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Effects of Hydrogen in Low-calorific Gases on Fuel Consumption and Emissions in a Diesel Engine

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Abstract: For one practical approach to utilizing hydrogen fuel, the efficient usage of low-calorific gases with small portion of hydrogen is demonstrated in diesel engines used for power generation. These gases originally produced in various chemical processes such as gasification of solid wastes or biomass. Effects of amount and composition of low-calorific gases with hydrogen on diesel-engine performance and emissions were experimentally investigated by adding hydrogen-nitrogen mixtures into intake gas of a direct-injection diesel engine. The results indicate that optimal usage of low-calorific gases reduces NO_x and Smoke emissions with remarkable saving in diesel fuel consumption.

Keywords: Hydrogen, Solid Waste, Diesel Engine, Emission, Thermal Efficiency, Low-calorific Gas.

Introduction

Hydrogen has a very wider flammability limit and an extremely higher burning velocity compared with other hydrocarbon fuels. These features may cause a rapid and complete combustion in high-performance clean hydrogen engines[1][2]. Also, the mixing of hydrogen into other hydrocarbon fuels is expected to promote the combustion of lean mixture for ensuring a stable operation in lean-burn engines[3][4]. Another approach to utilizing a peculiar characteristics of hydrogen is the effective use of the produced gases containing a certain amount of hydrogen. This implies a practical significance in energy conversion to low-calorific gases LCG through a thermal gasification technology that could contribute to power generation in the management of municipal waste and utilization of biomass [5][6]. LCG contain mainly nitrogen gas with a small fraction of hydrogen and carbon monoxide. Heating value of LCG; depending on chemical omposition; varies in the range of 900<1200kcal/Nm^3. This corresponds roughly to 10% of calorific value of natural gas. Operating an engine with net LCG in wide engine loading is very difficult due to low-calorific value of LCG. Nevertheless, LCG can be utilized with gasoline and diesel fuels in dual-fuelled engines [7][8].

Direct injection diesel engine with high thermal efficiency and low CO_2 emissions are proper candidates for utilization of LCG [5][9]. Diesel engines are widely used in energy generation and cogeneration systems. In direct injection diesel engines, utilizing LCG would give several effects on engine performance and emissions. At first, existence of hydrogen and carbon monoxide with high heating value and wide combustibility range would lower consumption of diesel fuel[8][10]. Addition of LCG to intake gas of a diesel engine would also lower the NOx emission. This is due to decrease in peak combustion temperature and reduction of oxygen concentration in the intake gas [11][12]. Nevertheless, decrease in oxygen concentration would cause an increase in Smoke, THC and CO emissions. These influences are observed when a high EGR ratio is used in a diesel engine [13]. At the same time, existence of hydrogen in LCG would compensate these effects. Hydrogen with wide combustibility range is used to activate combustion of other fuels in internal combustion engines. For example, induction of small amount of hydrogen to a Spark ignited natural gas engine expands the lean limit and improves the thermal efficiency [14]. And also, addition of hydrogen obtained from gasoline reforming decreases the combustion period and prevents knocking in a SI engine [15]. Carbon monoxide also enhances the burning rate of hydrocarbon fuels [10]. In diesel engines, hydrogen induction to the intake gas lowers the emissions of greenhouse, NOx and Smoke [16-19].
Due to its importance, utilization of LCG to diesel engine has been carried out by some researchers [8]. Their results indicate some effects mentioned above. Nevertheless, these studies are carried out using LCG with limited chemical composition. Composition of LCG strongly depends on type of waste and gasification process [6].

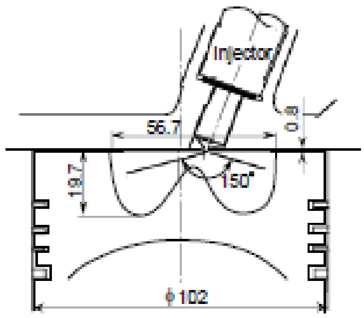
In this study, effects of LCG amount and composition on diesel engine performance and emission were parametrically studied using a single cylinder naturally aspirated direct injection diesel engine. LCG was synthesized using nitrogen and hydrogen mixture which were introduced into the intake gas. Due to the safety factor, composition of LCG was limited to the hydrogen and nitrogen mixture and CO gas was not used. However, based on the results, possible effects of CO gas in LCG on engine performance were discussed. Experimental results indicate that optimal usage of LCG can reduce diesel fuel consumption and improve emissions.

Experimental Apparatus and Procedure

The test engine used was a four-stroke single cylinder naturally aspirated direct-injection diesel engine (Yanmar NFD-170) with a bore of 102mm and a stroke of 105mm. Figure 1 shows the configuration of cylinder head and combustion chamber. The specification of the injection nozzle is spray angle of 150° and four holes with 0.29mm hole diameter. Figure 2 shows the schematic of experimental setup. Combustion analysis was carried out measuring in-cylinder pressure every 1 °CA by a piezoelectric pressure transducer (Kistler 6052A). Diesel fuel used was JIS#2 gas-oil (density of 828kg/m^3, lower heating value of 44200kJ/kg, and Cetane number of 55). All experiment was conducted at thermally steady states of the engine at; an inlet cooling water temperature of 80°C, a lubricating oil temperature of 90°C and injection timing of 12 °BTDC. Engine speed was fixed at 1800rpm.

Effects of low-calorific gases on engine performance were investigated adding hydrogen and nitrogen mixture into the engine intake gas. Nitrogen from a high pressure vessel was introduced into the intake using a gas mixer installed at downstream of surge tank. And hydrogen gas was induced using an orifice nozzle with diameter of 6 mm. Flow rate of both gases were preciously measured using thermal mass flow meters. In experiment, first flow rate and composition of LCG were adjusted and then amount of diesel fuel injected were increased to achieve considered output.

Several gas analyzers were used to clarify the effect of LCG addition on engine emissions. NOx emission was measured using a chemiluminescent analyzer (Yanaco ECL-30). Smoke density was measured using a Bosch Smoke meter (Zexel DSM-10). Unburned hydrocarbons were measured by a heated FID detector (Horiba Mexa-1160TFI-H). A gas chromatograph (Yanaco G6800) with thermal conductivity detector was used to measure the amount of unburned hydrogen in engine exhaust. Emissions of CO and CO_2 were measured with a NDIR analyzer (Altas-121).



Engine type	DI diesel engine
	Single cylinder, Water cooled
Bore× Stroke	102mm× 105mm
Displacment	857 cc
Compression ratio	17.8:1
Swirl ratio	2.6
Combu. chamber	Toroidal

Fig. 1 Engine specification.

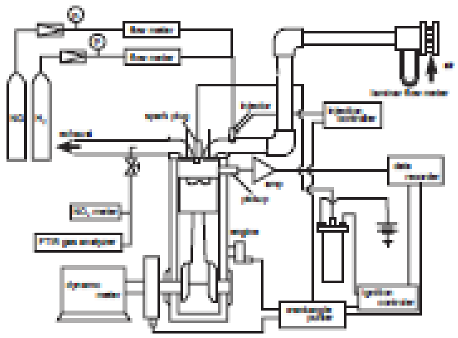


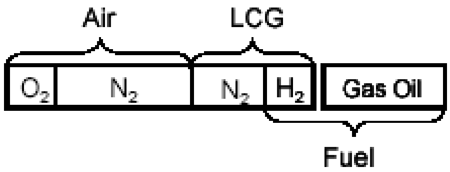
Fig. 2 Experimental setup

Results and Discussion

Effects of LCG addition amount on engine performance at high engine loads

At first, effects of LCG amount and investigated varying LCG amount r_{LCG} and hydrogen concentration r_H in the range of 0.1~0.25 and 0~0.3 respectively. As shown in Fig. 3, r_{LCG} corresponds to volume ratio of low-calorific fuel in intake gas and r_H indicates the volume ratio of hydrogen in low calorific gas. In this case, engine load were fixed at brake mean effective pressure of p_e=0.6MPa. As shown in Fig. 4, increasing amount of LCG and hydrogen concentration in intake gas does not affect the brake thermal efficiency η_e so considering both diesel and LCG fuels. Even at r_H=0 and r_{LCG}=25%, when 25% of intake air is replaced with nitrogen, η_e is slightly lower than diesel fuel operation DF. However, at each r_{LCG}, increasing hydrogen concentration lowers the consumption of diesel fuel be_{DF}. At r_{LCG}=25%, r_H=30%, be_{DF} is about 140g/kWh which corresponds to 40% saving in consumption of diesel fuel. Here, be_{DF} corresponds to the brake specific fuel consumption of diesel fuel only.

Next, effects of LCG addition on emission were investigated. Figure 5 reveals NOx, Smoke, THC and CO concentrations in engine exhaust at the same experimental condition as fig. 4. Increasing r_{LCG}, improves NOx emission substantially compared with that in diesel fuel operation DF. However, it increases CO, Smoke and THC emissions. Except for THC, increasing hydrogen concentration to r_H=0.3, emissions can be lowered to the same level as the diesel fuel operation DF.



$$r_{LCG} = \frac{V_{LCG}}{V_{Air} + V_{LCG}} \quad , r_H = \frac{V_{H2}}{V_{LCG}}$$

Fig. 3 Definition of LCG amount and composition.

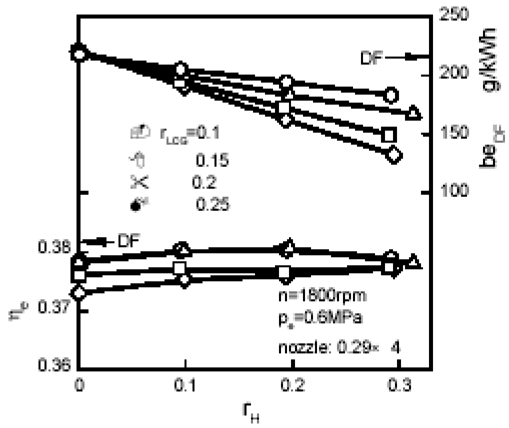


Fig. 4 Effects of LCG addition on engine performance at fixed engine load.

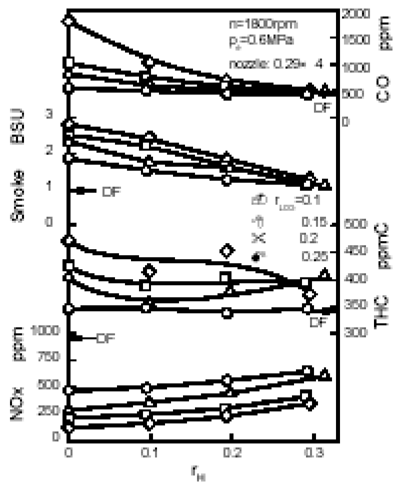


Fig. 5 Effects of LCG addition on emission at high engine load of p_e=0.6 MPa.

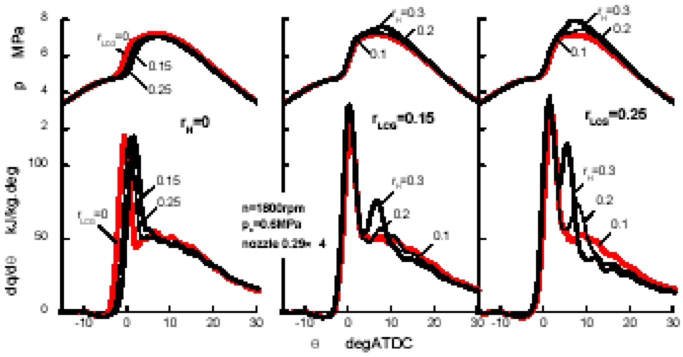


Fig. 6 Effects of LCG addition on combustion process at high engine load of p_e=0.6MPa.

Figure 6 shows the effects of LCG addition on in-cylinder pressure and heat release rate under the same condition as fig. 4. At r_H=0 when only nitrogen is added to the engine intake, increasing r_{LCG} prolongs the ignition delay but with little effects on combustion process. However, at given r_{LCG}, increasing hydrogen concentration r_H promotes the premixed and diffusion combustions giving higher peak combustion pressure. Nevertheless, in this case, little change was observed in ignition delay. In high LCG addition conditions a distinct peak in heat release rate at diffusion combustion stage can be seen. Increasing rH increases the peak level and advances its timing. This combustion characteristics would be due propagation of hydrogen flame initiated by diesel fuel combustion [16-19].

From above results, it can be summarized that addition of LCG with little amount of hydrogen, lowers the combustion temperature and oxygen concentration, therefore offers a low NOx emission. Nevertheless, reduction in oxygen concentration in engine intake could be the reason for increase in Smoke, CO and THC emissions. Increasing hydrogen concentration in LCG promotes the premixed and diffusion combustions and improves Smoke, CO and THC emissions.

LCG addition under various engine loadings

Effects of LCG addition on engine performance and emissions were studied at different engine loads when amount of LCG was fixed at r_{LCG}=0.15 and hydrogen concentration was varied in the range of r_H=0~.3. As shown in Fig. 7, in diesel operation DF, thermal efficiency η_e increases with p_e and peaks at p_e=0.6MPa. This trend is very similar when LCG gas is used. At p_e=0.4~.6MPa, variation of hydrogen content do not affect the thermal efficiency. However, at p_e smaller than 0.4MPa, increasing hydrogen content lowers the thermal efficiency η_e. However, as shown in top figure, increase in hydrogen content still lowers the consumption of diesel fuel be_{DF}.

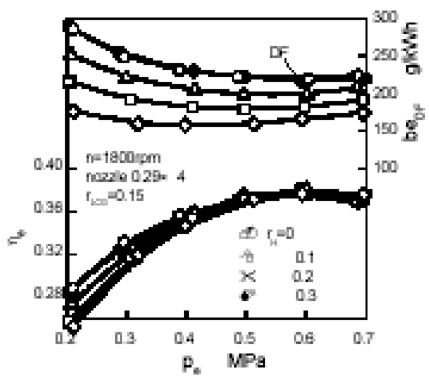


Fig. 7 Effects of LCG addition on engine performance under various engine loading.

Next, combustion analysis was carried out to clarify the negative effects of LCG addition on thermal efficiency. Figure 8 shows the effects of hydrogen concentration in LCG on in-cylinder pressure and rate of heat release at engine load of p_e=0.2MPa in which reduction in thermal efficiency was observed. This figure also includes combustion process for p_e=0.6MPa in which thermal efficiency is unchanged by LCG addition. At p_e=0.2MPa, addition of LCG delays the ignition and lowers the amount of heat released in pre-mixed combustion giving lower peak combustion pressure. In this case, diffusion combustion is not affected by LCG addition. However, at high engine load of p_e=0.6MPa, increasing hydrogen in LCG, promotes both pre-mixed and diffusion combustions.

Negative effects of LCG addition on thermal efficiency in low load was investigated measuring the amount of unburned hydrogen in engine exhaust. Figure 9 shows the concentration and combustion efficiency of hydrogen against engine load p_e at r_{LCG}=0.15 and r_H=0.3. It can be seen that at p_e<0.4MPa, concentration of unburned hydrogen UH_2 in exhaust gas is relatively high and at p_e=0.2MPa about 20% of hydrogen added to the intake gas leaves engine without combustion.

As shown in Fig. 10, hydrogen concentration of r_H=0.1~0.3 in LCG corresponds to equivalence ratio of ϕ_H=0.05~0.125 for hydrogen. In low engine loads, combustion of diesel fuel which is the ignition source for hydrogen is spatially limited and unable to burn the very lean mixture of hydrogen mixture distributed in whole combustion chamber. This would be reason for low thermal efficiency of LCG at low engine loads.

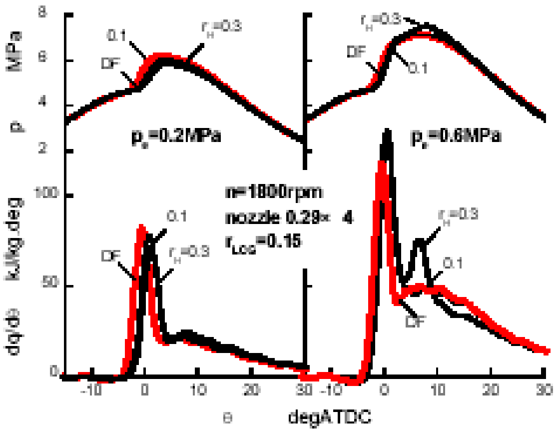


Fig. 8 Effects of LCG addition on combustion process under low and high engine loading.

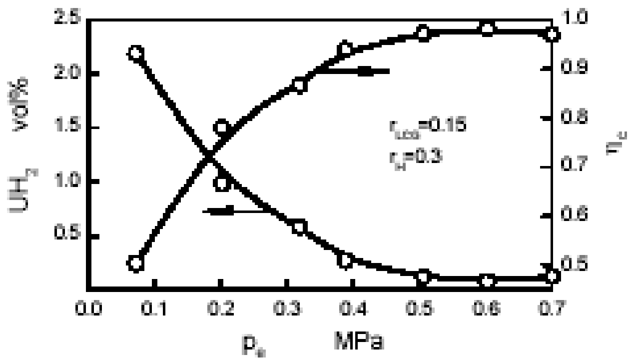


Fig. 9 Combustion efficiency of hydrogen against engine load.

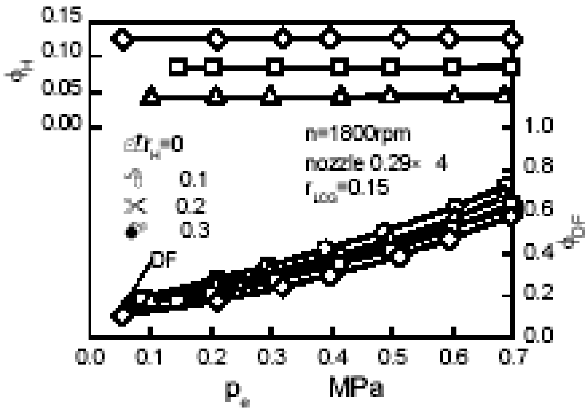


Fig. 10 Combustion efficiency of hydrogen against engine load.

Next, effects of LCG addition on emission were investigated under various engine loadings. Figure 11 shows engine emissions at the same experimental condition as Fig. 7. Increase in NOx concentration with p_e for LCG is similar to that in diesel fuel operations. However, its level is much lower. Concentrations of THC, CO and Smoke increase with LCG addition. However, when hydrogen concentration is increased up to r_H=0.3, the emission levels reach the diesel operation DF level. Summarizing above results, it can be suggested that in order to achieve high thermal efficiency and proper engine emission, operation of engine with LCG would be better to be limited to high engine loading. And hydrogen concentration of at least 30% is required.

LCG addition under various injection timing

In diesel engines, injection timing greatly affects the engine performance and emissions. Generally for diesel fuel operation, retarding injection timing offers lower NOx emission but higher smoke emissions. Advancing injection timing gives opposite results. An investigation was carried out to see the effects of injection timing when LCG is added to the engine intake gas. In this case, original injection pump was replaced with a jerk type pump (Zexel Type A) and nozzle (DLL-P) with four holes and hole size of 0.24mm is used to match the plunger size. Figure 12 and 13 show the engine performance and emissions when injection timing θj was varied in the range of 7.5~15 degBTDC at engine load of p_e=0.6MPa. In this case, amount and composition of LCG were fixed at r_{LCG}=0.15 and r_H=0.3 respectively. Results indicate that advancing injection timing improves thermal efficiency. This trend is similar for both fuels. As shown in Fig. 13, injection advancing improves Smoke, TC and CO emissions. Nevertheless, NOx emission is worsen. But for LCG addition, even at advanced injection condition still NOx emission level is much than that in diesel fuel operation.

This result reveals that using LCG at advancing injection condition, one can achieve low NOx emission, almost the same thermal efficiency, Smoke, THC and CO emissions as diesel fuel operation.

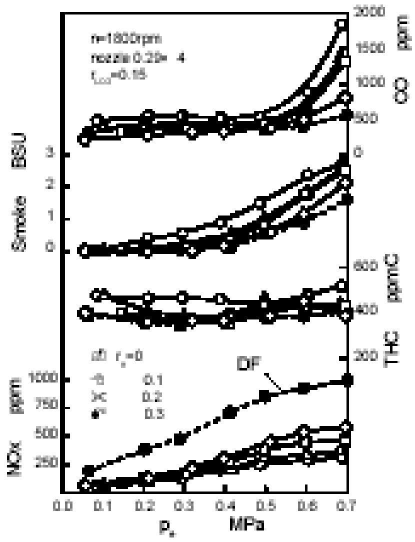


Fig. 11 Effects of LCG composition on emissions under various engine loading.

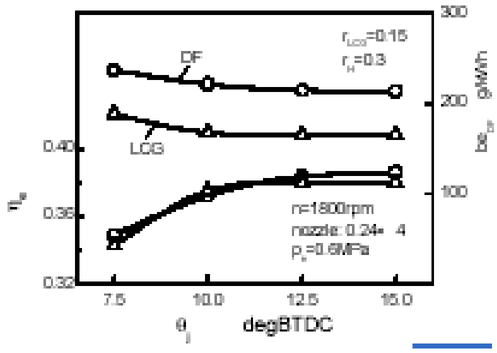


Fig. 12 LCG behavior under various injection timing.

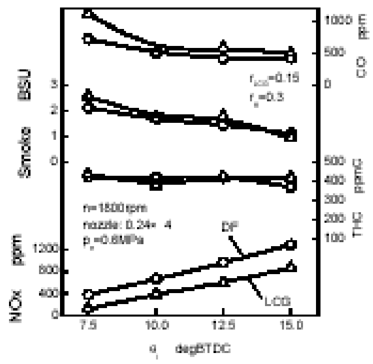


Fig. 13 LCG behavior under various injection timing.

Conclusions

This study demonstrates the optimized usage of law-calorific gaseous fuel in a direct injection diesel engine. The results are summarized as follows:

1. Addition of proper amount and composition of LCG to intake gas does not affect the thermal efficiency at middle and high engine loads. However, at low engine loads, thermal efficiency is decreased with LCG addition. Regardless of thermal efficiency, LCG addition offers a great saving in diesel fuel consumption.

2. At middle and high engine loads, promotion of the premixed and diffusion combustions due to the LCG addition is reason for the high thermal efficiency. However, at low engine loads, combustion

of small amount of injected diesel fuel is not sufficient to burn a very lean mixture of hydrogen. This would be reason for the low thermal efficiency of LCG.

3. LCG addition improves NOx emission due to the high amount of nitrogen added into the intake gas. Increasing hydrogen concentration to 30% lowers the NOx improvement. However, still level of NOx emission is lower than that in diesel fuel operation.
4. Increasing LCG concentration in intake gas gives an increase in Smoke, THC and CO emissions. This would be due to reduction in oxygen concentration. Nevertheless, increasing hydrogen concentration up to 30% compensates these disadvantages.
5. At high engine loads, advancing injection timing improves thermal efficiency and Smoke, THC and CO emissions for both diesel and LCG fuels. But LCG addition offers lower NOx emissions where other engine performance and emissions characteristics are the same as diesel fuel operation.

Finally, it must be mentioned that, in most studies (including this study) effects of LCG addition on engine performance and emissions were investigated using diesel engines with basic technologies. Nowadays, diesel engine employed in power generation are equipped with recent combustion control technologies such as optimized combustion chamber geometry, high pressure fuel injection system, cold EGR, supercharger and etc. The authors believe that utilization of low-calorific gas with low NOx emissions tendency in modern diesel engines generally with low smoke, CO and THC emission tendency would offer even better performance and emission characteristics than what is reported here in this study. These technologies are important also regarding CO gas in low-calorific gas. As mentioned earlier in this paper, due to safety factor CO gas was not added to the engine intake. Carbon monoxide with reasonable heating value and wide combustibility range is an important substance in LCG. Higher CO concentration in LCG would offer higher saving in diesel fuel consumption. However, if its concentration exceeds too much, then this would reflect on CO emission in engine exhaust. The authors believe that using LCG in diesel engines equipped with recent combustion control technologies would compensate this negative effect.

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