International Journal of Mechanical, Industrial and Aerospace Sciences
ISSN: 2517-9950
Vol:3, No:10, 2009

System Identification and Performance Improvement to a Micro Gas Turbine Applying Biogas

Chun Hsiang Yang, Cheng Chia Lee and Chiun Hsun Chen

Abstract—In this study, the effects of biogas fuels on the performance of an annular micro gas turbine (MGT) were assessed experimentally and numerically. In the experiments, the proposed MGT system was operated successfully under each test condition; minimum composition to the fuel with the biogas was roughly 50% CH_4 with 50% CO_2. The power output was around 170W at 85,000 RPM as 90% CH_4 with 10% CO_2 was used and 70W at 65,000 RPM as 70% CH_4 with 30% CO_2 was used. When a critical limit of 60% CH_4 was reached, the power output was extremely low. Furthermore, the theoretical Brayton cycle efficiency and electric efficiency of the MGT were calculated as 23% and 10%, respectively. Following the experiments, the measured data helped us identify the parameters of dynamic model in numerical simulation. Additionally, a numerical analysis of re-designed combustion chamber showed that the performance of MGT could be improved by raising the temperature at turbine inlet. This study presents a novel distributed power supply system that can utilize renewable biogas. The completed micro biogas power supply system is small, low cost, easy to maintain and suited to household use.

Keywords—Micro Gas Turbine; Biogas; System Identification;; Distributed power supply system

I. INTRODUCTION

The utilization of renewable energy and development of new energy sources are the present governmental energy policy to cope with the more and more stringent shortage of fossil fuels and environmental regulations for carbon dioxide reduction in the new century. This study examines the practicability of biogas fuel on a micro gas turbine (MGT) through experiment. The MGT used in this study is MW-54, whose original fuel is liquid (Jet A1). Its fuel supply system was re-designed to use biogas fuel.

There are three parts in this study. In the first part, the experiments were completed to evaluate the combustion efficiency of an annular MGT while applying the biogas fuel. The methane was mixed with different ratio of CO_2 to be our biogas fuel. Experimental results showed that the presented MGT system operated successfully under each tested condition when the minimum heating value of the simulated fuel was approximately 50% of pure methane. The power output was around 170W at 85,000 RPM as 90% CH_4 with 10% CO_2 was used and 50W at 65,000 RPM as 70% CH_4 with 30% CO_2 was used. When a critical limit of 60% CH_4 was used, the power output was extremely low. Furthermore, the best theoretical Brayton cycle efficiency and electric efficiency of the MGT were calculated as 23% and 10%, respectively.

In the second part, the system identification of MGT was completed for future studies. The model identification process is prerequisite for controller design research in the near future. The measured data helped us identify the parameters of dynamic model in numerical simulation. Finally, a numerical simulation of improved combustor is completed. The numerical simulation of the re-designed combustor showed the improvement on the performance of MGT. This dissertation presents a novel distributed power supply system that can utilize renewable biogas. The completed micro biogas power supply system is small, low cost, easy to maintain and suited to household use.

As powerful computing technologies are continuously and rapidly improved, computational fluid dynamics (CFD) methods have become a feasible tool in the turbine engine industry. Li et al. [1] employed a fluid-solid coupling simulation in an aero-engine annular combustor to investigate the integrated contribution of combustion and cooling to the thermal load in a completely structure annular tube. Gonzalez et al. [2] assessed the influence of the injection characteristics on the thermodynamic variables inside a commercial micro turbine through the aid of CFD software. Bio-mass as a renewable resource and an environmental friendly energy carrier is assigned an increasing importance for future energy supply. So far bio-mass have mainly been the focus of an alternative fuel for gas turbine engines. Yamashita et al. [3] indicated that the micro gas turbine system was successfully operated with low-heating value fuels without any modification of the combustor. Their presented MGT system was eventually successfully functioned under each tested condition, where the minimum heating-value of the simulated fuel was approximately 0.43 of pure LPG. However, in Yamashita’s research, the large size combustor chamber was adopted to generate enough combustion power and the combustor chamber was separated from the compressor and turbine.

C. H. Yang, C. C. Lee and C. H Chen are with the Department of Mechanical Engineering, National Chiao Tung University, 1001 Ta Hsueh Road, Hsinchu, Taiwan 300, ROC (corresponding author C. H. Yang to provide phone: 886-3-5712121; fax: 886-3-5737586; e-mail: seanyang.me93g@nctu.edu.tw).

II. METHODS

2.1. Experimental setup

The MGT is basically composed of compressor (Radius: 27mm) [Fig. 1 (a)]; combustion chamber (Length: 52.4mm, Radius: 38mm) [Fig. 1 (b)]; and turbine wheel (Radius: 25mm) [Fig. 1 (c)]. The compressor compresses the incoming air into high pressure. The combustion chamber burns the fuel as well as produces high-pressure and high-velocity production gases. The turbine is energized by the high-pressure and high-velocity gas flowing from the combustion chamber. The most common shaft design in a MGT is the single shaft design that a radial centrifugal compressor and turbine are attached to a shaft which is also adopted in this study.

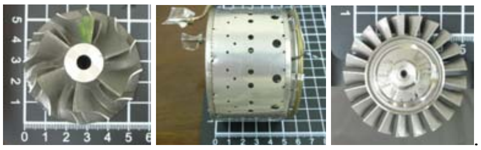
(a) (b) (c)

Fig. 1: Pictures of the major parts in MGT. (a) Compressor (b) Combustion chamber (c) Turbine wheel

Figure 2 shows the transmission gear box and generator, which are placed on a test frame made of 6061 aluminum alloy. The generator is a commercial product, which was taken from a motorcycle. The MGT thermal system is very similar to heavy duty turbines. However, due to the lower inertia of the compressor-turbine-generator shaft, it easily gets a high rotation speeds and may reach 100,000 rpm. Consequently, the MGT usually uses gear speed reducers to diminish the rotation speed to match the AC power grid frequency of the power generator. The gearbox drive in this research shown in Figure 2 consists of a large power turbine which drives the exhaust gas from the gas generator engine and reduction gear. The power turbine is mounted on a shaft running in high temperature bearings. The blower used to drive the MGT is connected to the MGT air inlet via a rubber tube. When the MGT reaches stable RPM, the rubber tube is removed and the turbine wheel keeps rotating by absorbing power from the air combustor.

The generator is connected to the MGT via a transmission gearbox, which transforms the power generated by the MGT into axial work. This axial work drives the generator to produce electrical power. The generated current is rectified to direct one for commercial use and the load is a set of high-power headlight, which is about 200W. Fuel pressure and flow rate at inlet nozzles of the combustion chamber can be adjusted using a pressure valve and flow meter. A mass flow controller (MFC) is a closed-loop device that sets, measures, and controls the flow of a particular gas or liquid. In this study, a TC-1350 MFC produced by Tokyo Keiso Company is adopted. The rotational speed of the MGT is measured using an induction tachometer installed close to the compression fans. A K-typed Chromel (chromium-nickel alloy)-alumel (aluminium-nickel alloy) thermocouple is used to measure temperature in the range of -200℃ to 1370℃, with an accuracy of ± 2.2℃ or 0.75% of the measurement. The temperatures at the compressor inlet and outlet, turbine inlet and outlet and exhaust are measured using thermocouples installed on the MGT. All measurement data are stored on disk via a laptop-controlled data-acquisition system CompactRIO-9072.

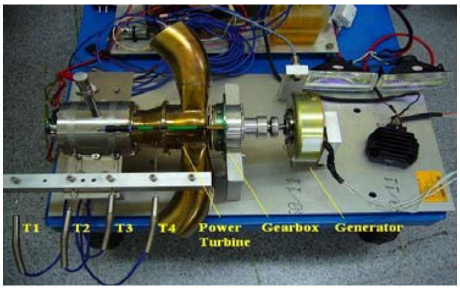

Fig. 2: Picture of the suspended test stand.

The parameters of the tests included fuel concentration (the mixing ratio of CH_4 and CO_2) and rotation speed of the turbine. The fuel mixtures contained 90% CH_4 with 10% CO_2, 80% CH_4 with 20% CO_2, 70% CH_4 with 30% CO_2, 60% CH_4 with 40% CO_2 and 50% CH_4 with 50% CO_2. In the experiments, stable RPM, 45,000 RPM, was reached. At each assigned time step, RPM was gently increased by a value of 5000 RPM. After the MGT was stabilized, then held the specific RPM and the engine would be maintained in this stable condition for 10 seconds to measure the data. The experiments were tested with six different fuels, and then each fuel was tested to confirm its maximum rotation speed. Each experimental condition was held at least twice for data consistency.

2.2 Dynamic model of MGT

This section describes the development of a dynamic model for the proposed MGT system. The model identification process is needed before the controller design research in the near future. According to the thermal process of the MGT, different models have been developed to predict the dynamic response behaviors of gas turbine systems. The MGT's dynamic model used in this study is adapted from that developed by Rowen [4] and modified to fit the proposed MGT system. This model is commonly used due to its simplicity and flexibility in adjusting to turbines with different characteristics. For an example, a single shaft gas turbine does not require a digital set point and inlet guide vane model is omitted. An outline of the structure, including the control and fuel systems, was generated using Matlab/Simulink; the relevant equations are

$$Tx = {}^{Tr - y\times\left[1-(V_{fuel}-0.4)\right]\times(N^2-4.21\times N+4.42)+z(1-N)}\Big/_{1+0.005(22-T_{amb})} \tag{1}$$

$$F_2 : Torque = k_{HHV}\times(V_{fuel}-0.4)+a\times(1-N) \tag{2}$$

where k_{HHV} is the high heating value factor, V_{fuel} is the volume flow rate of the fuel, T_{amb} is ambient temperature, Tr is the maximum exhaust temperature, Tx is predicted exhaust temperature, $Torque$ is predicted mechanic torque produced by the MGT, a , y and z are correlation factors, and N (p.u) is compressor rotational speed. These equations can calculate turbine torque and exhaust temperature algebraically.

2.3 Simulation of improved combustor

In this study, the authors were interested in improving the performance of MGT by re-design the combustor. A reliable steady state simulation result could help authors to achieve the demand. The authors found that there has been scarce published research on using the biogas fuel in a MGT numerically, except Yang et al. [5] had completed a numerical simulation process and model Numerically, this study first lightly modified the pre-existing numerical model for a combustion chamber of the MGT with CFD-ACE+(Fig. 3). The length of the fuel pipe is shorten compare to the previous design.

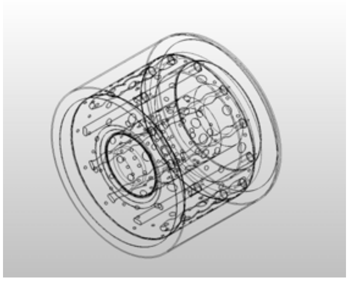

Fig. 3: Geometric diagram of the MGT.

2.3.1 Basic Assumption

In this paper, the simulation of the thermo-flow field inside the annular combustor chamber was three-dimensional and steady. In order to make the physical problem more tractable, several assumptions were made as follows: All gaseous mixtures are regarded as the ideal gases; The flow is steady, compressible, and turbulent; Properties in solid are constant; Neglect the turbulence-combustion interaction and radiation heat transfer; Soret diffusion, accounting for the mass diffusion resulting from temperature gradients, is neglected [5]. The governing equation; mass conservation; momentum conservation; numerical method; energy conservation and turbulent model were the same as adopted in the Yang' reference [5]

2.3.2 Four step reaction mechanism

Compared to the previous simulation results in Yang et al. [5]'s research, in order to capture the reaction kinetics more accurately, it was desirable that detailed reaction mechanisms should be used [6].

$$CH_4 + 2H + H_2O \rightarrow CO + 4H_2$$

$$CO + H_2O \rightarrow CO_2 + H_2 \qquad (3)$$

$$2H + M_T \rightarrow H_2 + M_T$$

$$3H_2 + O_2 \rightarrow 2H + 2H_2O$$

A diagram of the numerical simulation model used in this research can be seen in Fig. 2. This was a 30 degrees section, and only this one-twelfth part of the engine was meshed to reduce computational cost. For obtaining the acceptable numerical solution, this research applied the unstructured grids produced from geometry models to carry out grid-independence test. The grid numbers adopted for the grid-independence tests in this case are 477181, 717974, and 1484378. The test results are listed in Table 4. From the information given by the table, it can be seen that the maximum relative errors of various physical quantities are all less than 3%. Under such circumstance, it is naturally to select the grid number of 477181 to compromise the computational time and acceptable accuracy. The simulation was accomplished by a Pentium 4 PC with 3.0 GHz speed and 2 GB RAM. Furthermore, the convergence criterion was selected as 10-3. Figure 3 showed a section cut of this meshed model which utilized a non-conformal mesh algorithm to enhance the precision of simulation.

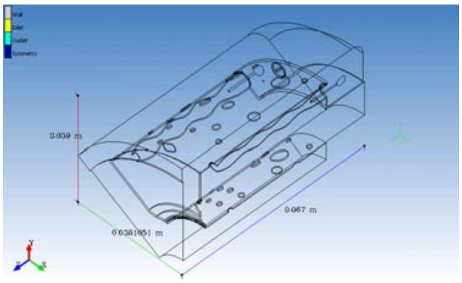

Fig. 4: One sub-chamber (one-twelfth) of annulus combustion chamber

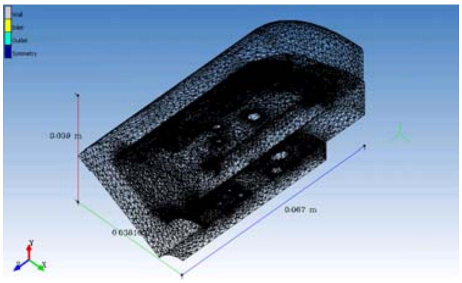

Fig. 5: Grids generation for numerical computation

III. RESULTS

3.1 Experiment results

The presented MGT system operated successfully under each tested condition when the minimum heating-value of the simulated fuel was approximately 0.5 of pure methane. The Fig. 6 showed the relation between the rotation speed of the compressor and the corresponding value of mass flow rate needed in different mixing ratio of the methane fuel. In order to make the MGT work with the low-heating-value fuel, the fuel supply system needed to afford enough pressure to ensure that the fuel has ample fuel density. Through the aforementioned experimental examine, the fuel system, which was modified to gas delivery system functioned properly. Then, the corresponding sensors and actuators for the micro gas turbine system were also established to verify the combustion efficiency of the MGT. The measurement data indicating the engine performance were analyzed and evaluated for the extending generator system. The Brayton cycle was calculated with various temperatures measured in different positions of MGT, and the calculated results were shown in Fig. 7. The power output obtained using 90% CH_4 fuel was roughly 170W, which was the maximum output of the generator, and 70W at 65,000 RPM as 70% CH_4 with 30% CO_2 was used (Fig. 8). When a critical limit of 60% CH_4 was used, the power output was extremely low. The aforementioned design procedure and measured data can be used as a model for future control design of micro gas turbine engine for power generation.

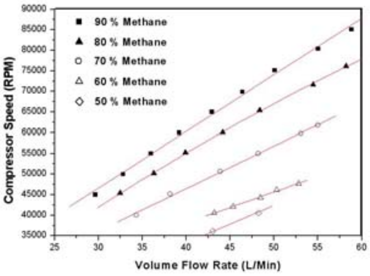

Fig. 6: Volume flow rate for different biogas fuels at various RPMs.

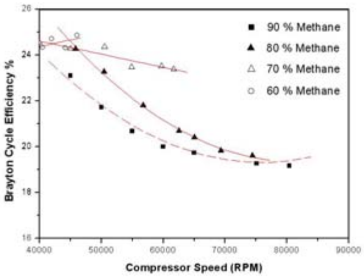

Fig. 7: Brayton cycle efficiency of different compressors speed with different concentrations of CH_4.

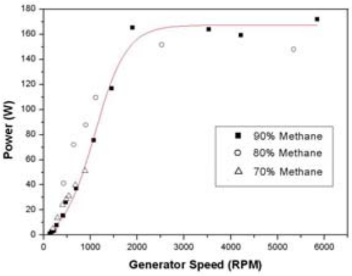

Fig. 8: Output power for different generator rotation speed with different biogas fuel.

3.2 System identification

All parameters in the dynamic model can be derived using experimental results for MGT performance. In Eq. 5.2, the HHV of the fuels influenced the required volume flow rate of fuel. As the HHV of methane fuel was 13255.95kcal/kg, kHHV factor was defining as 13.255 [4]. Correlation factor a can be derived based on experimental results with the conditions of $V_{fuel} = 0$, $Torque = 0$, and $N = 0$ input into Eq. 1. The turbine-torque prediction function was then rewritten as $0 = 13.255 \times (0 - 0.4) + a \times (1 - 0)$, and $a = 5.302$ was calculated algebraically. An experimental result for volume flow rate of fuel was input into the dynamic model to confirm the reliability of proposed numerical simulation model. The simulation results for variations in compressor speed in the dynamic model shows a great consistency with the experiment data (Fig. 9). However, simulation and experimental data differ before 100 sec and after 350 sec. In these periods, the MGT was considered unstable; this status was not discussed herein.

Variations in volume flow rate versus turbine outlet temperature indicate these variables are nonlinearly correlated. Equation 2.1 in this numerical simulation model should be restricted to represent only the stable status of the MGT system based on experimental results and phenomena. The required inputs for Eq. 4.1 were compressor rotation speed, fuel volume flow rate, and ambient temperature. The effect of ambient pressure on gas turbine output is not addressed herein. Correlation factor y can be calculated using experimental results with the conditions of $V_{fuel} = 0.4$, $T_{amb} = 22$, and $N = 1$ (p.u) input into Eq. 2. After correlation factor y was calculated as 20.66, correlation factor z was calculated based on experimental results with the conditions of $V_{fuel} = 00$, $T_{amb} = 22$, and $N = 0$ (p.u); $y = 20.66$ was then input into Eq. 2. Correlation factor z was 507.57. The simulation result for the effect of variables, including that of compressor rotation speed, fuel volume flow rate, and ambient temperature, on exhaust temperature are the same as experimental data when the MGT system is in stable status (Fig. 10). The completed simulation model will prove to be a helpful base structure when designing an optimal control strategy.

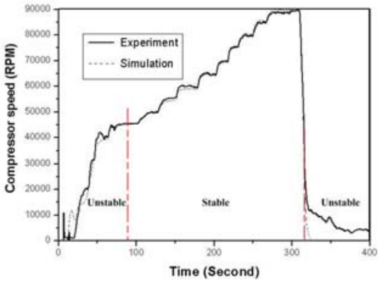

Fig. 9: The numerical data of compressor speed in dynamic model and the experimental results of compressor speed.

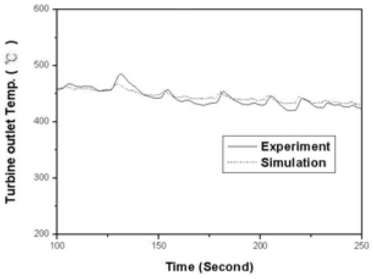

Fig. 10: Numerical result of turbine outlet temperature versus experimental time.

3.3 Numerical simulation results of re-designed combustor

From the experimental results shown in section 3.1, the authors observed that the temperature at turbine inlet was way below the endurance temperature of turbine wheel. A re-designed combustor leads to higher value at turbine inlet is expected for future studies. The simulation result of temperature distribution in the redesigned combustion chamber is shown in Fig. 11. The temperature at turbine inlet reached 900K, and still below the endurance temperature of turbine wheel. The numerical result shown that with a shorten fuel pipe, the flame had keep distance from the front of combustor wall. The temperature distribution shown in Fig. 12 demonstrated the liner the combustion chamber also had been less affected by high temperature compare to the original design.

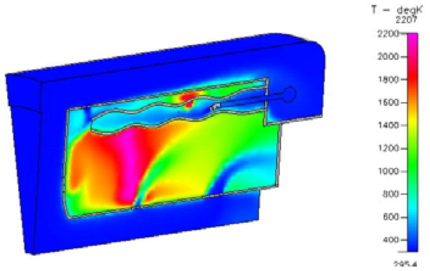

Fig. 10: Numerical result of temperature distribution of re-designed combustion chamber.

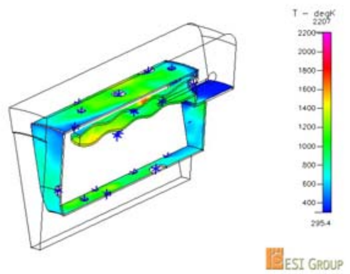

Fig. 11: Numerical result of temperature distribution on the liner of re-designed combustion chamber.

IV. CONCLUSIONS AND RECOMMENDATIONS

In this study, the effects of biogas fuels on the performance of an annular MGT were assessed experimentally and numerically. In the experiments, the proposed MGT system was operated successfully under each test condition; minimum composition to the fuel with the biogas was roughly 50% CH_4 with 50% CO_2. The power output was around 170W at 85,000 RPM as 90% CH_4 with 10% CO_2 was used and 70W at 65,000 RPM as 70% CH_4 with 30% CO_2 was used. When a critical limit of 60% CH_4 was reached, the power output was extremely low. Furthermore, the theoretical Brayton cycle efficiency and electric efficiency of the MGT were calculated as 23% and 10%, respectively. Following the experiments, the measured data helped us identify the parameters of dynamic model in numerical simulation. Additionally, a numerical analysis of re-designed combustion chamber showed that the performance of MGT could be improved by raising the temperature at turbine inlet. This study presents a novel distributed power supply system that can utilize renewable biogas. The completed micro biogas power supply system is small, low cost, easy to maintain and suited to household use.

ACKNOWLEDGEMENT

The authors would like to thank the National Science Council of the Republic of China, Taiwan, for financially supporting this research under Contract No. NSC 96-2218-E-009-002

REFERENCES

[1] L. Li, X. F. Peng, and T. Liu, Combustion and cooling performance in an aero-engine annular combustor, Applied Thermal Engineering, Vol. 25, pp. 1171-1179, 2006.

[2] C. A Gonzalez, K. C. Wong, and S. Armfield, A computational study of the influence of the injection characteristics on micro-turbine combustion, The 16th Australasian Fluid Mechanics Conference, pp. 1148-1152, Australia, 2007.

[3] D. Yamashita, K. Kuwabara, K. Tatsumi, and K. Nakabe, Experimental evaluation on low-heating value fuel acceptability of micro gas turbine system operation, The 16th International Symposium on Transport Phenomena, pp. 1-7, Prague, 2005.

[4] W. J. Rowen, Simplified Mathematical Represmeyations of Heavy Duty Gas Turbine, Journal of Engineering Power, pp. 865-869, 1983.

[5] C. H. Yang, D. H. Wu, and C. H. Chen, Optimal Design of a Methane-used Combustor: Applying CFD Modeling, The 3rd International Green Energy Conference, Vasteras, Sweden, 2007.

[6] CFD User Manual, CFD Research Corp, 2004.