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Experimental investigation of the equivalence ratio influence on combustion, performance and exhaust emissions of a dual fuel diesel engine operating on synthetic biogas fuel

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ABSTRACT

In this work, an experimental investigation was conducted to analyze dual fuel (DF) engine operation using synthetic biogas fuel under high load at constant percentage energy substitution rate (PES). The performance, ignition delay, and other combustion characteristics of engines operating in dual fuel mode (biogas/diesel), are compared to the conventional mode. The synthetic biogas, composed of 60% methane and 40% carbon dioxide, is the primary fuel which is blended with the air in the engine inlet manifold, whereas the pilot fuel is diesel. The equivalence ratio (fuel-air) (ϕ) was varied by changing air flow rate while the energy introduced into the engine remained constant for all the examined cases. Combustion analysis showed that with increasing ϕ, the ignition delay tends to become longer and the peak of heat release rate was increased. Furthermore, as ϕ increased from 0.35 to 0.7, HC and CO emissions were reduced by 77% and 58% respectively. The NOx emissions decreased at 60% PES by 24% while the BTE was improved by 13%.

1. Introduction

The development of internal combustion engines and the process of reducing pollutant produced by fuel combustion have become mandatory requirements for propulsion systems designers. One of the main objectives is to find the best way to minimize the emissions without considerably modifying the engine's mechanical structure while maintaining the same performance. One of the proposed solutions is the method of injection of diesel fuel and the use of diverse gaseous fuels like biogas, natural gas, etc.

As a result of the gradual depletion of fossil oil and environmental degradation, the utilization of gaseous fuels from biomass has attracted the attention of researchers. Thus, the use of some alternative gaseous fuels in the diesel engine is increasing worldwide. Biogas is an alternative fuel produced through a biological process. In the absence of oxygen (anaerobic condition), the methanization reaction starts spontaneously when organic matter is in a tepid environment, where it decomposes to form a gaseous mixture called biogas. Raw materials, like industrial waste, agricultural and biomass present an important potential for the generation of biogas but are underutilized [1]. The biogas composition varies according to parameters such as humidity, gas pockets, and variations of the waste location.

Because of the increasing demand to reduce pollutant emissions from existing technologies of internal combustion engine (ICE), several researches have been carried out investigating new approaches to achieve this goal. However, amongst several studies, the conversion of the diesel engine into a dual fuel (DF) engine with minor modifications [2], so as to use the alternative fuel, showed interesting results. In fact, a compression ignition (CI) engine running in conventional mode can be altered into DF mode by branching a gas blender to its intake manifold. In this mode, gaseous fuel is injected into the inlet manifold where it is mixed with air. After that, the gaseous mixture enters into the combustion chamber where the pilot fuel, which has a high cetane number, is injected directly and then, ignites to initiate the combustion [3]. It is noted that biogas fuel is more suitable for engines with high compression ratio due to its relatively high octane number in order to maximize thermal efficiency. Moreover, it was suggested that the engine operating in DF mode running in biogas can be used to reduce the quantity of the diesel injected, and at the same time, diminish the compromise between NOx and smoke [3,4].

In diesel engines, the air temperature is more than 553 K close to the moment of diesel injection. However, in dual fuel mode, under these conditions, the biogas cannot ignite without the presence of a little quantity of pilot fuel to raise the temperature up to about 1087 K [5].

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Nomenclature

Q	heat [J]
γ	ratio of specific heats [–]
P	cylinder pressure [bar]
V	cylinder volume [m^3]
BTE	brake thermal efficiency [%]
LHV	lower heating value [MJ/kg]
$\dot{m}$	mass flow rate [kg/s]
P_b	brake power [kW]
PES	percentage energy substitution [%]
ID	IGNITION delay [deg CA]
θ	crank angle [deg CA]
L	connecting rod length [m]
V_d	displacement volume [m]
C	stroke [m]
IVO	intake valve open [deg CA]
IVC	intake valve close [deg CA]
EVO	exhaust valve open [deg CA]
EVC	exhaust valve close [deg CA]
AFR	air fuel ratio
WOT	wide open throttle
CA	crank angle
CR	compression ratio
ϕ	equivalence ratio
TDC	top dead center
BDC	bottom dead center
DF	dual fuel
CI	compression ignition
HC	hydrocarbon
NOx	nitrogen oxides
CO_2	carbon dioxide
CO	carbon monoxide
CNG	compressed natural gas
LPG	liquid natural gas
NG	natural gas

Subscripts

net	net
w	Wall of cylinder
c	Combustion
D	Diesel
B	Biogas
b	brake

Furthermore, it has been observed that the dual fuel engine requires a shortened combustion duration of (biogas/diesel) compared to that with diesel conventional mode, which shows that in case of dual fuel modes combustion finishes much quicker [6]. Various gaseous fuels (methane, propane, CNG, LPG, hydrogen) can be used to power the diesel engine operating in DF mode while maintaining engine efficiency and reducing exhaust emissions [7]. Moreover, the reduction of some exhausts emissions and the improvement of the engine efficiency can be achieved by optimizing certain parameters influencing the engine such as substitution ratio, injection timing, engine loads [8], and inlet air temperature [9].

Additionally, Luijten and Kerkhof [10] have replaced diesel with Jatropha oil to ignite the DF engine operating with biogas. A reduction of about 10% of the brake thermal efficiency was observed. Furthermore, Bora et al. [11] have varied the compression ratio (CR) of DF engine operating with biogas from 16 to 18. They found that the best BTE was achieved for CR = 18.

On the other hand, the effect of the biogas composition in DF mode was studied by Daouk et al. [12]. They noted that biogas, containing 70% methane (CH_4) (by volume) and about 30% carbon dioxide (CO_2), has advantages in terms of emissions compared to the conventional mode. In addition, they found that the variation of the composition of biogas did not have a significant effect on engine performance [12]. Also, the study of the performance of dual fuel (biogas-diesel) was established by Lounici et al. [7], where a good knock resistance was observed from measured torque at the knock onset. The same observation was achieved by Ibrahim et al. [13] by suggesting predominantly premixed charge compression ignition mode of combustion to improve the performance of biogas Dual fuel engines. In addition, Sorathia et al. [14] found that the Dual fuel mode fueled with biogas did not show any performance deterioration.

It was reported by several researchers that the high levels of HC emissions produced by DF combustion is a disadvantage of this mode. In fact, it was achieved in other works that the hydrocarbon emission in normal diesel mode was lower than that in dual fuel (NG/diesel) operation, by about 6000 ppm [15]. Though, HC emissions decrease as engine load increases; at full load, the value of hydrocarbon emissions were still about 2000 ppm, i.e., 2.5 times compared to DF mode with natural gas [16]. Thus, the need to get a method to diminish the HC emissions on a DF mode emerges.

Various methods such as using injection timing [17], gas recirculation burning [18], raising the quantity of pilot fuel [19], etc. have been used in DF engine (NG/diesel) to reduce the HC without lowering the thermal efficiency.

Previous studies focused mainly on the use of natural gas for engines running in DF mode with respect to biogas. There are many studies about biogas as a high potential alternative source of energy for compression ignition engines. However, these studies stated that the use of biogas can be limited by the high levels of pollutant emissions, especially unburned hydrocarbon. Thus, the main objective of the present study was to investigate the effect of equivalence ratio on the combustion process, thermal efficiency and the exhaust emissions at high load. The motivation behind this research work is to find a technique to reduce pollutant emissions without any drawbacks regarding the performance of CI engine using biogas as primary fuel. The proposed technique is based on varying the total equivalence ratio using a throttle valve to adjust the air mass flow rate. To carry out this investigation, a 7.5 kW single cylinder, DI, Air cooler, diesel engine was converted to run in dual fuel mode (biogas/diesel). Experiments were conducted at different total equivalence ratio conditions at a fixed energy input. This technique has allowed us to reduce 77% and 58% HC, CO respectively when ϕ was varied from 0.35 to 0.7, with an improvement of BTE of about 19%.

2. Materials and procedure

2.1. Biogas used in engine test

In general, the composition of biogas fuel ranges from 50% to 70% (by volume) for methane and 30% to 50% for carbon dioxide [20]. In this study, CH_4 and CO_2, stored separately in pressurized bottles, were used in the engine test with a percentage of 60% and 40% respectively.