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Investigation on combustion performance and emission characteristics of a DI (direct injection) diesel engine fueled with biogas–diesel in dual fuel mode

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ABSTRACT

In this research work, biogas was produced by the anaerobic digestion of non-edible de-oiled cakes obtained from oil crushing units. Further, the biogas was used as an alternative gaseous fuel in a DI (direct injection) diesel engine, in the dual fuel mode. Diesel was used as an injected fuel and biogas was inducted through the intake manifold, at four different flow rates, viz., 0.3 kg/h, 0.6 kg/h, 0.9 kg/h and 1.2 kg/h, along with the air. The combustion, performance and emission characteristics of the engine in the dual fuel operation were experimentally analyzed, and compared with those of diesel operation. The results indicated that, the biogas inducted at a flow rate of 0.9 kg/h was found to give a better performance and lower emission, than that of the other flow rates. The ignition delay in the dual fuel operation is found to be longer than that of diesel throughout the load spectrum. The cylinder peak pressure in the dual fuel operation is found to be overall higher by about 11 bar than that of diesel operation. The NO (nitric oxide) and smoke emissions in the dual fuel operation are found to be lower overall by about 39% and 49%, compared to that of diesel operation.

1. Introduction

Gaseous fuels are considered to be good for IC (internal combustion) engines, because of their good mixing characteristics with air. The high self-ignition temperature enables them to operate with lean mixtures and higher compression ratios, resulting in an improvement in the thermal efficiency and reduction in emissions. Biogas is a good renewable gaseous fuel, and is produced by the anaerobic digestion of cow dung, non-edible seed cakes, animal waste, food waste, agricultural waste, municipal waste, sewage sludge, etc. [1]. Methane is the main constituent of biogas, and the proportion varies from feed stock to feed stock. Table 1 gives the biogas yield and methane percentage of some commonly used feed stocks [2–6].

The European Union has planned to use at least 25% of bioenergy from biomass sources in future [7]. Among all types of feed stocks, non-edible de-oiled cakes have a higher potential to produce biogas, because they have a higher percentage of carbon and other useful ingredients, for the survival and growth of anaerobic microorganisms [7]. Cow dung is considered as a normal feed stock, since many years. It has 36.13% carbon by weight, and the water content is 81.2% by weight on a dry basis, with the TS (total solid) is only 18.8% by weight, which is very low in comparison to non-edible seed cakes. These lower elemental values of cow dung lead to relatively low specific methanogenic capacities [8,9]. Generally, cow dung is required to mix with the de-oiled cakes before anaerobic digestion, because the fresh dung possesses anaerobic microorganisms for initiating the biochemical digestion process.

Now-a-days, biodiesel production from non-edible seeds such as *Jatropha curcas* (Jatropha), *Pongamia pinnata* (Karanja), *Scheleichera oleosa* (Kusum), *Shorea robusta* (Sal) and *Madhuca indica* (Mahua) are receiving more attention worldwide [10]. The oil extracted from these seeds is about 25% and the remaining 75% is the seed cake, a waste by-product. The de-oiled cakes of non-edible nature are of no use, and disposed in the open land, because these can neither be used as cattle feed nor directly in agricultural farming, due to their toxic nature (i.e. presence of crucin, saponins etc.). So, if these cakes are kept in an open environment, they would create environmental problems, by generating various gases, such as CH_4 (methane), N_2O (nitrous oxide), H_2S (hydrogen sulfide),

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Table 1
Biogas yield and methane content in feed stocks [2–6].

Feed stock	Biogas yield, m^3/kg	Methane, %
Cattle dung	0.297	55
Pig manure	0.40	65
Straw	0.341	51
Municipal solid waste	0.308	60
Jatropha curcas de-oiled cake	0.640	66.5
Pongamia pinnata de-oiled cake	0.738	62.5
Spent wash	0.65	58.7
Leaves	0.210	58
Wheat straw	0.432	59

NH_3 (ammonia), CO_2 (carbon dioxide) and VOCs (volatile organic compounds), by the action of various microorganisms. The utilization of such de-oiled cakes is a challenge today. In recent years, anaerobic digestion technology has gained importance, especially for biomass wastes [11]. The production of biogas from de-oiled cakes would be the best solution for its efficient utilization. Biogas is a carbon neutral gaseous fuel, because it can be derived from nature's photosynthetic products, giving zero addition of greenhouse gases to the environment [3,12]. As the biogas is in a gaseous form and a low cetane fuel, it can be used in CI (compression ignition) engines in the dual fuel mode [13]. Many researchers have studied the combustion, performance and the emission characteristics of engines fueled with both gaseous and liquid fuels in dual fuel mode [14–19]. In a dual fuel engine, after the compression of the charge, comprising the inducted fuel and air, a small amount of diesel, called the pilot fuel is injected into the engine. This injected pilot fuel gets self-ignited and becomes the ignition source for the inducted fuel [15]. The main advantage of a dual fuel engine is that, it can run with a wide variety of liquid and gaseous fuel without any major engine modifications [16].

Duc and Wattanavichien [20] gave an overview of several studies on the engine performance of diesel and dual fuel operation with biogas, which is not conclusive. The overview revealed that, some research works indicated an increase, some a decrease, and some reported no difference of performance in comparison with diesel operation. These seemingly contradictory results are the consequence of the combustion timing, which is affected by both the operating conditions and the fuel choice. Cacua et al. [21] reported that, the ignition delay is a critical parameter to control the performance and emissions of a biogas fueled dual fuel engine. Nathan et al. [22] reported that, the biogas dual fuel engines generally exhibit low thermal efficiency, due to the presence of CO_2. At lower loads, the biogas addition results in a decrease (up to 10%) in the thermal efficiency, depending on the biogas quality (CH_4/CO_2 ratios), but it hardly matters, at higher loads [13]. Moreover, as the compression ratio increases, the brake mean effective pressure and the brake thermal efficiency increase. At a higher compression ratio, the combustion temperature becomes higher, causing more NO emission [23]. Karim [18,19] claimed that the dual fuel operation results in a higher power output, better specific fuel consumption, superior emissions, and quieter and smoother operation.

The main objectives of the experimental investigation were to produce, and characterize the biogas obtained from *P. pinnata* de-oiled cake, through the anaerobic digestion carried out in a floating dome type digester. Also, the aim was to evaluate the combustion, performance and emission characteristics of a DI diesel engine running in the dual fuel mode. For dual fuel operation, the biogas at four different flow rates, viz., 0.3 kg/h, 0.6 kg/h, 0.9 kg/h and 1.2 kg/h was inducted through the suction, and diesel was injected as a pilot fuel. Finally, the results obtained from the dual fuel operation were compared with those of diesel operation, and presented in this paper.

2. Methodologies and experimental details

2.1. Biogas production

Anaerobic digestion is a commonly used method for the biochemical treatment of organic waste materials, due to its stabilization and higher performance in volume reduction. It is a biochemical degradation process, in which biodegradable organic matter is decomposed by bacteria forming gaseous by-products (biogas). These gaseous by-products consist of methane, carbon dioxide, and traces of other gases. Anaerobic digestion is a complex process, which can be divided into four stages: (i) hydrolysis, (ii) acidogenesis, (iii) acetogenesis or dehydrogenation, and (iv) methanation. In the first stage, the hydrolyzing microorganisms convert the polymers and monomers into acetate, hydrogen, and some amount of VFA (volatile fatty acids), such as butyrate and propionate. Then, a complex consortium of hydrolytic microorganisms excretes the elements of the organic materials, such as cellulose, cellobiase, xylanase, lipase, protease and amylase into amino acids, and long chain fatty acids. The higher VFA that are formed by hydrolyzing microorganisms are again converted into acetate and hydrogen, by obligate hydrogen producing acetogenic bacteria. These bacteria, typically characterized as homoacetogenic are named as *Acetobacterium woodii* and *Clostridium aceticum*. The metabolism of the acetogenic bacteria is inhibited rapidly by the hydrogen accumulation. Therefore, it is essential to maintain an extremely low partial pressure of hydrogen inside the digester, for the survival of the acetogenic and hydrogen producing bacteria. The daily biogas production can also be increased by adding hydrogen producing bacteria to the digester feed slurry [24,25]. At the end of the biochemical degradation process, two groups of bacteria produce CH_4, CO_2 and hydrogen from acetate. And, only a few species, e.g., *Methanosarcina barkeri*, *Metanonococcus mazei*, and *Methanotrix soehngenii* are able to degrade acetate into CH_4 and CO_2, whereas all other bacteria use the hydrogen to form CH_4 [26].

Biodiesel production from non-edible oil seeds such as *P. pinnata* and *J. curcas* is of primary importance in a country like India. The use of edible oil for biodiesel production is not encouraged, because of less production and heavy dependence on import. *P. pinnata* is abundantly found along the banks of rivers and tidal forests in India. It is reported that about 0.145 million metric tons/year of *P. pinnata* seeds are produced annually [6,27]. The de-oiled cakes of such non-edible oil seeds from the expeller units will be disposed in a considerable quantity, which may cause severe land pollution. These de-oiled cakes can be converted into useful energy, either by biochemical or thermo chemical processes. In this investigation, biogas was produced from the de-oiled cakes of *P. pinnata* in a floating dome type digester. Fig. 1 shows the schematic diagram of the floating dome type biogas plant.

The floating dome biogas plant consisted of two parts; digester (part A) and gas holder (part B), and both were made up of PVC (polyvinyl chloride) material. The diameter of the digester was 0.25 m more than that of the gas holder (diameter 1.10 m). The detailed specifications of the biogas plant are given in Table 2. The gas holder was placed inversely over the digester for collecting the biogas from the slurry. The gas holder always floated over the slurry, and a 12 mm hose pipe was connected from the gas holder to the engine experimental setup, for carrying the biogas. The feed stock used for the experiment was *P. pinnata* de-oiled cake, with cow dung in the proportion of 25%:75% on a mass basis. The measured quantities of *P. pinnata* de-oiled cake (3 kg/day) and cow dung were taken, and mixed with water in the ratio of 1:3.5 and 1:1 for feeding the digester.

The physical parameters of the feed stock are given in Table 3. The total volume of the inoculum formed (de-oiled cake + cow dung + water) was measured with a cylindrical vertical measuring