Review of theoretical and experimental studies implemented on (CHP) Micro turbine using natural gas and biogas fuels

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Abstract
The utilization of combine heat and power (CHP) micro turbines are highly considered in energy policies since distributed generation has become one of the most promising alternatives of generation and transmission of electricity. Biogas as natural source of energy plays significant role in current energy supply since it has some positive points such as being CO$_2$ neutral, saving fossil reservoirs and reducing environmental emission. On the other hand it has also some undesired points as low calorific value and costly and complex pure gas production system. Some theoretical and experimental research have been done about utilization of biogas in micro turbines. This paper review the studies with respect to summarizing the progress achieved on generating power by micro turbine and biogas fuel with focus on combustion and emission subjects. CHP Micro turbine and biogas is shortly described in two sections. The effect of biogas on combustion chamber and emission is summarized in the next part. Simulation and modeling of micro turbines by one of data driven methods, artificial neural network, is documented. Researchers presented that emissions especially NO$_x$ and CO will be increased with using biogas and flame instability is related to chemical composition of fuel and flame speed. Chemical reaction is the main reason of flame instability that causes increasing of emission elements. This paper will clarify the problems occurred by using bio fuels in combustion chamber and the effect of fuel on emission elements will be considered as reference for the future progress of biogas used in micro turbine.

Keywords
Bio gas, natural gas, micro gas turbine (CHP), ANN

Introduction
Utilization of bio gas as CO$_2$ natural fuel and distributed power generation are the current governmental energy policy since they have significant effects on controlling global warming and depletion of our fossil reservoirs. On the other hand the Kyoto protocol and other agreements impose more and more stringent standard meaning that green house gases have to be limited. Therefore, the energy production strategy will tend to generating power by micro turbines (CHP) or small-scale distributed cogeneration units using low heating value gas which is locally produced through gasification process of waste biological material. Although micro turbine CHP units are installed easily with low cost and short payback time but there are several technical and economical issues still remaining that researchers work on. For instance using low heating value fuels has its own combustion problems as well as producing pure biogas without corrosive elements is still one of the expensive procedures. Besides, CHP units

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are installed generally in farmed and urban areas so maintenance, control and monitoring of the
units have to be done systematically in order to have reliable and sustainable electricity
generators. The main goal of the current paper is investigating criteria and limitations in
combustion chambers using low heating value biogas and the effect of the fuel on emission.
Besides, studies about modelling and monitoring micro turbine by artificial neural network
method are investigated because this method reduces many unnecessary costs of maintenance
and can predict the faults before they cause severe damages.
The results of author’s research project will introduce the possibility of installing CHP micro
turbines using mixture of bio gas and natural gas with knowledge of combustion chamber
criteria. Furthermore, by implementing online monitoring, a decentralized CHP unit will be
controlled properly and maintenance costs will be decreased.

Micro turbine (CHP)

Micro turbines are small combustion gas turbines producing power from approximately 10-
200KW, electrical efficiency of 30% and heat via heat exchanger [1]. Unit produces electricity
and heat simultaneously and it could be used for district power and heat production. In order to
reduce NOx emissions the micro turbine is usually installed with the dry low NOx combustor,
where the fuel is premixed with air before it is ignited. The behavior of a micro turbine is quite
different from conventional industrial gas turbines, mainly because of the using power
electronic, which allows for variable shaft speeds. Major advantages of variable shaft speed are
high part- load efficiency by maintaining high turbine TIT (Turbine Inlet Temperature) values,
absence of a gear box, and less sensitivity to different load [2].

Micro turbines are offering some advantages for small scale combine heat and power units such
as low emission of NOx and low noise and vibration, reliable operation with minimal
maintenance, small size and lower operating and installation cost. The bold characteristic is
they are able to run with different composition of fuels as natural gas, landfill gas, sewage gas,
LPG and diesel [1], [4].

Micro turbines consist of following major parts: radial compressor and turbine mounted back to
back on a single shaft, combustor, recuperator, high speed generator, power conditioning
system and casing [2], [4]. Recuperator made of stainless steel increases the efficiency of micro
turbine about 10% [1]. More detail about specifications of micro turbine is documented in
Turbec technical specification [2]. Leading manufacturing companies are Capstone in USA and
Turbec in Sweden. NewEnco is a company which has implemented a program to prove the
operation of micro turbine on landfill gas and digester gas [3]. As an example, micro turbines
are considered for production of heat and power for residential building and even domestic hot
water and cooling energy. An investigation presented the possibility of using one 40KW micro
turbine for providing energy to a 10 story high building in Tehran Iran [5].

Another research about using CHP for clustered dwelling presents still there are many technical
and economical uncertainties about using micro biomass-fuelled CHP systems which require
considerable technical researches [6].

Two other studies presented utilization of CHP micro turbine and increasing performance of
the generating heat and power for residential places [7], [8].

Bio gas

Renewable energy must be developed in order to meet environmental and climate related
target, reduce greenhouse gases, reduce our dependency to oil and secure future energy supply
considering that fossil reservoirs are depleting fast. Biogas produced in an anaerobic digestion
of organic material plays significant role in future of renewable energy and could be used for
producing heat and electricity. Biogas is carbon dioxide natural and after upgrading could be
used as vehicle fuel rather than only for micro turbines applications. The advantages of biogas
energy are that produced locally and can be avoiding long distance transportation of fuel. Organic waste material will be managed properly as well instead of firing them or hiding them under ground.

Methane constitutes the energy rich part of biogas. Biogas is composed of 45-85% methane and 15-45% carbon dioxide depending on the conditions during production and also small amount of hydrogen sulphide, ammonia and nitrogen and it is often saturated with water vapor.

Biogas can be separated into three main groups: (1) digestion gas obtained from sewage sludge, manure and agricultural crops (2) landfill gas that has the smallest amount of methane and (3) bio methane from thermal gasification that extracted from biological material.

Biogas must be dried and purified from hydrogen sulphide before using in CHP units to produce heat and electricity. Many researches carrying out to optimize the gasification process and increase the amount of pure methane and also about possibility of having stable and clean combustion with biogas are another interesting subjects that are being focused on [9],[10]. It is possible to see Table 1 and Table 2 that illustrate different composition of biogas and average heating value and adiabatic flame temperature [24].

<table>
<thead>
<tr>
<th>Fuel</th>
<th>CH₄</th>
<th>CO₂</th>
<th>N₂</th>
<th>O₂</th>
<th>CO</th>
<th>H₂</th>
<th>others</th>
</tr>
</thead>
<tbody>
<tr>
<td>Natural gas</td>
<td>97.9</td>
<td>0.1</td>
<td>1</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>1</td>
</tr>
<tr>
<td>Biogas</td>
<td>65.3</td>
<td>34.4</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.3 H₂S</td>
</tr>
<tr>
<td>Sewage gas</td>
<td>60</td>
<td>32.5</td>
<td>5</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>3</td>
</tr>
<tr>
<td>Landfill gas</td>
<td>52.5</td>
<td>37.8</td>
<td>7</td>
<td>1</td>
<td>-</td>
<td>0.27</td>
<td>1.43</td>
</tr>
<tr>
<td>Wood gas</td>
<td>1.5</td>
<td>9.1</td>
<td>53.2</td>
<td>-</td>
<td>19.2</td>
<td>17</td>
<td>-</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Fuel</th>
<th>Fuel heating value (MJ/Nm³)</th>
<th>Average adiabatic flame temperature in Kelvin</th>
</tr>
</thead>
<tbody>
<tr>
<td>Natural gas</td>
<td>38.5 ±6.0</td>
<td>2547</td>
</tr>
<tr>
<td>Biogas</td>
<td>23.0 ± 3.0</td>
<td>2425</td>
</tr>
<tr>
<td>Sewage gas</td>
<td>19.0 ± 2.0</td>
<td>2417</td>
</tr>
<tr>
<td>Landfill gas</td>
<td>16.5 ± 3.0</td>
<td>2376</td>
</tr>
<tr>
<td>Wood gas</td>
<td>5.3± 1.0</td>
<td>2126</td>
</tr>
</tbody>
</table>

Fuel composition (Natural gas, biogas) and emissions

Ingersoll-Rand energy constructed a mixing station in order to run different fuel composition (LHV<34 MJ/m³) in Micro turbine IR250KW and 70KW and investigated the effect of composition on exhaust emissions and combustion performance. Finally the results of model were validated with landfill gas. Since there are different bio fuel composition are produced though different production process so different performance and emissions of the micro turbines were studied. Three types of biogas fuels available are landfill gas (LFG), waste water treatment/digester gases and syngases (recovered from waste or coal gasification process) [16]. The aim of the paper was on biological decomposition process that produces diluted methane based fuel. The composition of such a gas is CH₄, CO₂, N₂ and O₂ that may differ in a same site as well. In order to test different composition of fuels, mixing station was constructed and different percentage of CO₂ was mixed with propane and then mixed with natural gas. Different LHV from 11.9 to 85.2 MJ/m³ were tested [16]. Figure 1 shows scheme of mixing station:
High accuracy Coriolis mass flow meters were installed on both lines with 2% tolerance. The engine ran in steady state condition and pollutants as NO\textsubscript{x}, CO and CO\textsubscript{2} were measured according to ASME B133.9 [17]. Tests ran on Ingersoll Rand lean premixed low NO\textsubscript{x} radial inflow combustor design and several changes were made such as enlargement of fuel passages to accommodate the increased volumetric flow of the fuel with decreasing LHV to avoid excessive parasitic losses from the fuel compression equipment and the stoichiometry was richened after flame out issue were observed at low LHV fuel. Results show that production of NO\textsubscript{x} and CO is increased by using LHV fuel in both modified combustion and original one. It was declared that the adiabatic flame temperature in combustor primary zone had a controlling effect on rate of chemical reaction and chemical reaction has direct relationship with CO and NO\textsubscript{x} formation. Adiabatic flame temperature is dependent on fuel type and fuel air ratio. The method proposed in this paper is looking at correlation between LHV fuel and emission and calculation of adiabatic flame temperature based on combustion geometry and fuel types [16].

Another research about the effect of biogas on flame stability comprised stability combustion, flame structures and flame dynamics between CH\textsubscript{4} and air flames and a biogas flames (issued from waste gasification) in a lean premixed combustion conditions. Velocity profiles were obtained by Laser Doppler Anemometry measurement techniques [17]. Chemiluminescence measurements and temporal acquisition of chamber pressure were performed in order to describe flame structure and instabilities. It was declared that changing in flame structure was highly related to laminar flame speed and it was not related to instable flame and reaction zone penetration [18]. Results of the experimental research showed that three different areas could be seen with burning high methane to CO\textsubscript{2} ratio and flame become more unstable when CO\textsubscript{2} highly increased. These instabilities that occurred in lean premixed combustion could lead to an increase of NO\textsubscript{x} emissions. Several researches have studied how to reduce emission in biogas combustion. Bradley studied that generation of NO is not related to residence time and it is produced in reaction zone [19]. Kroner et and Huang studied heat release and flame wall interaction influence on the combustion instabilities. Combustion instabilities cannot be reduced to one simple phenomenon and studies generally focus on one of them. This paper mainly focuses on influence of chemical fuel composition on instabilities [20]. The dilution of methane, N\textsubscript{2}, O\textsubscript{2} with CO\textsubscript{2} numerically studied by Ju et. al. The authors focused their analyses on the possible effect on the flame speed and flammability limits of the radiation absorption by the CO\textsubscript{2} in the reactants. They found that the CO\textsubscript{2} effect on laminar flame velocity is the highest at very lean mixture [21].

The aim of paper was investigating the effects of biogas fuels on the performance of an annular combustion chamber of micro gas turbine. Results showed that power output was around 170KW at 85000 RPM with 90%CH\textsubscript{4} and 10% CO\textsubscript{2} and power decreased to 70KW at 65000
RPM with 70% CH4 and 30% CO2. The critical limit introduced in 60% CH4 that power output extremely decreased and on that point Brayton cycle efficiency and electric efficiency was calculated 23% and 10%. Numerical analysis of redesigned combustion chamber showed that performance of micro gas turbine can be improved by raising the temperature at turbine inlet. Paper finally presented a numerical simulation of improved combustor using different biogas LHV fuel and CFD was used as the modeling tool [22].

Several researches have been studied about the effect of biogas on combustion. Yamashita et al indicated that micro turbine system successfully operated with low heating value fuels without any special modification of combustor. It is presented micro gas turbine system was successfully functioned under each tested condition where the minimum heating value of the simulated fuel was approximately 0.43 of pure LPG. However, large size combustor was adapted to generate enough combustion power and the combustor chamber was separated from compressor and turbine [23].

Fuel supply system needed to prepare enough pressure to ensure that the fuel has ample fuel density in order to compensate its LHV amount.

Dieter Bohn investigated the effect of biogas on the characteristics of operation of a micro turbine. Particularly it was analyzed and presented when biogas is burnt instead of natural gas efficiency will be decreased. Furthermore, overall view of the effect of low heating value fuels on gas turbine materials and pollutant emission was expressed. Micro turbine which was used for running tests generate 80KW power with 26% efficiency, pressure ration was 3.3 and turbine inlet temperature about 900 C. Different cases of operation were considered for running the tests and change the composition of fuels. Results presented that significant increase in pressure ratio of the micro turbine only occurs if methane content is low and turbine inlet temperature is kept constant. At methane content below 15% the surge margin of the compressor was reached. However, such low amounts of methane contents were only likely to occur if disturbances in the digester process occurred or if the quality of biomass was poor. Emissions showed acceptable values throughout the range of fuel composition investigated if the turbine inlet temperature is kept constant [24].

ANN modelling

ANN is a tool that mimics the neural structure of the human brain. In contrary to traditional mathematical models, which are programmed, ANN learns the relations between selected inputs and outputs by training [11]. Numbers of neurons are interconnecting together with linear and non linear transferring function that present ANN tool suitable for modeling nonlinear interconnections and complicated correlations between inputs and outputs [12]. Some applications of ANN could be highlighted as modeling, optimization, online monitoring, sensor validation and fault diagnosis [13]. Multi layer network consists of one input layer, one or more hidden layer and one output layer. In learning procedure input is introduced to network then multiplied by adjustable weights and then they are summed and transferred to output layer. At each iteration (epoch) mean square error (MSE) as network accuracy indicator is calculated and weights are adjusted accordingly [14]. Training is terminated when MSE reaches to satisfactory accuracy. Then training is completed and weights are fixed. ANN can be classified to two groups with respect to topology: feed forward and feedback. When input and output are defined ANN can be trained as supervised method but also this is applicable to train a network only with input parameters that the learning method is named unsupervised learning method. Four transferred functions can be summarized as linear function, threshold, log-sigmoid and tanh-sigmoid function [12]. One commercial program for training ANNs is Neuro Solution that is used in the ongoing research. When training is finished model is validated by data that are not used in training data set. If satisfactory accuracy of the desired model is achieved it is ready to be employed in practice. The inherent properties of ANN controllers such as low sensitivity to
noise and incomplete information make the ANN as a promising controller candidate for micro
turbine system [15].
ANN as one of the powerful simulation and modeling tools is used in thermal energy systems
and lots of researches have studied on gas turbine monitoring up to now. M. Fast and M.
Assadi presented application of ANN for performance monitoring and simulation of a CHP
plant and results show that operational and performance parameters of GT can be predicted
with good accuracy for varying local ambient conditions [25]. Condition based maintenance is
another ANN application that may reduce unnecessary shut downs and has lots of economical
advantages for plants. It can be developed by means of ANN with healthy historical operational
data then online measured data is compared with predicted data and in case of any deviation
machine alarms. This method is highly considerable since micro turbines are used as
decentralized generator, online monitoring will reduce further unnecessary maintenance costs
[26]. Since efficient model and controller are essential to investigate the micro turbine
operation characteristic, Sisworahardjo produces a controller model based on ANN for micro
turbine plant and they compared the ANN controller with conventional one. ANN controller
with four inputs as rms voltage, speed, generated power and temperature were correlated to
outputs as excitation voltage, speed, temperature control signal and power control. Comparison
showed that in terms of error ANN presented better results [27].

Conclusion

Micro turbine (CHP) working with biogas as low heat value fuel has been identified as one of
the promising methods for generating power and heat in urban areas. Several researches about
producing pure biogas and economical gasification procedure have been studied. On the other
side researches are going forward to increase the efficiency of micro turbines using biogas and
decrease the emissions since urban area has its own stringent environmental regulation. One of
the dominant subjects surveyed in this paper is about investigating combustion of micro turbine
using bio fuel and its effect on emission theoretically and experimentally. Besides,
investigating about modeling and monitoring of process with one of data driven modeling
methods. Researchers presented that emission especially NOₓ and CO will be increased with
using biogas flame instability is related to chemical composition of fuel and flame speed.
Combustion instability cannot be modified to one single reason chemical reaction was the main
reason of flame instability that causes increasing of emission elements. The missing link of the
researches in this direction is the objective of the author’s project is mixing biogas and natural
gas as fuel of Turbec T100 and combustion chamber will be modified in order to reach to
maximum efficient power and heat output. Utilization of biogas and natural gas mixture will be
studied thermodynamically and experimentally. Moreover, by using applications of ANN such
as online monitoring and performance degradation, process will be modeled and monitored.
Consequently the cost of maintenance in micro turbine installed in urban area will be reduced
as well as due to different composition of biogas and also non continuity of production biogas,
the criteria of using mixture biogas and natural gas will be defined.
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