Applied Energy 117 (2014) 30–41

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Experimental evaluation and ANN modeling of a recuperative micro gas turbine burning mixtures of natural gas and biogas

H. Nikpey [a,*], M. Assadi [a,b], P. Breuhaus [b], P.T. Mørkved [c]

[a] Faculty of Science and Technology, University of Stavanger, 4036 Stavanger, Norway
[b] International Research Institute of Stavanger, P.O. Box 8046, 4068 Stavanger, Norway
[c] Institute for Energy Technology, P.O. Box 40, 2027 Kjeller, Norway

HIGHLIGHTS

- The MGT behavior affected by increased biogas content of the fuel was investigated.
- An operational window representing the proper fuel mixtures was mapped out.
- The efficiency was affected marginally and CO_2 emission was reduced significantly.
- A validated ANN model was developed to simulate the performance of the MGT.
- A user-friendly graphical user interface was created for the ANN model.

ARTICLE INFO

Article history:
Received 16 July 2013
Received in revised form 18 November 2013
Accepted 30 November 2013
Available online 22 December 2013

Keywords:
Micro gas turbine
Biogas
Fuel mixtures
Experimental evaluation
ANN modeling
Graphical user interface

ABSTRACT

Previously published studies have addressed modifications to the engines when operating with biogas, i.e. a low heating value fuel. This study focuses on mapping out the possible biogas share in a fuel mixture of biogas and natural gas in micro combined heat and power (CHP) installations without any engine modifications. This contributes to a reduction in CO_2 emissions from existing CHP installations and makes it possible to avoid a costly upgrade of biogas to the natural gas quality as well as engine modifications. Moreover, this approach allows the use of natural gas as a "fallback" solution in the case of eventual variations of the biogas composition and or shortage of biogas, providing improved availability.

In this study, the performance and emissions of a commercial 100 kW micro gas turbine (MGT) at full and part loads are experimentally evaluated when fed by varying mixtures of natural gas and biogas. The MGT is equipped with additional instrumentation, and a gas mixing station is used to supply the demanded fuel mixtures from zero biogas to the maximum possible level by diluting natural gas with CO_2. A typical biogas composition with 0.6 CH_4 and 0.4 CO_2 (in mole fraction) was used as reference, and corresponding biogas content in the supplied mixtures was computed.

This paper presents the test rig setup used for the experimental activities and reports the results, demonstrating the impact of burning a mixture of biogas and natural gas on the performance and emissions of the MGT. The results indicate that the electrical efficiency is almost unchanged and no significant changes were observed in operating parameters, comparing with the natural gas fired case. It was also shown that burning a mixture of natural gas and biogas contributes to a significant reduction in CO_2 emissions from the plant by about 19% at full load operation. Given the extensive data obtained during the experimental tests, a data-driven model based on an artificial neural network (ANN) was developed to simulate the performance of the MGT. The mean relative error (MRE) was used to evaluate the prediction accuracy of the developed ANN model with respect to experimental data which were not used during the training. It was demonstrated that the ANN model can predict the performance parameters of the MGT with high accuracy and the error of most samples is less than 1%. A graphical user interface (GUI) was created for the ANN model in Microsoft Visual Basic. The GUI is presented as a user-friendly tool for modeling and condition monitoring of the plant.

1. Introduction

Rapid growth in the generation of electricity using fossil fuels will contribute to a significant increase in greenhouse gas emis-

* Corresponding author. Tel.: +47 51832294; fax: +47 51831750.
E-mail address: homam.nikpey@uis.no (H. Nikpey).

0306-2619/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.apenergy.2013.11.074

Nomenclature

Alt.	alternator
ANN	artificial neural network
Ar	argon
CC	combustion chamber
CHP	combined heat and power
Comp.	compressor
CH_4	methane
CO	carbon monoxide
CO_2	carbon dioxide
DAQ	data acquisition
FID	flame ionization detector
GMS	gas mixing station
GUI	graphical user interface
He	helium
H_2	hydrogen
H_2O	water
FSO	full scale output
LHV	low heating value (MJ/kg)
MGT	micro gas turbine
MLP	multi-layer perceptron
MRE	mean relative error
MSE	mean square error
$\dot{m}_f$	fuel mass flow rate (kg/h)
N	shaft speed (rpm)
NG	natural gas
N_2	nitrogen
n_{CO_2}	number of moles of CO_2 in the exhaust gas
$n_{CO_2,mix}$	number of moles of CO_2 in the fuel mixture
n_{H_2O}	number of moles of H_2O in the exhaust gas
n_{N_2}	number of moles of N_2 in the exhaust gas
$n_{N_2,mix}$	number of moles of N_2 in the fuel mixture
O_2	oxygen
Power	power output (kW)
P_{set}	power set (kW)
P_{el}	electrical power output (kW)
P_f	fuel pressure (bar)
P_{3i}	combustion chamber inlet pressure (bar)
P_{5o}	compressor outlet pressure (bar)
P_{5i}	compressor inlet pressure (bar)
Q_f	fuel flow (Sm^3/h)
Rec.	recuperator
RGC	Risavika Gas Center
SFC	specific fuel consumption (kg/kW h)
TCD	thermal conductivity detector
TIT	turbine inlet temperature (°C)
TOT	turbine outlet temperature (°C)
Turb.	turbine
T_{amb}	ambient temperature (°C)
T_f	fuel temperature (°C)
T_{oil}	oil temperature (°C)
T_{10}	exhaust gas temperature
T_{11}	hot water temperature (°C)
T_{3i}	combustion chamber inlet temperature (°C)
T_{5i}	compressor inlet temperature (°C)
T_{5o}	compressor outlet temperature (°C)
T_{6o}	turbine outlet temperature (°C)
UHC	unburned hydrocarbons
X_{Bio}	biogas fraction of the fuel mixture (%)
$y_{C_{O_2}}$	molar fraction of CO_2 in the exhaust gas
η_{el}	electrical efficiency

sions in the coming two decades unless urgent actions are taken to introduce low-emission technologies and renewable fuels [1,2].

Micro gas turbines (MGTs) are considered to be one of the promising technologies, thanks to their fuel flexibility, low emissions, high power density and low maintenance costs [3]. MGTs are usually designed for natural gas, but there is the ability to utilize other fuels such as those based on biomass. A growing interest in using biogas from small-scale digestion plants has been recognized [4].

Combined heat and power (CHP) production, using biogas from small-scale anaerobic digestion, has emerged as a profitable match, especially for distributed power generation. Its many advantages include reductions in greenhouse gas emissions and fossil fuel consumption. Consequently, several studies have been carried out on biogas fueled MGTs, such as on the performance and emission characteristics of MGTs, the effect of inlet air temperature changes on their performance, and the application of MGTs in cogeneration and trigeneration systems [5–10].

Since the characteristics of biogas differ from those of natural gas, it is not practically possible to directly burn biogas in the combustion chamber originally designated for natural gas. The heating value of biogas is much lower than that of natural gas; hence, a higher fuel flow rate is required to maintain the same heat input. Therefore, MGTs need to be modified before burning pure biogas. The modifications include redesign of the combustion chamber and/or minor modifications of the fueling system i.e. fuel injectors, fuel valve, fuel path, and control system [11–14].

Alternatively, by mixing biogas with natural gas, the characteristics of the fuel mixture, such as low heating value (LHV) and flame temperature increase, reaching values close to those of natural gas. Thus, stable operation of the combustor might be maintained without any engine modifications. As a result, the environmental advantage of burning an amount of renewable fuel to reduce greenhouse gas emissions can be achieved, still using existing MGTs. This approach also allows the use of natural gas as a "fallback" solution in the case of e.g. shortage of biogas and or the eventual variation of the biogas composition due to changes in digestion process parameters, resulting in improved availability of the MGT. In addition, the use of a mixture of natural gas and biogas is economically viable for small-scale plants, since the costly upgrade of biogas to the natural gas quality and engine modifications can be avoided, while at the same time, the natural gas consumption is reduced.

Therefore, the aim of this study is to demonstrate the possibility of using a mixture of natural gas and biogas as fuel in existing MGTs without any engine modifications. This study tries to map out an operational window by increasing the share of biogas from zero to the maximum possible level at various load levels, suggesting proper fuel mixtures for satisfactory performance of the engine. The performance and emissions changes due to the increased biogas content of the fuel mixture were evaluated at the full range of power loads, at steady state conditions and compared with the base case with only natural gas. A gas mixing station was used to supply a variety of fuel mixtures by diluting natural gas with CO_2. The typical biogas composition with 0.6 CH_4 and 0.4 CO_2 (in mole fraction) was considered as reference and the corresponding biogas fraction of the supplied fuel mixtures was calculated.

The test rig used in this project was based on a Turbec T100 MGT. The test rig was instrumented with additional pressure and temperature sensors, providing the possibility to consider additional performance parameters, which were not part of the standard engine instrumentation.