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Development of an engine control system using city gas and biogas fuel mixture

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HIGHLIGHTS

- ▶ The gas engine control system was developed using both city gas and biogas flexibly.
- ▶ The developed control system corporates with an original controller.
- ▶ The target value of O_2 emission is decided by Wobbe index of mixture fuel and load.
- ▶ The controller achieved stable operation for fuel mix ratio and load changing.

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ABSTRACT

In this paper, a gas engine system capable of stable operation at any mix ratio of city gas 13A and biogas was developed. The gas engine system consists of a spark-ignition gas engine, an additional electric throttle valve for fuel and our own control algorithm. The engine is a 3-cylinder 1.6-l engine that was originally used for co-generation, and the fuel throttle valve was added to respond to different fuel compositions. The control algorithm was also designed to adjust the fuel and air ratio to attain a higher generation efficiency and lower NOx emission with different mix ratios of city gas 13A, biogas and load. Before developing the controller, the effect of the mix ratio on generation efficiency and NOx emission was investigated under various load conditions. The following summarizes the experimental results: a control algorithm using the Wobbe index for mixed fuels was formulated; this index determines the target fuel-to-air ratio. Next, operation tests were performed under varying fuel mix ratios and loads by applying the control algorithm to the gas engine. The target engine rotational speed and exhaust O_2 concentration was realized in 5 s when the biogas fraction varied from 20% to 40% and from 70% to 40%. When the load was also varied from 9.4 kW to 0.5 kW and from 0.5 kW to 9.4 kW at a constant rate, the rotational speed and exhaust O_2 concentration achieved the target values in 20 s. Under both transient operation conditions, the engine system met the NOx emission requirement, and the results indicate that the simple hardware modification to a conventional gas engine and our original control algorithm are capable of achieving stable engine operation at any mix ratio of city gas 13A and biogas.

1. Introduction

Biomass is an attractive alternative energy source due to its ability to reduce dependence on fossil fuels, realize a sustainable society and also reduce the amount of waste. Various biomass resources are used in different ways. Solid fuels produced from wood biomass are fired directly and are often used in stoves. Liquid fuels, such as ethanol and biodiesel, are also produced from plants and are used in automobiles due to their portability. Gas fuels are also produced from wood biomass by thermochemical conversion processes or from domestic wastes and sewage which contain much water by a fermentation process. Gas fuels are used in reciprocating engines and/or micro-gas turbines, such as those used in distributed generation systems, but not in large-scale concentrated power-generating systems due to their inefficiency and high cost attributed to their distribution and low energy density, particularly in Japan.

There are two main types of gas fuels produced from biomass: producer gas produced by thermochemical conversion processes and biogas produced by fermentation processes. The main components of producer gases are hydrogen (H_2), carbon monoxide (CO) as the combustible, nitrogen (N_2), carbon dioxide (CO_2) as the incombustible, and a few hydrocarbons [1–3]. The main components of biogas are methane (CH_4) and CO_2 [4,5]. One of the characteristics of gas fuels produced from biomass is a low calorific

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value; their lower heating values (LHV) are less than 25 MJ/m^3 [1–5], which is lower than that of city gas 13A (LHV 40.4 MJ/m^3) [6]. Another characteristic that is particular to producer gases is its variety of components. The components of producer gases depend on the resource type [7], gasification condition [8], and gasification methods. The feed material and the digestion method also affect the composition of the biogas; however, the effect is not much significant than producer gas. The composition is typically within 50–70% CH_4 and 25–50% CO_2 [4,5]. These fuel component variations are evaluated from the perspective of a well-rounded static state, which means that the product gas characteristics are often discussed using time-averaged values; however the product gas characteristics vary to some extent from time to time because the gasification conditions, etc., vary, even if the setup values are kept at constants. One example is pyrolysis gas, in which an LHV fluctuation greater than 0.5% in 30 s arises almost 50% of the time [9]. In addition, the amount of gas fuel supplied to engines varies because of a lack of a feed rate for biomass resources for various reasons. Fuel characteristics also exhibit a non-steady variability. In these situations, engines are desired to work in a stable state.

Engine specifications and control systems that effectively use biomass fuels in the stable state have been studied and developed. It has been validated that a prechamber and a higher compression ratio are effective to realize a stable operation for simulated biogas when the composition is constant. A prechamber jets hot gas into a main chamber to realize a stable ignition for low calorific fuels, which have more inert gases that leads to low ignition performance [10]. Diesel fuel injection is also effective [11]. The energy of jet ignition and pilot fuel is greater than that of a spark plug. However, the installing a prechamber and other parts is difficult due to limited space and increased costs. A higher compression ratio of 13.3 for biogas achieves faster combustion, even with a leaner mixture condition, and a higher efficiency than for a compression ratio of 12.0 for natural gas with the same emissions range [10]. Other researchers have attempted to use different fuel together with biomass fuels to improve ignition and combustion. Hydrogen addition and exhaust gas recirculation (EGR) have been used and their effects have been investigated for a model biogas to improve both generation efficiency and NOx emission. The generation efficiency of biogas with hydrogen increases by approximately 1.5% compared with using only biogas for adjusting the spark timing and EGR ratio to satisfy the NOx regulation [12]. For liquid biomass fuels, dual injection has been proposed. With dual injection, different quantities of gasoline and biofuel are separately injected using a port injector and a direct injector into the engine to achieve more fuel flexibility by altering the fuel mix ratio based on engine demand and in-vehicle fuel availability for a spark ignition engine. The combustion and emission characteristics of dual injection have been investigated at steady states. Because the fuels mix ratio influences the composition and due to the difficulty in controlling the air–fuel ratio because of different theoretical air–fuel ratios, this paper uses the cross-over theory using the relationship between O_2 and CO emissions to maintain a constant air–fuel ratio of 1.0 for various fuel mix ratios [13]. Other studies have worked on fuel fluctuations. The main countermeasures against fuel fluctuations in large-scale engines that have been used include diesel fuel injection, which can achieve stable ignition and combustion as mentioned previously, and diesel fuel injection, which also compensates for the lack of gas fuel produced from biomass to maintain power [14].

We have developed a small gas engine system that is capable of stable operation using gas fuel produced from biomass. An automatic control algorithm was developed; this algorithm defines the target equivalence ratio and ignition timing to achieve a high generation efficiency for varying fuel components using the in-cylinder gas pressure in real time [15]. The efficient use of biomass gas by the engine with the automatic control system was verified experimentally. This system, however, uses an in-cylinder gas pressure sensor, which requires special manufacturing for installation and leads to high costs. We developed another engine control algorithm that allows gas fuel produced from biomass to minimize the number of hardware modifications, reduce costs and to take full advantage of a commercial gas engine and the original engine equipped with the control unit. The developed engine system can use two fuels, biogas and city gas, in any mix ratio to compensate the deficiency in biogas. Biogas produced by fermentation does not exhibit large component fluctuations over time; however, the engine is required to maintain stable operation for any mix ratio of two fuels in this situation. In this paper, we report a developmental procedure and the availability of our engine system.

2. Experimental set-up

2.1. Gas engine

A 3-cylinder 1.6-l gas engine mounted in a co-generation package was used in this work. Table 1 shows the engine specifications. The engine uses traditional spark ignition and a throttle valve for load control to adjust air flow. Fuel flow was controlled in the original setup by a poppet valve in the throttle valve, as shown in Fig. 1. The opening ratio of the poppet valve, which depends on the valve lift and is generally defined as the ratio of an equivalent opening area to the maximum equivalent opening area for a flow, was governed by the manifold pressure and the spring set on a diaphragm. The manifold pressure depends on the opening ratio of the throttle valve for air flow control and the valve lift was determined by the pressure difference between the fuel pressure and the manifold pressure and the rate of the spring on a diaphragm, which were designed for a constant fuel composition to supply adequate fuel flow against air flow. In addition, the fuel pressure was greater than that at the intake manifold, and the rate of the spring on the diaphragm was higher than that below the poppet valve. An active

Table 1
Engine specification.

YANMAR	CP10VBZ
Cylinder	3
Bore × Stroke mm	88 × 90
Displacement cc	1642
Compression ratio	9.5
Power kW/1700 rpm	11.5
Ignition timing deg. ATDC	−20

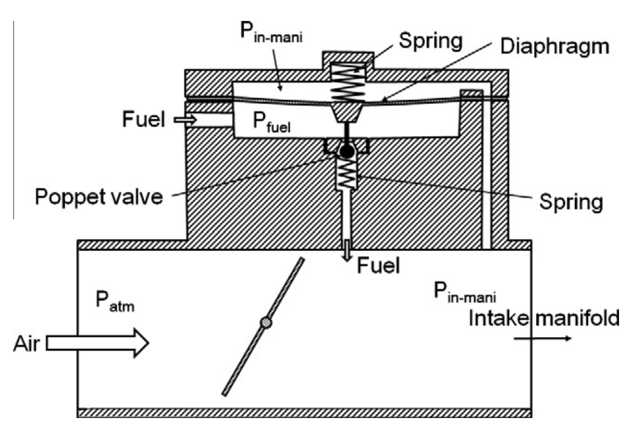

Fig. 1. Control mechanism of air and fuel flows in the original setup.