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Experimentally tested performance and emissions advantages of using natural-gas and hydrogen fuel mixture with diesel and rapeseed methyl ester as pilot fuels

S. Imran[a,b], T. Korakianitis[b,*], R. Shaukat[a], M. Farooq[a], S. Condoor[b], S. Jayaram[b]

[a] Department of Mechanical Engineering, University of Engineering and Technology, City Campus Lahore, Pakistan
[b] Parks College of Engineering, Aviation and Technology, Saint Louis University, St. Louis, MO 63103, USA

HIGHLIGHTS

- Triple fuelling of CI engines with hydrogen and natural gas.
- Diesel and RME used as pilot fuels.
- Triple fuelling presents better trade-off between specific HC and specific NOx.
- Reduction in specific HC was more prominent at lower loads.

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ABSTRACT

Higher unburned hydrocarbon emissions are attributed to the relatively low temperature combustion of natural gas in compression ignition engines whereas the combustion of hydrogen in compression ignition environment results in higher NO_X. These emissions characteristics are explained on the basis of different physio-chemical properties of the two gaseous fuel: higher C_p value in case of natural gas and higher diffusion coefficient, wider flammability limits and shorter quenching gaps for hydrogen are held responsible for these trends. This study assesses the potential of hydrogen being used in combination with natural gas with diesel and rapeseed methyl ester (RME) as pilot fuels. This type of fueling can be referred as 'triple fueling of the compression ignition engines' and has the potential to achieve a better trade-off between the higher NO_X associated with hydrogen and higher hydrocarbon emissions associated with natural gas based dual fueling of compression ignition engines. The present study has investigated the potential of the triple fueling of the compression ignition engines so far the attainment of a better trade-off between NO_X and hydrocarbon emissions are concerned. Comparing the specific NO_X and hydrocarbon emissions in different cases reveals that a significant drop in specific hydrocarbon emissions can be achieved at the cost of a small increment in specific NO_X. At both speeds (1000 rev/min and 1500 rev/min), the reduction in hydrocarbon emissions is more prominent at relatively lower loads, which can be a potential solution of reducing specific hydrocarbon emissions at lower loads in diesel engine operations. The stoichiometric equation for the triple fueling (Diesel or RME piloted mixture of natural gas and hydrogen) is also presented.

1. Introduction

Managing energy supply line has been a challenge for many decades now and the fast depletion of the fossil fuels and the political instability in the oil producing regions have made it really worse [1]. These factors have put a question mark on the sustainabilty of the energy supply line of these fossil derivatives [2] which continue to dominate the global petroleum spectrum [3]. To make the picture more complicated, engine manufacturers are under constant pressure to show compliance to the fast changing emissions standards [4]. This brings two questions for the engine researchers to answer.

- Is there a way to replace the fossil derivative fuels or replace a part of them to enhance their life if the gap between their supply and demand can not be made up?
- Is there a way to burn these fossil derivatives or their possible

* Corresponding author.
E-mail address: korakianitis@alum.mit.edu (T. Korakianitis).

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Nomenclature

Abbreviations

BMEP	brake mean effective pressure
CI	compression ignition
LNG	liquefied natural gas
HC	hydrocarbons
IC	internal combustion
NO_X	oxides of nitrogen
RME	rape methyl ester
IVO	inlet valve opens
IVC	inlet valve closes
EVO	exhaust valve opens
EVC	exhaust valve closes

replacement fuels better in slightly modified or totally unmodified engines?

Different strategies including split injection [5] and low pressure and hot EGR in premixed compression ignition (PCI) [6], have been investigated with a view to optimize the combustion performance. In continuation of the previous work [7–13], this study is an effort to answer these questions with special emphasis on the latter question. Various alternative fuels have been widely investigated in compression ignition (CI) engines. The fuels tested in CI environment include both liquid as well as gaseous fuels. The liquid fuels investigated as a possible replacement for diesel, mostly, include different biofuels derived from sustainable resources [14,15] such as rapeseed [16], jatropha [17] and palm [18] and soybeen [19,20] oils. The gaseous fuels investigated in CI engines and widely reported in literature include natural gas [1,9] and hydrogen [21]. While testing natural or hydroogen, the CI engines have been mostly run in 'dual fueling' mode [1,7]. The 'dual fueling' is a term used when a small quantity of a high cetane liquid fuel (such as diesel or RME) is used to start the ignition process of the gaseous fuel in an unmodified diesel engines. The high cetane fuel utilized to start the ignition process is called 'pilot fuel'. Both diesel as well as RME have been used as pilot fuels in the dual fueling of CI engines with natural gas or hydrogen as primary (main) fuels. Dual fuels have the potential to reduce the diesel consumption by 70% [22]. The use of these alternative fuels (both liqud as well as gaseous) produces different levels of emissions depending upon the thermo-physical characteristics of the fuels employed in addition to the engine operating conditions. Different authors have reported different trend in the emission resulting from the combustion of the sustainable fuels in CI engines operating under seemingly similar operating conditions. Three of the earlier studies in the group [16,21,23] have developed complete performance and emissions maps for diesel, RME, diesel (as well as RME) piloted natural gas and diesel (as well as RME) piloted hydrogen combustion in CI environment. These maps provide complete picture so far as the performance and emission characteristics of the CI engines, when fueled with fossil or sustainable fuel, are concerned. The performance of diesel and RME as pilot fuels in the dual fueling of natural gas and hydrogen have also been investigated, assessed and reported [24]. The same study also investigated the effect of pilot fuel quantity on the performance and emissions of the CI engine when fueled by natural gas and hydrogen (piloted by different quantities of diesel and RME). Similar results have been reported recently on an engine of different type and make [25]. It has been reported that the quantity of pilot fuel does affect the ignition delay phenomenon and hence has a direct bearing on the emissions characteristics of the dual fueled engines [26,27]. The effect of compression ratio, injection parameters and air throttling has been investigated when the engine was operated under dual fueling mode, with methane [4], methanol [28] and LNG [29] being the main fuels. Intake air strategies have employed to control equivalence ratio to mitigate the quenching phenomenon in dual fueled engines leading to reduced emissions of unburned hydrocarbons (HC) and CO [30].

Most of the literature reported on the dual fueling of natural gas and hydrogen has concluded the following [32–35].

- Higher NO_X and lower HC are resulted when the CI engine is dual fueled by diesel or RME piloted hydrogen
- Lower NO_X and higher HC are resulted when the CI engine is dual fueled by diesel or RME piloted natural gas

Table 1
Comparison of the combustion properties of CH_4 and H2 [31].

Sr.No.	Property	CH4	H2
1	Density @ NTP (kg/m^3)	0.6512	0.0838
2	Lower Heat of Combustion (MJ/m^3)	39.72	10.78
3	Higher Heat of Combustion (MJ/m^3)	35.80	12.75
4	Flammability range in air (%)	5.3–15	4.1–75
5	Stoichiometric composition in air (%)	9.48	29.53
6	Minimum Ignition Energy (m J)	0.29	0.02
7	Minimum Ignition Temperature (K)	813	858
8	Adiabatic Flame Temperature (K)	2158	2318
9	Burning Velocity (cm s^{-1})	42	237
10	Detonability (% in air)	6.3–13.5	18–59
11	Energy of explosion for gaseous fuel (MJ)	32.3	9.9

These trends for these two type of CI engine dual fueling cases have been and can be explained on the basis of thermo-physical properties of the two gaseous fuels. Some of the relevant thermo-physical properties are listed in the Table 1.

Dual fueling of CI engines with diesel or RME piloted natural gas or hydrogen has provided alternative fuels but the emissions concern remain un-addressed, higher NO_X in case of hydrogen and higher HC in case of natural gas based dual fueling of CI engines. Experimental and numerical investigations have been conducted to test hydrogen in natural gas compressed engines under various ignition timings and excess air ratios [36]. Very few studies have investigated the performance and emission characteristics of diesel engines when fueled by diesel (or RME) piloted mixture of hydrogen and natural gas [37–39] but the investigations were limited to one engine speed and one type of pilot fuel. This type of fueling can be referred as 'triple fueling of the CI engines' and has the potential to achieve a better trade-off between the higher NO_X associated with H_2 and higher HC associated with natural gas because of the thermo-physical properties of these gaseous fuels. The present study has investigated the potential of the triple fueling of the CI engines so far the attainment of a better trade-off between NO_X and HC emissions are concerned.

2. Experimental set up

A four-stroke single-cylinder, direct-injection Gardner 1L2 compression ignition engine was used. Table 2 summarizes the key feature of the experimental test rig. Fig. 1 shows the schematic layout of the test rig, which includes a dynamo-meter, fuel supply lines for both liquid (Diesel and RME) and gaseous (Natural Gas and Hydrogen), various emission analyzers and instrumentation.

Standard CI fuel injection system is used to inject the pilot fuel directly into the engine' cylinder. A hydrogen (compressed) tank maintained at 20 MPa is used to supply 99.995% pure hydrogen through a pressure regulator fitted on the tank with a flame arrestor. The hydrogen is fed to the hydrogen fuel line at 0.15 MPa. A hydrogen flow meter (CT Platon glass variable area flow meter, 44 l/min scale) is used