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Performance of small spark ignition engine fueled with biogas at different compression ratio and various carbon dioxide dilution

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ABSTRACT

In order to cope with power shortage in rural areas of developing countries and to reduce greenhouse gas emissions, we study the performance of small biogas-fueled internal combustion engines of which power is less than 5 kW. In particular, the influence of compression ratio on the engine is primarily examined. By decreasing the combustion chamber volume (from 19.3 cc to 16.6 cc), compression ratio (from 8.01:1 to 9.22:1) is increased to enhance brake power output (from 2.2 kW to 2.68 kW), brake thermal efficiency (from 22.0% to 29.8%) and brake specific fuel consumption of the engine (from 290.6 $\frac{g}{h \times PS}$ to 218.6 $\frac{g}{h \times PS}$). In addition, as means to examine the effect of the biogas composition on engine performances, various carbon dioxide dilution ratios (from 0% to 50%) are tested. At lowest carbon dioxide dilution, maximum engine performance is obtained.

1. Introduction

The ratification of 2016 Paris Agreement imposes the regulation to hold global average temperature rise to well below 2 °C and pursue efforts to limit the temperature increase to 1.5 °C above pre-industrial levels [1], thus preventing the emission of greenhouse gases. Unlike the Kyoto Protocol of 1997, which was a previous climate agreement that only regulated 37 advanced countries, the Paris Agreement will have legal binding to all 195 countries. In response to this global policy change, renewable energy researches are to be re-oriented to decrease carbon emissions.

Using biogas as an alternative fuel to generate power contributes to mitigate global warming in two ways: (1) reduce fossil fuel consumption and (2) utilize the methane that is regarded to increase the greenhouse effect for power generation. Biogas is produced by anaerobic digestion from anaerobic organisms or biomass [2]. It is typically composed of methane (50–70 vol%), carbon dioxide (25–50 vol%), hydrogen (1–5 vol%), nitrogen (0.3–3 vol%) and various minor impurities including hydrogen sulfide [3]. Biogas is a gaseous fuel that can be easily mixed with air to form a homogeneous air-fuel mixture. By supplying biogas as a fuel to IC engines via proper modification [4], power can be generated. In fact, there are numerous, previous works that address utilizing biogas to generate power by using IC engines [5–16].

In general, when biogas is used as a fuel, the CI engine is more preferable than the SI engine. First, the CI engine operates in the range of higher compression ratio than the SI engine. Ideally, thermal efficiency improves as compression ratio increases. Since biogas has higher octane number than regular gasoline fuel [17], it can endure high compression ratio that is exerted by the CI engine. Accordingly, the biogas-fueled CI engine has higher thermal efficiency than the biogas-fueled SI engine [18]. Also, power output of the SI engine decreases when biogas is used as a fuel while power is maintained in the similar range in case of the CI engine [19] because the SI engine is more sensitive to biogas composition and has high cycle-to-cycle variations [20]. As a result, most of recent studies that discusses power generation by biogas are based upon the CI engine.

However, for generating small power lower than 5 kW, CI engines become less effective. CI engines for this power range are hardly found in markets and more expensive than SI engines that have the equivalent power scale. In particular, power requirements of the residential unit in rural areas are generally less than 1 kW. If CI engines are to be used in this power range, they need to operate in part-load conditions and it tends to degrade power output and thermal efficiency of the engines. In addition, large scale engines are not viable in remote areas due to their costs and maintenance problems [21]. Therefore, in a small-scale power generation, the SI engine is considered to be more effective than the CI engine. With regard to the implementation of the Paris Agreement to developing countries in which remote rural areas are still dominating, biogas is an effective fuel because it is locally generated and there is no

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Nomenclature

IC	internal combustion
SI	spark ignition
CI	compression ignition
CR	compression ratio
VCR	variable compression ratio
BSFC	brake specific fuel consumption
TDC	top dead center
BDC	bottom dead center
$\eta_{theoretical}$	thermal efficiency of ideal Otto cycle
$\eta_{generator}$	thermal efficiency of generator
η_{engine}	thermal efficiency of engine
$\eta_{alternator}$	thermal efficiency of alternator
H_l	lower heating value
γ	ratio of specific heats
V_{TDC}	cylinder volume at top dead center
V_{BDC}	cylinder volume at bottom dead center
$V_{Displacement}$	displacement volume
$V_{Chamber}$	combustion chamber volume
$V_{Clearance}$	clearance volume
Q	flow rate
D	dilution
rpm	revolution per minute
min	minute
h	hour
g	gram
°C	celsius degree
K	kelvin
Hz	Hertz
mm	millimeter
mL	milliliter
cc	cubic centimeter
LCH_4	liter of methane
LCO_2	liter of carbon dioxide
kW	kilowatt
kVA	kilovolt-ampere
PS	Pferdestärke
mmHg	millimeter of mercury
%	percent

need for additional gas supply infrastructure. Moreover, biogas can save costs for fossil fuels to be transported from sources to the demand sites. Therefore, it is important to study the performance of the small biogas-fueled SI engines and explore possibilities to apply these engines to those areas.

In order to examine power-generating performance of the SI engine, there have been a number of studies on engine parameters that are related to the operating performance of the SI engine. Poulos and Heywood [22] investigated the geometric effect of combustion chamber on SI engine performances. Huang and Crookes [23] studied the influence of air-fuel ratio on a Ricardo E6 single-cylinder SI engine operating on simulated biogas. The test indicated that power and thermal efficiency reached their peaks with the air-fuel ratio between 0.95 and 1.05.

In addition to the variables mentioned above, compression ratio is a critical factor that affects engine performances and is directly related to its thermal efficiency. As prescribed in the earlier section, thermal efficiency of the SI engine enhances as compression ratio increases. However, when compression ratio is too high, knocking phenomenon occurs, which degrades the engine performance. When biogas is used as a fuel in the SI engine, compression ratio becomes even more important. Biogas-fueled SI engine is more likely to have knocking problems than gasoline engines due to the higher self-ignition temperature of biogases. [14]. Accordingly, a SI engine can operate in higher compression ratio condition with biogas as a fuel and is expected to show improved engine performance. Also, for those who live in rural areas of developing countries, compression ratio is the most straight-forward parameter to control to characterize the engine performance.

Some studies investigated the influence of compression ratio on the performance of SI engines using a variable compression ratio (VCR) engine [23–26]. VCR is a technology to alter compression ratio of the IC engine while the engine is operating. It controls compression ratio by changing the volume above a piston when the piston is at top dead center (TDC). Unfortunately, VCR engines are not feasible in rural areas of developing countries because it is expensive and it can cause maintenance problems given that they are much more complicated than ordinary engines. Also, a displacement of VCR engines is yet too large for rural use. Therefore, by far, it is reasonable to argue that SI engine is the best choice to be implemented in rural areas.

This research aims to study the performance of a biogas-fueled SI engine smaller than 5 kW. The ultimate goal is to promote the use of biogas in rural areas and provide a more comprehensive understanding of small IC engine behavior using biogas. In order to investigate the influence of compression ratio on the engine, compression ratio of the engine was changed by simple modifications that are viable in rural areas. In addition, carbon dioxide dilution effect was also examined to map engine performance with various parameters.

2. Experimental equipment

Genex generator SG3500SX was used in the experiment. The generator is composed of a Honda GX200 engine and a Linz electric SP-E1C/2 alternator. The specification of the generator is shown in Table 1. A tri-fuel conversion kit, which is composed of a regulator and an adapter, makes it possible to operate an engine on three different fuels; gasoline, propane and natural gas. In order to modify the generator to be operated on biogas, which is a gaseous fuel, the tri-fuel conversion kit purchased from US Carburetion, Inc. was installed on the generator, as shown in Fig. 1. The regulator regulates a steady flow of biogas under constant pressure in order to

Table 1
Specification of the generator SG3500SX.

Alternator	Model	SP-E1C/2
	Maximum power output	3.4 kVA
	Power factor	$\cos\varphi = 1$
Engine	Model	GX200
	Type	Air-cooled 4-stroke Over Head Valve
	Displacement	196 cm^3
	Maximum power output	4.1 kW @ 3600 rpm
	Fuel	Unleaded 86 Octane or higher
	Fuel consumption	313 g/kW h
Size	(Length) × (Width) × (Height)	(580) × (430) × (455) mm
	Dry weight	39 kg