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Performance and NO_x emissions of a biogas-fueled turbocharged internal combustion engine

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ABSTRACT

The performance and NO_x (nitrous oxide) emissions of a biogas-fueled turbocharged internal combustion engine were investigated using one-dimensional cycle simulation. Analyses were carried out using the design of experiment method, and the results were verified by comparison with experimentally measured data. The combustion behaviors were improved as the CH_4 content in the biogas increased. The brake power, brake thermal efficiency, and NO_x emissions increased as the CH_4 content or the boost pressure increased. Appropriate boost pressures to produce the same brake power at a given relative air/fuel ratio of 1.1 without boost were determined for each relative air/fuel ratio or each biogas composition considering brake power. In general, the lean operation limit was extended up to a relative air/fuel ratio of 1.5 with various biogas compositions and up to a relative air/fuel ratio of 1.7 for CH_4:CO_2 volume ratios of 65%:35% and 70%:30% without knocking. The maximum brake thermal efficiency was 35.9%, which was observed with a relative air/fuel ratio of 1.7 and a boost pressure of 1.44 bar at CH_4:CO_2 = 70%:30%. The NO_x emissions were reduced by more than 90% via a reduction in the combustion temperature, which was achieved as a result of the lean combustion.

1. Introduction

Renewable energy sources have received much attention recently because of the depletion of fossil fuel reserves and because of environmental concerns. In addition, a RPS (renewable portfolio standard) has been implemented by numerous governments to encourage the use of renewable energy sources, including wind, solar, tidal, and biomass. Typically, an RPS places obligations on electricity-generation companies to produce a specified fraction of their electricity from renewable energy sources [1–3].

Distributed generation (also termed on-site generation) is a potential means to utilize renewable energy sources more effectively. In contrast to conventional centralized generation, distributed generation involves generating electricity locally using small-scale generating units [4,5]. Gas-fueled internal combustion generators with a power output of <2 MW can be used as part of a distributed power system, and are relatively common, especially for combined heat and power generation. Biogas is an attractive renewable energy source, and can be employed as a fuel for such generators, particularly in rural areas [6,7].

Biogas typically refers to gas produced by the breakdown of biodegradable organic waste, and mainly consists of CH_4 and CO_2. One of the characteristics of biogas is that it has a composition that depends on where it was produced and what material was used in the breakdown process [8–10]. It is not straightforward to obtain common operating conditions for engines fueled by biogas because there is a significant difference in the composition of the fuel, as shown in Table 1. Therefore, the effects of the biogas composition on the performance and emissions of the engine must be investigated. Crookes [11] examined the performance and emissions from spark ignition and compression ignition engines running on a variety of bio-fuels, including synthetic biogas. Porpatham et al. [7] investigated the influence of a reduction in the concentration of CO_2 in biogas on the performance, emissions, and combustion characteristics of a constant-speed spark ignition engine. They found that there was a significant improvement in performance, as

Abbreviations: ATDC, After top dead center; CA, Crank angle; CARB, California Air Resources Board; DOE, Design of experiment; LOL, Lean operation limit; MBT, Maximum brake torque; NOX, Nitrous oxides; ON, Octane number; RBF, Radial basis function; RPS, Renewable portfolio standard; SI, Spark ignition; WOT, Wide-open throttle; 1D, One-dimensional.

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Nomenclature

A_e	entrainment surface area, m^2
e_b	burned zone energy, kW
e_u	unburned zone energy, kW
h_a	enthalpy of air mass, J/kg
h_f	enthalpy of fuel mass, J/kg
$h_{f,i}$	enthalpy of injected fuel mass, J/kg
k	specific heat ratio
m_a	air mass, kg
m_b	burned zone mass, kg
m_f	fuel mass, kg
$m_{f,i}$	injected fuel mass, kg
m_u	unburned zone mass, kg
M_b	entrained mass of burned mixture, kg
M_e	entrained mass of unburned mixture, kg
p_u	absolute pressure of end gas, atm
P_{boost}	boost pressure, bar
Q_b	burned zone heat transfer, kW
Q_u	unburned zone heat transfer, kW
r	compression ratio
S_L	laminar flame speed, m/s
$S_{L,o}$	laminar flame speed at initial conditions of 298 K, m/s
S_T	turbulent flame speed, m/s
t	elapsed time, s
t_i	time of auto-ignition, s
T_u	temperature of end gas, K
V_b	burned zone volume, m^3
V_u	unburned zone volume, m^3
Ε	laminar flame speed correlation constant
Η	thermal efficiency
Λ	Taylor microscale, m
ρ_u	unburned gas density, kg/m^3
ρ_{uo}	unburned gas density at initial conditions of 298 K, kg/m^3
Τ	time constant, s
τ_i	induction time, ms

well as a reduction in the emissions of hydrocarbons, when the engine was operated at low CO_2 levels. They also found that the lean operation limit was extended at low CO_2 levels.

Table 2 shows another characteristic of biogas: the heating value and laminar flame speed are both smaller compared to natural gas due to the low CH_4 content and the presence of CO_2 [12–15], which leads to less power output and a decrease in the LOL (lean operation limit) of the gas engine [16]. There are two approaches used to address these problems: adding H_2 and increasing the compression ratio. Porpatham et al. [17] reported that adding H_2 to the biogas used in a spark ignition engine at constant speed at different equivalence ratios improves the brake thermal efficiency and the brake power, and achieves significant reductions in the amount of unburnt hydrocarbons. Park et al. [18] studied the effects of adding H_2 on the behavior of an engine with various excess air ratios and CH_4 concentrations in the biogas. They found that adding H_2 improved the in–cylinder combustion characteristics and extended the LO while reducing the hydrocarbon emissions. Porpatham et al. [19] carried out tests to compare the performance, emissions, and combustion characteristics of a biogas-fueled spark-ignition engine with different compression ratios. They reported an increase in the brake thermal efficiency and brake power when the compression ratio increased. They also found that when the compression ratio was above a critical value of 13:1, the brake thermal efficiency and brake power increased slightly.

Table 1
Composition of different biogases [9].

Components	Unit	Sewage gas	Biogases agricultural gas	Landfill gas
CH_4	% by volume	65–75	45–75	45–55
CO_2		20–35	25–55	25–30
N_2		3.4	0.01–5.00	10–25
CO		<0.2	<0.2	<0.2
Other		Trace	Trace	Trace

Table 2
Properties of biogases [12–15].

	Natural gas	Biogas with 65% CH_4	Biogas with 45% CH_4
Lower heating value (MJ/kg)	48	20.2	12.3
Laminar flame speed (m/s)	0.39	0.27	0.20

Adding H_2 to biogas incurs additional costs. According to a recent study, the normalized cost to produce a unit of electricity increases by a factor of 2.2 by including H_2, and also by a factor of 1.6 or 1.2 by using a steam reformer or an auto-thermal reformer, respectively [20]. Increasing the compression ratio of the engine is not straightforward because the engine itself must be modified; however, the use of a turbocharger can produce many of the same benefits, and is simple to implement since gas engines are typically based on diesel engines, which usually use a turbocharger for forced induction [21–23].

Most studies into biogas-fueled internal combustion engines (including those cited above) have been experimental. Commercial engine manufacturers, however, typically take advantage 1D cycle simulations to model the operation of an engine. Here, we describe investigations of the performance and NO_x (nitrous oxide) emissions of a biogas-fueled turbocharged internal combustion engine using the 1D (one-dimensional) cycle simulation tool GT-POWER.

2. Methodology

2.1. Overview

The performance and NO_x emissions of a biogas-fueled turbocharged internal combustion generator were investigated with various compositions of the biogas. We used the 1D cycle simulation tool GT-POWER, and the model was validated using experimentally measured data with a fuel consisting of 100% CH_4. The specifications of the engine are listed in Table 3. The biogas composition varied from a volume ratio of CH_4:CO_2 of 50:50 to 70:30 in steps of 5%, and numerical analyses were carried out for relative air/fuel ratios of 1.1, 1.3, 1.5, 1.7, and 1.9. The DOE (design of experiment) method was applied with two main parameters: ignition (spark) timing and

Table 3
Engine specifications.

Item	Specification
Engine type	Water-cooled turbocharged spark ignition
Bore × Stroke (mm)	88 × 94
Displacement (cc)	2286
Compression ratio	13:1
Engine operating speed (rpm)	1800
Firing order	1-3-4-2