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Strategies for high efficiency and stability in biogas-fuelled small engines

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ABSTRACT

This work assesses the performance of small biogas-fuelled engines and explores high-efficiency strategies for power generation in the very low power range of less than 1000 W. Experiments were performed on a small 95-cc, single-cylinder, four-stroke spark-ignition engine operating on biogas. The engine was operated in two modes, i.e., ‘premixed’ and ‘fuel injection’ modes, using both single and dual spark plug configurations. Measurements of in-cylinder pressure, crank angle, brake power, air and fuel flow rates, and exhaust emissions were conducted. Cycle-to-cycle variations in engine in-cylinder pressure and power were also studied and assessed quantitatively for various loading conditions. Results suggest that biogas combustion can be fairly sensitive to the ignition strategies thereby affecting the power output and efficiency. Further, results indicate that continuous fuel injection shows superior performance compared to the premixed case especially at low loads owing to possible charge stratification in the engine cylinder. Overall, this study has demonstrated for the first time that a combination of technologies such as lean burn, fuel injection, and dual spark plug ignition can provide highly efficient and stable operation in a biogas-fuelled small S.I. engine, especially in the low power range of 450–1000 W.

1. Introduction

The lack of power sources, especially in rural areas of developing countries necessitates the search for efficient power producing devices for small scale operation. Also, the depleting fossil fuel-based energy resources necessitate the search for new and renewable energy resources. In this respect, biogas can act as a promising alternative fuel. The ease of generating biogas with the available biomass imparts an advantage for its utilization. The two most common types of biogas are landfill gas and digester gas, both of which are by-products of anaerobic decomposition of organic matter. It primarily contains methane (CH_4) and carbon dioxide (CO_2). The usual composition is: CH_4 (50–70%), CO_2 (25–50%), N_2 (0.3–3%), H_2 (1–5%), and minor traces of H_2S.

The presence of CO_2 and N_2 reduces the heat content of biogas as compared to natural gas. Further, the increase in the specific heat of CO_2 with temperature causes a reduction in the adiabatic flame temperature. Although these factors result in poorer engine performance, they also account for lower NO_x emissions from engines running on biogas [1]. Flame speed, ignition delay, and knock characteristics are affected by fuel composition. Therefore, understanding the impact of gas composition on the engine performance and emissions is important especially to minimize the losses due to incomplete combustion. A comprehensive review was provided by Mustafi et al. [2] on use of biogas in internal combustion engines, where some of the above-mentioned aspects have been discussed in detail. Huang and Crookes [3] had assessed the performance of simulated biogas in spark ignition engine and concluded that the compression ratio can be increased up to 13:1 without knocking. This leads to high power and thermal efficiency for relative air–fuel ratio of between 1.05 and 0.95. Porpatham et al. [4] found that the reduction in the concentration of CO_2 in biogas leads to higher efficiency and power output in S.I. engines. With increase in CO_2 concentration, maximum brake power shifts toward the leaner side. Midkiff et al. [1] also suggested lean operation for high power and efficiency and similar effect of CO_2 on power and emissions were observed by Shrestha and karim [5]. According to an earlier study on CFR engines (diesel engines fumigated with natural gas), engine power was lower with biogas, but HC, NO_x, and CO emissions were also lower [6]. Significant lowering of flame propagation rates with the increased proportion of carbon dioxide in S.I. engine was also observed. This correspondingly increases the average length of the combustion period and ignition lag times. Catapano et al. [7] reported optical measurements in a 250-cc single cylinder S.I. engine using pure methane and CH_4/H_2 blends. The flame propagation speed, which was observed to be very low for pure methane, increased with increasing H_2 content. Additionally, large HC emissions were observed in all tested fuel combinations; possibly due to slow flame speeds and long quenching distance of methane. This study brings out the challenges involved in the complete combustion of a slow burning fuel (methane). Biogas is expected to burn even slower, due to the presence of diluents such

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as CO_2; potentially making the twin spark plug configuration very attractive for stable combustion.

Computational studies by Yoseffi et al. [8] showed that the early stages of combustion are more sensitive to the characteristics of the ignition source than to even large changes in fuel composition. Diluent in the fuel slows down the reaction rates and chemical heat release rates, resulting in a lower flame propagation speed. This is mainly due to the increase in the molar heat capacity of the mixtures in comparison with air, the influence of which becomes more pronounced as temperature increases. Kapadia [9] studied two different modes of fuelling namely, premixed mode of gas supply and manifold gas supply into the engine. The results showed high overall efficiencies at power levels of up to 1.4 kW using manifold gas injection. Meyer et al. [10] discussed the effect of the number of spark plugs and their location in natural gas engines and found that the use of multiple spark plugs is better than a single centrally located spark plug for high power and thermal efficiency at leaner equivalence ratios. There are several recent investigations on biogas which focus on the dual fuel mode [11–15], namely the use of biogas with an additional fuel such as diesel, biodiesel or hydrogen. In most of these investigations such as those of Luijten and Kerkhof [11] and Crookes [14], the performance of biogas has been assessed in the dual-fuel mode in terms of the power output and efficiency. Recent studies have focused on the use of biogas in the HCCI mode for improved efficiency, both in the dual-fuel mode [12] and in the pure biogas mode [16]. These studies show that biogas is a promising option for stationary power generation applications.

Most of the above work concerns medium or relatively high power, multi-cylinder engines. There is no information available in the literature on the operation of very small S.I. engines with biogas, or performance studies with biogas for very low power applications in the range of less than 1 kW. Such low-power generators are especially suitable in remote rural areas, where individual houses usually have power requirements of less than 1 kW. This is important as power output and efficiency at these power levels with larger engines tend to be very low owing to the fact that part load operation of engines is always inefficient. Furthermore, installation of larger more expensive generation and distribution systems is generally not feasible in rural areas due to the high capital and maintenance costs involved in such projects. On the other hand, use of small biogas-fuelled generators can provide a cost effective and reliable source of electric supply to many rural areas that are either still not connected to the grid or suffer from prolonged power outages. Therefore, the main objective of this study was to assess the performance of very small engines ($\sim$100 cc capacity) operating on biogas, while also focusing on exploring strategies to enhance engine efficiency. The tested strategies include the use of multiple spark plugs and an electronically controlled manifold gas injection system. In this work, the implementation of electronically controlled, biogas manifold injection on a small S.I. engine is reported for the first time, to the best of our knowledge.

2. Experimental system and procedure

2.1. Experimental system

The experimental system is represented in Fig. 1. The setup consists of regulating and metering devices for air and fuel, test engine, a dynamometer, an electronic engine control unit (ECU), a computer-based in-cylinder pressure and crank angle measurement system, a compressed biogas reservoir, and an exhaust gas analyzer. Tests were performed while operating the engine with single and dual spark plugs, at a constant speed of 3000 rpm. In these tests, parameters such as brake power, air and fuel flow rates, exhaust emissions and in-cylinder pressure were measured.

Performance tests were carried on a single cylinder, four-stroke, S.I. engine with single and dual spark plugs. The engine specifications are listed in Table 1. The two spark plugs were located diametrically opposite to each other. Engine was controlled using a hysteresis brake dynamometer that was set to operate the engine at 3000 rpm. By varying the throttle position and fuel flow rate, desired engine power output could be obtained. An ECU was developed to control the injection duration and electronically throttle the air flow to achieve leanest engine operation without any compromise on engine power output. Biogas was injected at 30 °. BTDC during the intake stroke and the injection duration could be varied up to 23 ms as the load increases. The optimal spark timing was found to be 42 °. BTDC for continuous injection and was maintained the same for premixed mode also. The programmable ECU also acted as an interface to control the engine using a computer.

To study the effect of the aforementioned strategies (manifold injection and premixing) on engine performance, in-cylinder pressure-crank angle data is required. The small bore size (53 mm) of the engine cylinder coupled with the presence of two spark plugs and two valves meant that the space available in the cylinder head was very limited as shown in Fig. 2. Hence, a KISTLER 6052C-U20 pressure sensor with small diameter (5 mm) was selected for measuring in-cylinder pressure. Precise machining was required for seal-proof mounting of the pressure sensor. Pressure corrections were done for the negative pressure signals of the sensor as suggested by Lee et al. [17]. For crank angle measurement, a KISTLER 2613-B1 crank angle encoder was used.

Further, experiments were also conducted to study engine performances under the two gas induction modes using both single and dual spark plugs. The engine was run using synthetic biogas, which is stored in a high pressure cylinder and containing 65% methane (CH_4) and 35% carbon dioxide (CO_2) by volume. Biogas flow was controlled using a manually operated needle valve for the premixed and continuous injection modes. A pressure regulator was used to reduce the biogas pressure (to 0.1 bar) in order to simulate the low-pressure biogas generated in typical biomass digesters. A Cole–Palmer digital laminar volume flow meter was used to measure the biogas flow rate. An electronic throttle valve was used to control the amount of air being transferred to the engine cylinder from the air filter. The air flow was measured using an orifice flow meter at the inlet of a 200 l plenum chamber. The plenum chamber serves as a reservoir for air and dampens oscillations in the air flow caused by engine suction; therefore providing an average air flow at the orifice. This study used a quarter-circle orifice plate with a pipe diameter of 50 mm and orifice diameter of 22 mm. Pressure across the orifice plate was measured using a water based U-Tube manometer. Apart from these measurements, oxides of nitrogen and hydrocarbons were also measured using a MRU exhaust gas analyzer.

2.2. Biogas induction

Manifold injection and premixed mode are the two ways of inducting a gaseous fuel into the engine.

Manifold injection: As shown in Fig. 3, this mode involves inducting the fuel after the throttle body, which is expected to increase volumetric efficiency (as only air is throttled by the throttle body) and also potentially increase the in-cylinder charge stratification. Stratification is the phenomenon associated with the presence of a spatially fuel-rich region in the engine cylinder. If the rich zone is in the vicinity of the spark plug, then combustion is expected to be stable. However, combustion quality is expected to be poor (along with increased chances of misfire) if the leaner pockets are in the vicinity of the spark plug. Chintala and Subramanian