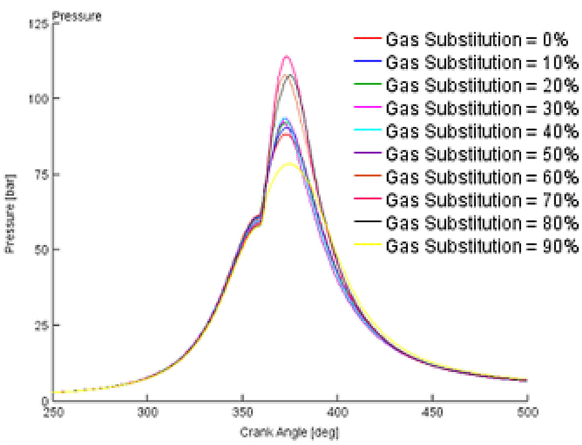

Figure 1. Maximum cylinder pressure versus methane concentration

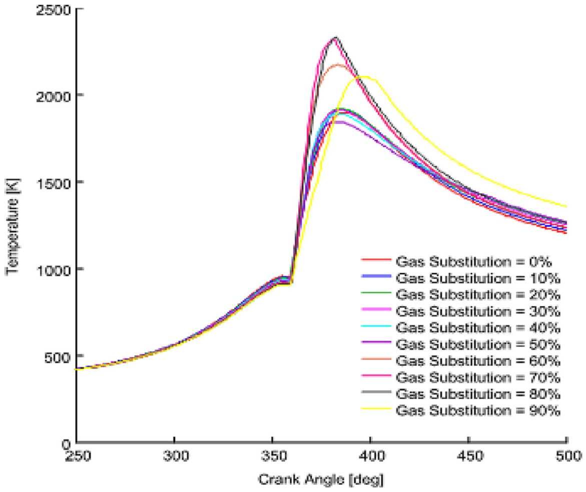

Figure 2. In-cylinder temperature versus methane concentration

tion. The results show that the increase of CH_4 by 80% causes a 22% increase in cylinder temperature compared to conventional diesel fuel.

The effect of methane addition on the heat release rate is presented in Figure 3. It is shown that the addition of methane between (60–70%) increases the heat release rate drastically compared to neat diesel fuel. Moreover, the heat release is retarded when CH_4 is added to diesel. The results agree with [Yu et al., 1986]. They performed that the increase of hydrogen mass in hydrocarbon fuels results in increasing the laminar flame speed and consequently, the cylinder pressure and heat release rate. For methane/diesel combustion, compared to neat diesel fuel, the heat release rate increased between (15–30%) depending on the methane concentration in the fuel mixture. In addition, the accumulation of heat by methane and diesel resulted in a remarkable increase in the heat release rate. Figure 4 shows the burn rate for different methane/diesel mixtures. The burn rate increased along with the methane ratio in the mixture due to high flame speed of methane.

Engine performance

The major engine outputs are presented in Figure 5. The variation of engine brake power versus CH_4 concentration is presented in Figure 5a. As shown, the increase of methane concentration raises the brake power approximately by 20%, compared to diesel baseline. Moreover, the addition of (40–50%) of CH_4 decreases the power output. The effect of CH_4 concentration on the thermal efficiency is presented in Figure 5b. The brake thermal efficiency can be calculated using Eq. (2).

$$b.thermal\ efficiency = \frac{brake\ power}{\dot{m}_{CH4} \cdot LHV_{CH4} + \dot{m}_{diesel} \cdot LHV_{diesel}} \tag{2}$$

The engine efficiency decreases when the CH_4 ratio is lesser than 50% compared to neat diesel, due to incomplete combustion [Gattes et al., 2012] as well as the high amount of input energy and low output power [Ghazal, 2013]. On the other hand, the efficiency increased when the methane ratio was higher than 60% due to raised indicated mean effective pressure (IMEP). The effect of methane addition on the fuel consumption and indicated mean effective pressure are illustrated in Figure 5c and Fig-

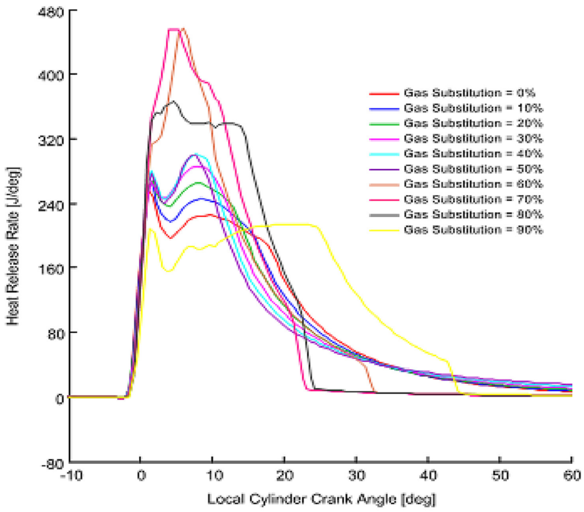

Figure 3. Heat release rate versus methane concentration mixture

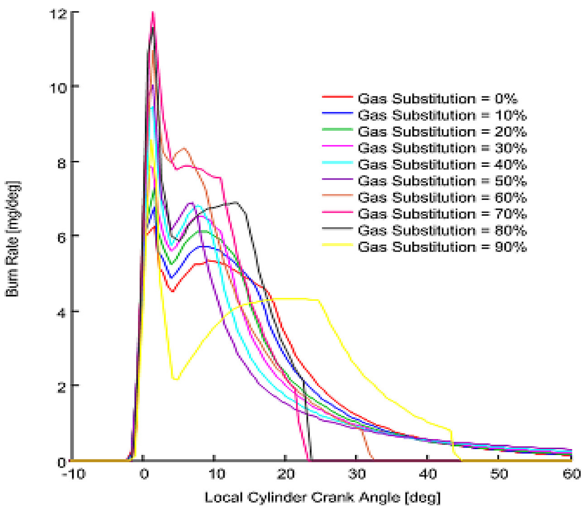

Figure 4. The burn rate of the CH_4/diesel versus gas substitution

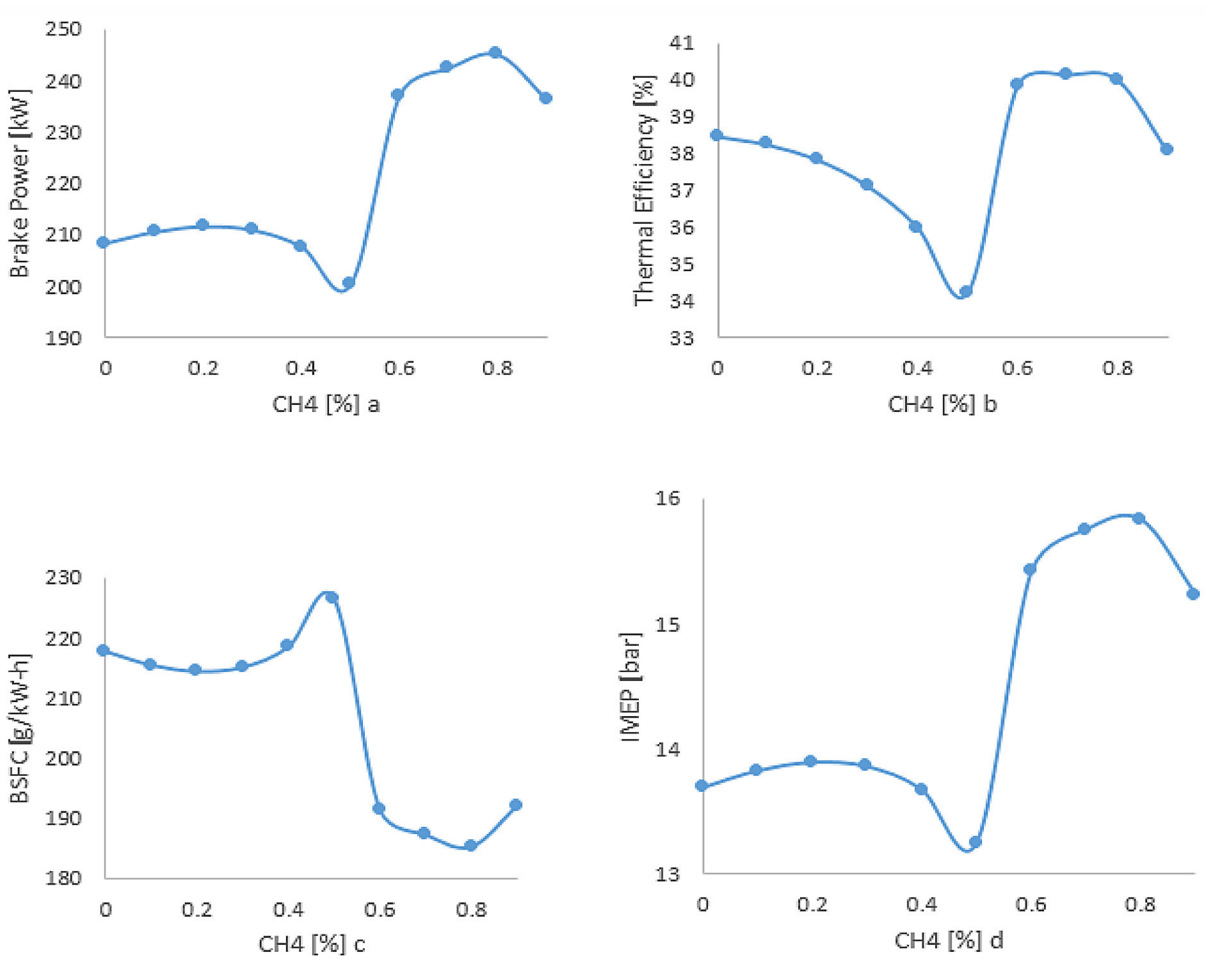

Figure 5. The engine b. power, efficiency, fuel consumption and effective pressure versus CH_4 fraction

ure 5d. The fuel efficiency slightly decreased when CH_4 added was less than 50% in the mixture at full engine load. On the other hand, the increase of methane percentage in the mixture of more than 60% decreases the fuel consumption up to 15% compared to neat diesel combustion. Additionally, the high methane concentration results in an increase in the mean effective pressure. The same results have been obtained by [Ausquiza et al., 2011]. They reported that when the NG ratio increased, the fuel consumption increased as well, both at low load and at high load.

Engine emissions

The exhaust emissions characteristics are presented in Figure 6. The NO emission decrease drastically when gaseous fuel is added to the mixture. The 35% NO reduction can be achieved when 50% methane is added compared to neat diesel fuel as shown in Figure 6a and 6b. The NO concentration is presented in Figure 6a as a function of CH_4 mass fraction. The results show a reduction in the NO emissions when methane fraction is increased in the mixture. However, the NO formation increased when methane was added to diesel due to high combustion temperature, but the NO oxidation rate also increased resulting in lower NO exhaust emissions. Conversely, the CO concentration increased slightly compared to neat diesel combustion when the engine was operating at full load and the methane ratio increased up to 50%. On the other hand, the CO concentration is lesser than base diesel line when the CH_4 ratio increased up to 90% as presented in Figure 6b. This is due to incomplete combustion of methane. The same results were demonstrated by [Gatts et al., 2012]. The HC production characteristic is illustrated in the Figure 6c. The increase of CH_4 concentration up to 50% results in an increased HC amount in the exhaust gases.

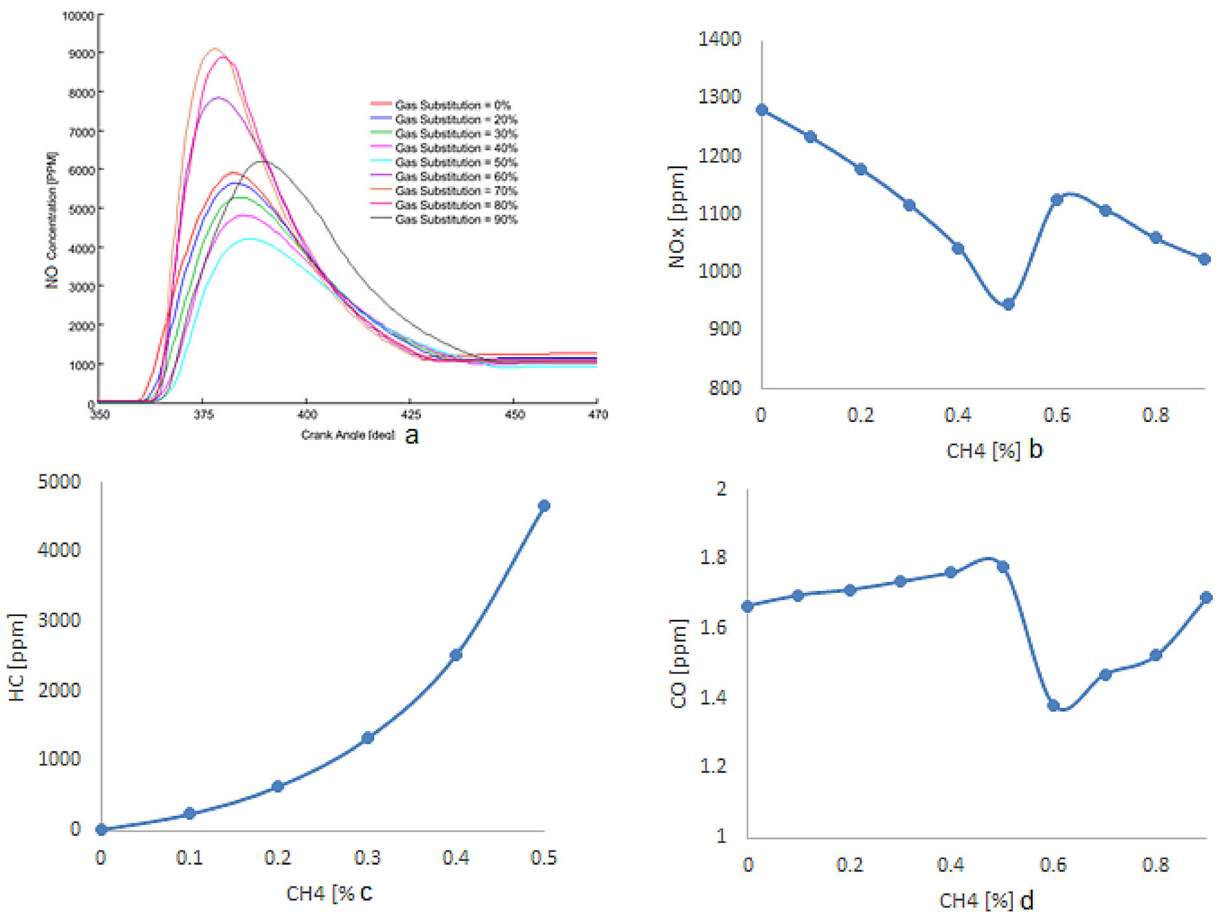

Figure 6. The effect of CH_4 concentration on No, CO and HC emissions

CONCLUSIONS

In this study the effect of methane gaseous fuel on the performance and emissions of turbocharged compression ignition engine was investigated. The engine ran with various CH_4/diesel ratios under full load. The results show that the brake power and thermal efficiency increased while the fuel consumption decreased for high CH_4 concentration in the mixture. Moreover, NO emission reduced by 35% compared to neat diesel fuel when 50% of methane was added to the mixture. Conversely, the CO and HC concentration increased when the methane ratio was less than 50% compared to neat diesel combustion. To conclude, the turbocharger and alternative fuel are promising green techniques to reduce the engine emissions and air pollution.

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