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Performance analysis of a biogas-fueled micro gas turbine using a validated thermodynamic model

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HIGHLIGHTS

- The MGT performance and fuel flexibility were investigated in biogas application.
- A thermodynamic model of the MGT was developed and validated with experimental data.
- Changes in performance and operating conditions of components were studied.
- The results showed the viability of the MGT for use in biogas application.

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ABSTRACT

This study focuses on an investigation of the fuel flexibility and performance analysis of micro gas turbines (MGTs) in biogas application. For this purpose, a steady state thermodynamic model of an MGT was developed and validated by experimental data obtained from a 100 kW MGT test rig. Quite good agreement was obtained between the measurements and the simulation results. A wide range of biogas compositions with varying methane content was simulated for this study. Necessary minor modifications to fuel valves and compressor were assumed to allow engine operation with the simulated biogas composition. The effects of biogas on the engine performance were fully analyzed at various operational conditions by changing the power demand and also the ambient temperature. Compared to the natural gas fueled case, the mass flow and pressure ratio in the MGT decreased, which resulted in a slight reduction of the surge margin. This effect became more severe, however, at low power loads and/or low ambient temperatures. For all operational conditions, the electrical efficiency decreased with decreasing methane content of the biogas. The results also indicated the negative effect of the biogas on the heat recovery in the recuperator, which lowered as the methane content of the fuel decreased.

1. Introduction

The rapid growth of both industry and the world population has led to an increasing global demand for energy, more specifically for electrical power. Coupled with concerns raised by increasing greenhouse gas emissions, this demand for electricity has created serious global challenges. A part of this additional demand comes from urban areas, where improved living standards have led to higher levels of electricity consumption [1]. Supplying this energy demand, according to the stricter environmental regulations, requires considerable effort to develop clean and decentralized power generation technologies.

In this context, micro gas turbines (MGTs), which are usually defined as small gas turbines up to a few hundred kilowatts, are considered as promising power generators. This technology benefits from the advantages of both gas turbine technology and small-scale combined heat and power (CHP) application. Gas turbines provide high fuel flexibility, low emissions, small footprint, and low maintenance costs [2], while CHP systems have a high overall efficiency (~85%) [3] and low energy losses during transmission [4]. Nevertheless, some challenges, such as the plant's economy, durability, and reliability, need to be addressed in order to achieve successful commercialization of MGT systems [5].

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Nomenclature

CC	combustion chamber
CHP	combined heat and power
Comp.	compressor
CH_4	methane
CO_2	carbon dioxide
DAQ	data acquisition
Gen.	generator
h	enthalpy (kJ/kg)
H_2S	hydrogen sulfide
FSO	full-scale output
MGT	micro gas turbine
$\dot{m}$	mass flow rate (kg/s)
N	shaft speed (rpm)
NG	natural gas
Power	power output (kW)
P	pressure (bar)
ΔP	pressure loss (bar)
Rec.	recuperator
SM	surge margin (%)
TIT	turbine inlet temperature (°C)
TOT	turbine outlet temperature (°C)
Turb.	turbine
T	temperature (°C)
α	pressure loss coefficient
ε	recuperator effectiveness
η_t	turbine isentropic efficiency
π	compressor pressure ratio

Subscript

air	air
cr	corrected values
gas	exhaust gas
in	component inlet value
out	component outlet value
rel	relative
surge	value at surge line
s	static value
t	total value

The MGT system might be especially interesting when fueled by green biogas. The most important small-scale biogas production method is anaerobic (absence of air) digestion, where biowaste in the presence of bacteria can be converted to a mixture consisting mainly of CH_4 and CO_2 [6]. The composition and thermal characteristics of biogas are significantly different from those of natural gas. Though commercialized MGTs are usually designed for natural gas, they are still capable of utilizing other gaseous fuels such as biogas with only a few modifications. These modifications include adjusting the fueling system i.e. fuel injectors, fuel valve and fuel manifold [7–9]. However, some more advanced designs are equipped with a biogas combustion system to cope with the low heating value of such gaseous fuels [10].

As the combination of biogas-MGT has emerged as a profitable match, especially for distributed power generation, a growing interest in the utilization of biogas in the MGT system is noticeable in scientific literature. Cáceres et al. reported the development of a thermodynamic model to predict the potential of biogas production using agricultural waste. The dynamic characteristics of power production using a generic MGT model have also been reported in their study [11]. The performance of several hybrid configurations containing an MGT fueled by a specified biogas and absorption cooling technologies has been techno-economically assessed by Bruno et al. [12]. Basrawi et al. investigated the effect of ambient temperature variation on a hybrid system containing a biogas-fueled MGT and an absorption cooling/heating system. They also reported that such a hybrid system could substantially reduce the fuel consumption and CO_2 emissions [13]. In another study, Basrawi et al. investigated the optimized size of the MGT-absorption cooling system based on the scale of the particular biogas source, sewage treatment plants, under various ambient temperature conditions [14].

Contrary to the aforementioned publications, which have mostly investigated the application of the MGT, some researchers have studied the effect of biogas utilization from the gas turbine perspective. When the fuel is changed from natural gas to biogas in an MGT system, a larger quantity of fuel needs to be injected into the combustor as a result of the lower heating value of the biogas, which impacts the performance and the operating conditions of the MGT. The major sub-systems of the engine, such as the compressor, need to operate at conditions that deviate from the original design. Compressor surge is a particular concern when firing low heating value fuels such as biogas. However, in contrast to large-scale gas turbines, the surge problem in MGT systems does not seem to be very critical when fed by biogas. This is due to the utilization of centrifugal compressors and the much lower fuel flow rate relative to the air flow [15]. Moreover, MGTs have a variable speed engine, which gives them additional freedom in operation. The effects of fuel change from natural gas to biogas with variable composition on a generic microturbine have been theoretically discussed by Bohn and Lepers [2]. They concluded that a biogas containing more than 15% methane was acceptable in terms of keeping a certain margin to the compressor surge at a constant turbine inlet temperature. Dolak and Armstrong demonstrated the significant impact of fuel change from natural gas to biogas on the emissions of the MGT [7]. They reported that given the inevitable variation of fuel composition, due to the biogas production process and the high dependence on the composition of the feedstock, the use of a representative test fuel is useful during the engine development process. They also proposed a promising way to predict engine pollutant emissions for different methane-based diluted fuels comprised of natural gas and carbon dioxide. Kataoka et al. reported the positive effect of preheating of the sewage digester's biogas on the combustor efficiency of a microturbine [8]. A successful operation of the MGT in terms of keeping power output at a certain level was demonstrated with a biogas containing less than 50% CO_2 (~higher than 50% methane) and reported by Yang et al. [9]. Cameretti et al. showed the suitable behavior of a typical combustor of an MGT fueled by biogas with 65% methane in terms of combustion completion through a CFD analysis [16].

Although the application of MGT systems in the utilization of biogas has been extensively addressed in the literature, a comprehensive investigation of the influences of the fuel change, from natural gas to biogas, on the MGT's operability has rarely been touched on. Thus, the analysis of the consequence of fuel changes at various operating conditions of the micro gas turbine is vital.

The main objective of this study is, therefore, to investigate the capability for fuel flexibility in existing MGT systems in biogas application. In this regard, the performance of a Turbec T100 MGT, when fed with biogas instead of natural gas, was analyzed for a wide range of fuel compositions and operating conditions. For this purpose, a steady state thermodynamic model of the baseline configuration, running on natural gas, has been developed in IPSEpro, which is a commercial mass and energy balance software