Proceedings of ASME Turbo Expo 2011
GT2011
June 6-10, 2011, Vancouver, British Columbia, Canada

GT2011-46655

Modeling of Biodiesel Fueled Micro Gas Turbine

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ABSTRACT

Biodiesel is an environmentally benign renewable alternative for conventional diesel fuel, and its utilization in macro gas turbines (MGT) is an interesting option for many applications. The objective of this work is to develop a steady-state model to evaluate the performance of a micro gas turbine fueled by the blends of biodiesel and petrodiesel. The concentration of inlet biodiesel to the model was 10%, 20%, and 30%. In order to validate the developed model, the results of modelling work were compared against the experimental data obtained from a micro gas turbine experimental unit. The engine was modified by mounting various sensors to monitor and record system performance parameters, such as pressure, temperatures, and flow rates at various locations as well as output power, and ambient conditions. The results indicate that most parameters are influenced, to some degree, by changes in the fuel composition. This indicates that although most MGTs can be potentially operated by a high concentration of biodiesel blends, before this fuel switching can be implemented, the system operational parameters should be evaluated by the system modeling to predict possible negative impacts of biodiesel in the inlet fuel on the engine.

INTRODUCTION

Micro gas turbine (MGT) is a power generation technology that is suitable for the distributed and residential power generation, peak shaving, uninterrupted generation, back-up power, mechanical drive, premium power, remote power, and combined heat and power (CHP) or combined cooling, heat and power (CCHP) due to its compact size and relatively low costs. Historically its development started for automotive and transportation applications but then switched toward distributed, mobile, and military electric power generation. MGTs are typically composed of a compressor, turbine, and generator connected by a single shaft, a combustor, and regenerator (recuperator) [1]. The objective of recuperator, both rotating and stationary configurations, is to recover thermal energy from the turbine exhaust stream and increase inlet air temperature to the

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combustor, which results in a lower fuel consumption and significantly higher efficiency.

The efficiency of MGTs can be increased and their environmental impacts can be reduced by utilization of micro turbines in combined cooling, heating, and power (CCHP) plants [2]; hybrid solid oxide fuel cell and MGT cycles [3], and biodiesel fueled MGTs [4]. Biodiesel is environmentally friendly alternative for conventional diesel. It can be driven from vegetable oils, recycled cooking oil, and animal fat. Its application in internal engines results in: very low emissions (especially when the life cycle emissions are taken into account), easy to use in conventional engines, nontoxic, biodegradable, improved lubricity, and free of sulfur and aromatics [4]. However, there are few problems that should be addressed. Biodiesel's heating value is lower than that of petroleum-based diesel, and its NO_x emission can be potentially higher [5]. It suffers from poor cold flow performance, due to higher viscosity and density, which may cause some problems in injection system [6].

Biodiesel can be used alone or can be blended with petroleum diesel at any level to form a biodiesel blend. The "B" factor is an internationally accepted system, which refer to the percentage of biodiesel in the biodiesel blend (mass-based). For instance, B10 refers to a blend with 10% biodiesel and 90% petroleum-based diesel and B100 refers to a pure biodiesel. Blended biodiesel, particularly with the low concentration of biodiesel (<B20), can be easily used in conventional engines with little or no modifications [4].

The objective of this work is to present the results of the modeling of micro gas turbine, when it is fueled by blends of biodiesel and petroleum-based diesel with different concentrations. In the following subsections, first the modeling approach will be explained. Then the model will be validated against experimental data. Finally, the modeling results will be presented.

MODELING APPROACH

The proposed model was intended for the steady-state simulation of a MGT fueled with biodiesel and was developed in Aspen Plus®. Aspen Plus® is a process simulation tool that can be used for the realistic steady-state simulation of thermodynamic cycles. In this software, built-in and user-defined models can be connected with material, work, and heat streams to form a model of an actual system. For this study, a macro level model was developed based on fundamental equations of thermodynamics and chemical reactions. To complete this hybrid cycle, thermodynamic models for the compressors, gas turbine, combustor, material stream mixers and splitters, and heat exchangers were used. It was assumed that all chemical components in the model behave as ideal gases at the operating temperature and pressure of the system.

The basic configuration of the MGT cycle investigated in this research is shown in Figure 1. In the model the inlet air (AIR-IN), entering the system at ambient conditions, is compressed at AIR-COMP to the system operating pressure. The compressor pressure ratio in this case is 3.5. Then the high pressure inlet air is divided into two streams. The majority of the stream (about 96%) goes to the power generation cycle and approximately 4% is used for turbine blade cooling. The air stream then is heated at REGEN by recovering heat from exhaust stream. On the other hand, the inlet fuel to the system is first pumped from the specified conditions to the system pressure (at FUELPUMP) and mixed with high pressure inlet air before being fed the combustor. The combustion products are passed through the turbine to generate power. The waste heat in the gas turbine exhaust stream is recovered at REGEN before being discharged to the atmosphere.

The model requires some constants, and the equipment operating parameters should be defined. These parameters and constants are listed in Table 1.

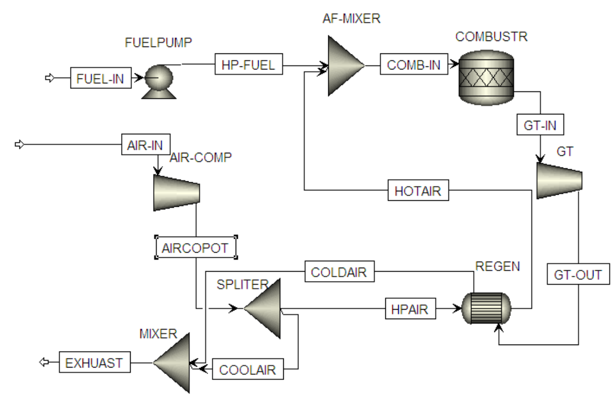

Figure 1: MGT CYCLE CONFIGURATION IN THIS STUDY

The developed model can be used to estimate all parameters in the cycle. However, before it can be used for any analysis, it should be validated against experimental data. The following subsection describes the experimental setup used for validation of this model.

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Table 1: INPUT PARAMETERS FOR MACRO GAS TURBINE MODEL

Parameter	Default Value
Inlet fuel temperature/ pressure	Ambient conditions
Inlet fuel pump/driver efficiency	80% / 80%
Inlet fuel pump discharge pressure	4.1 atm
Inlet air temperature/ pressure	Ambient conditions
Inlet air composition (vol. %)	21% O_2-79% N_2
Air compressor pressure ratio	3.53
Air compressor isentropic efficiency	80%
Air compressor mechanical efficiency	85%
Gas turbine isentropic efficiency	88%
Gas turbine mechanical efficiency	89%
Gas turbine discharge pressure	1.2 atm
Regenerator effectiveness	89%

DESCRIPTION OF MICRO GAS TURBINE SET

Measurements from a dual-shaft 100 kW Teledyne RGT-3600 micro gas turbine generator set, shown in Figure 2, was used to validate this model. As the Figure 3 shows, the inlet air is pressurized in the centrifugal compressor and discharges through the diffuser and directed to the regenerator. The temperature of high pressure air increases as it passes the regenerator disks and then enters the combustor. In the combustion chamber, biodiesel blend fuel is burnt and the high temperature and pressure products expand first through the compressor turbine and then through the power turbine. The turbine outlet stream passes through the hot portion of the regenerator disks before it is discharged to the exhaust pipe. Figure 4 illustrates the schematic of the system components and material streams.

Figure 2: REGENERATIVE MICRO TURBINE GENERATOR SET

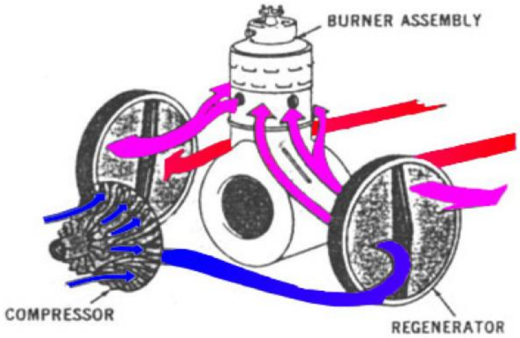

Figure 3: FLOW PATTERN FOR TWIN ROTATING DISK REGENERATOR MICRO GAS TURBINE [4]

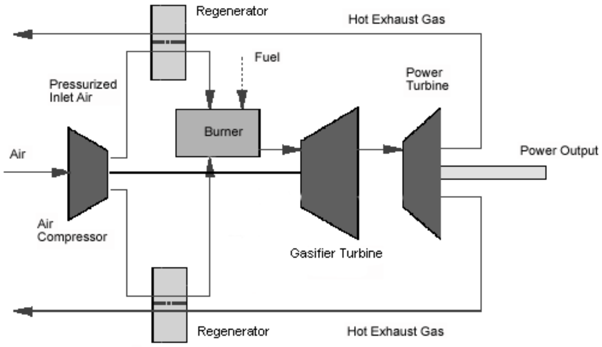

Figure 4: SCHEMATIC OF THE MICRO GAS TURBINE COMPONENTS AND MATERIAL STREAMS [7]

The compressor assembly consists of a radial flow compressor with a single-stage, cast-aluminum impeller at front end of common shaft and a single-stage, axial flow turbine at the other end, which drive the compressor. The compressor also includes a vane type diffuser. The combustor is a can-type and mounted on the top of the machine and is equipped with single fuel nozzle and igniter. The regenerator subsystem is composed of two ceramic matrix disks at the sides of the engine. The disks are rim-driven with rotational speed of about 14.5 rpm. Finally, the power turbine has a variable nozzle guide vane and is connected to the generator by a

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common shaft. The system also includes a reduction and accessory drive gearbox, fuel management system, start-up equipment. The system design specifications are presented in Table 2. The MGT set testing facility (Figure 5, a) includes a Teledyne RGT-3600 micro gas turbine generator set (Figure 2), a three-phase AC 100 kW generator, a load bank to simulate the load (Figure 5, b), and instruments to measure engine critical parameters as well as a computer-based data acquisition system to record the measured parameters at the sample rate of 1 Hz per channel.

Table 2: MICRO GAS TURBINE (RGT-3600) MEASURED SPECIFICATIONS

Parameters	Spec.
Max power (kW)	100
Max fuel consumption (L/min)	1.3
Max air flow rate (kg/sec)	2.0
Max combustor exit temperature (°C)	1035
Max exhaust stream temperature (°C)	330
Max compressor pressure ratio	4.1
Compressor isentropic efficiency (%)	80
Turbine isentropic efficiency (%)	88
Regenerator effectiveness (%)	89

a b

Figure 5: a) THE MICRO GAS TURBINE SET TESTING FACILITY b) THE LOAD BANK

In order to measure and record the required parameters for model validation, including temperature, pressure, and flow rate at different locations in the cycle, the MGT was equipped with various sensors and instruments. The measured parameters in the test engine are as follows: compressor outlet pressure (P3, Figure 6, a), combustor outlet stream temperature (turbine inlet temperature, T4, Figure 6, b), exhaust stream temperature (T7, Figure 6, c), fuel volumetric flow rate (W_f, Figure 6, d), compressor inlet air mass flow rate (W_a, Figure 6, e and f), output power, and ambient temperature, pressure, and relative humidity (T0, P0, and RH0, Figure 6, g),

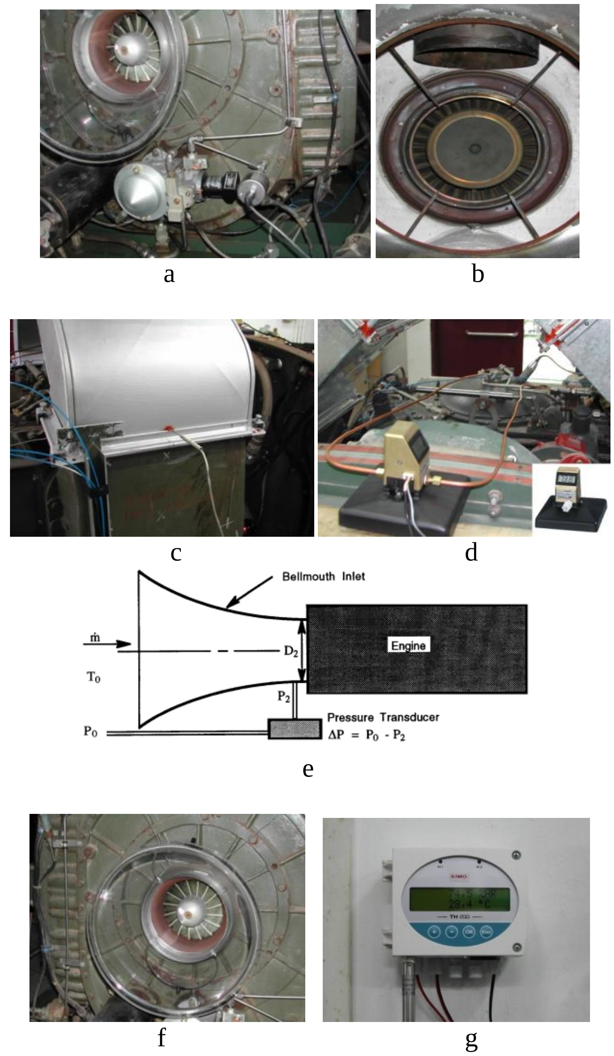

Figure 6: MEASURING INSTRUMENT LOCATIONS [8] a) COMPRESSOR OUTLET PRESSURE (P3) b) COMBUSTOR OUTLET STREAM TEMPERATURE (T4) c) EXHAUST STREAM TEMPERATURE (T7) d) FUEL VOLUMETRIC FLOW RATE (W_f) e and f) COMPRESSOR INLET AIR MASS FLOW RATE (W_a) g) AMBIENT PRESSURE (P0), TEMPERATURE, AND RELATIVE HUMIDITY (T0 and RH0)

Figure 7 illustrates some sample measurements from the test set when the engine is fueled by B10 [9], including the turbine inlet temperature (T4), exhaust stream temperature (T7), compressor inlet air mass flow rate, and ambient temperature (T0). In order to conduct the experiments, the MGT was fueled by 3 biodiesel blends: B10, B20, and B30. For each fuel, the external load was varied from idle to full load (0, 25, 48, 69, 89, and 98 kW). The biodiesel was manufactured by the Taiwan NJC Corporation. The characteristics of the biodiesel were according to ASTM D6751 standard.

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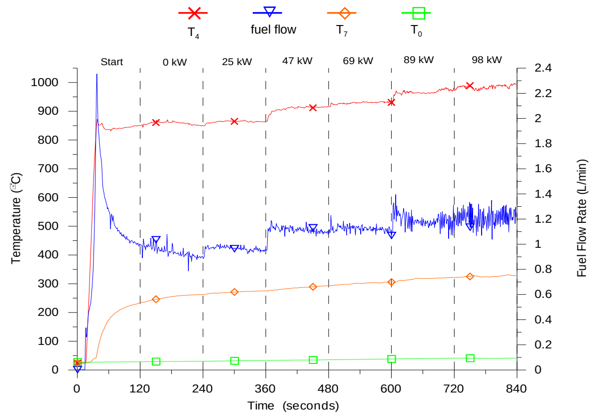
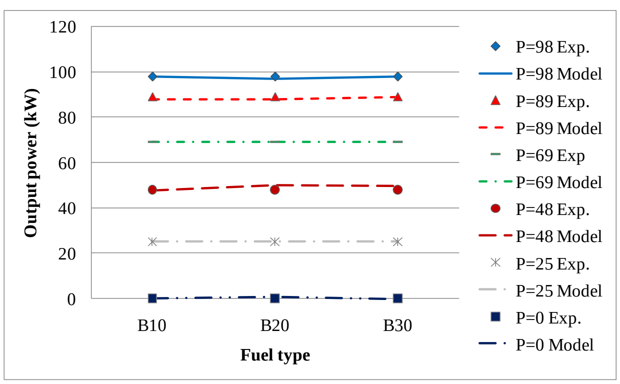


Figure 7: THE TURBINE INLET TEMPERATURE, EXHAUST STREAM TEMPERATURE, COMPRESSOR INLET AIR MASS FLOW RATE, AND AMBIENT TEMPERATURE FOR VARIOUS OUTPUT POWERS WHEN THE SYSTEM WAS FUELED BY B10 [9]

MODEL VALIDATION

The model's major operating parameters, including output power, system efficiency, turbine inlet temperature (TIT), and exhaust temperature, are compared with experimental data for three types of biodiesel blends: B10, B20, and B30 at various loads in Figure 8. The figures indicate an excellent agreement between the modeling results and experimental measurements, especially for output power and efficiency.



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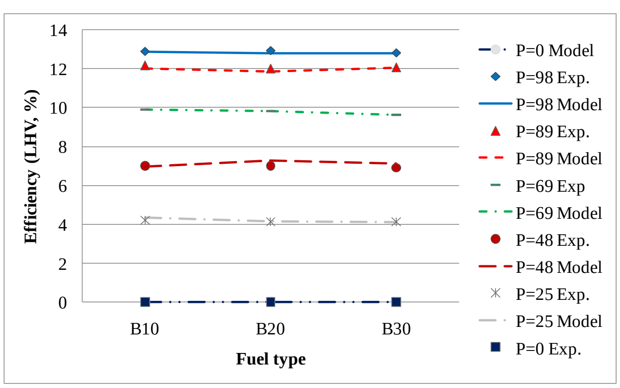

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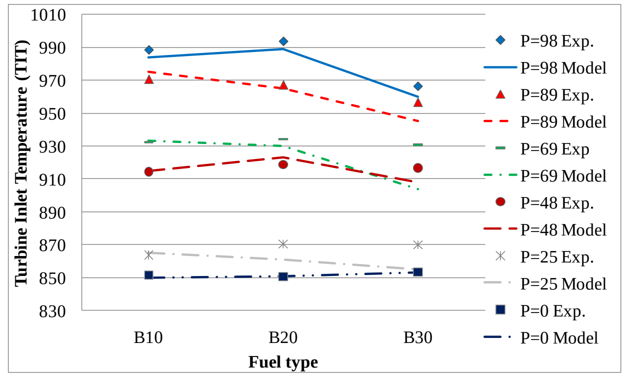

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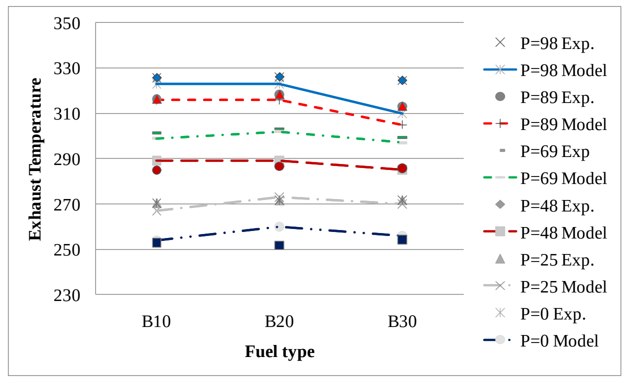

d

Figure 8: COMPARISON OF MODELING RESULTS WITH EXPERIMENTAL DATA
a) OUTPUT POWER b) EFFICIENCY c) TURBINE INLET TEMPERATURE d) EXHAUST TEMPERATURE

MODELING RESULTS AND DISCUSSION

The diagrams in Figures 9 to 11 show how the performance parameters of the MGT model are influenced by the fuel type. In these diagrams, for constant output power, the parameter variations are investigated for three fuels; B10, B20, and B30. Figure 9 shows that the electrical efficiency of the system slightly reduces at most loads, when the concentration of biodiesel increases in the fuel. Also, the efficiency of the cycle reduces with reduction in the output power due to lower efficiency of the components at partial loads.

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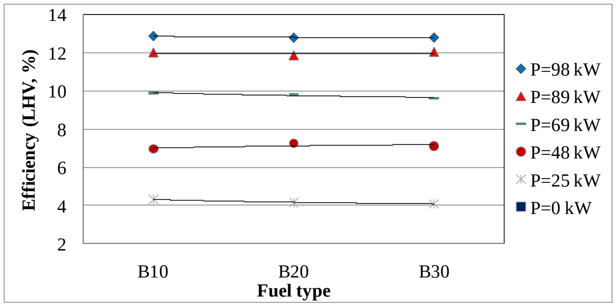
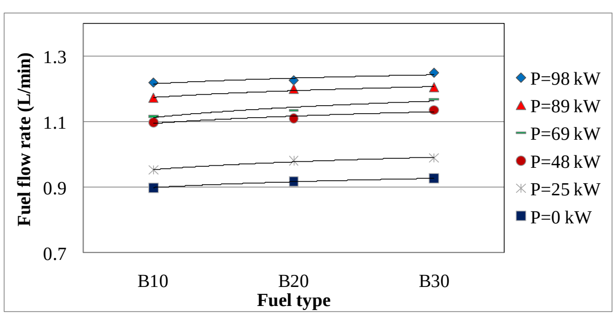


Figure 9: MGT ELECTRICAL EFFICIENCY VS. FUEL TYPE FOR CONSTANT OUTPUT POWERS

Figure 10 (a) shows the variation of fuel flow rate and indicates that the fuel volumetric flow rate increases with the higher percentage of biodiesel in the fuel. In order to investigate this diagram, the variations of the fuel density and its heating value should be considered. Figure 10 (b) illustrates that mass and volumetric lower heating value (LHV) of the fuel reduces and density increases with the increase of the concentration of biodiesel in the blended fuel (based on the data from [9]). These two effects, increase in density and reduction of heating value, affect the fuel volumetric flow rate in opposite directions. According to Figure 9, the electrical efficiency of the MGT slightly reduces; therefore, for a particular output power, the energy content of inlet fuel should only increase slightly. This can be seen in Figure 10 (c), where the graph shows that the energy content of inlet fuel (kJ/sec) slightly increases with the increase in the biodiesel content of the fuel. Since the heating value of the fuel decreases, the fuel mass and volumetric flow rate should increase. On the other hand, increase in density results in decrease in volumetric flow rate. But, Figure 10 (d) shows that the mass flow rate of the inlet fuel increases, which means the effect of decrease in fuel heating value overtakes the effect of increase in the fuel density.



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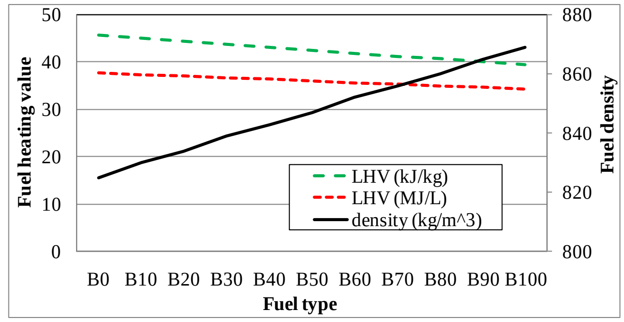

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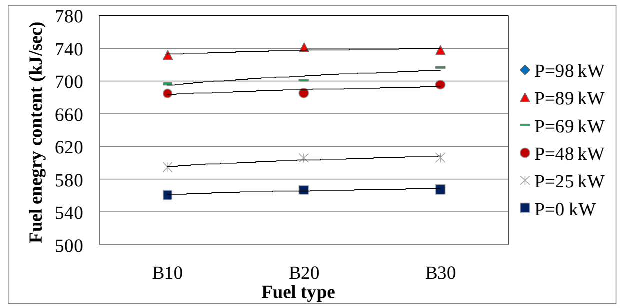

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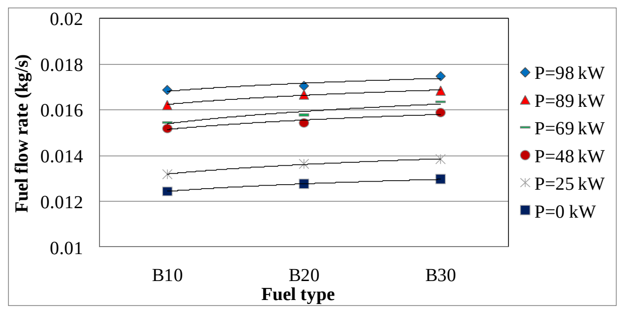

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Figure 10: DIAGRAMS TO INVESTIGATE THE VARIATION OF THE INLET FUEL FLOW RATE a) THE INLET FUEL VOLUMETRIC FLOW RATE b) THE FUEL LOWER HEAT VALUE AND DENSITY VS. THE BIODIESEL CONTENT OF FUEL BLEND c) THE ENERGY CONTENT OF INLET FUEL d) THE INLET FUEL MASS FLOW RATE

Figure 11 (a) and (b) show the turbine inlet temperature (TIT) and exhaust temperature of the MGT. As Figure 11 (a) shows, at the full load or close to full load operations, the TIT reduces when the concentration of biodiesel increases in the fuel. At lower loads, however, for most cases, the TIT does not change significantly with the fuel composition. The observation of Figure 11 (b) indicates that the exhaust temperature follows almost the same trend. Obviously, all these parameters decrease at lower output power (partial loads).

The next step and future work for this research is to use the model to predict and evaluate the system

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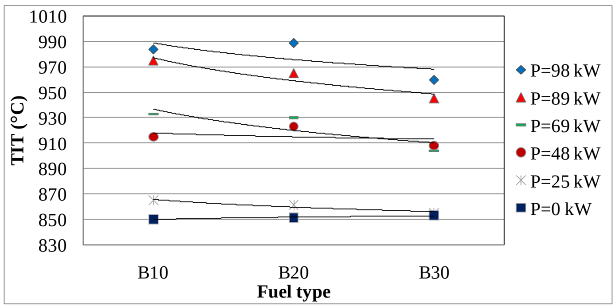
performance when it is fueled by the blends with a higher concentration of biodiesel. The understanding of the system behavior when fueled by the various blends of biodiesel can help to design engines with optimum performance with these fuels.



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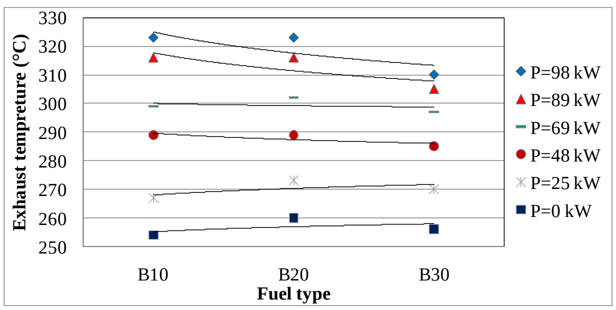

b

Figure 11: THE VARIATION OF THE MGT PERFORMANCE PARAMETERS WHEN THE SYSTEM IN FUELED BY B10, B20, AND B30 a) TURBINE INLET TEMPERATURE b) EXHAUST TEMPERATURE

CONCLUTION

The steady-state model of a regenerative micro gas turbine was developed based on the specification of a dual-shaft 100 kW Teledyne RGT-3600 micro gas turbine generator set. The model was validated against the experimental performance data from the same system. In the modified micro gas turbine set various parameters, including compressor outlet pressure; combustor outlet (turbine inlet) and exhaust stream temperature; fuel volumetric flow rate; compressor inlet air mass flow rate; output power; and ambient temperature, pressure, and relative humidity were measured, recorded, and used for the model validation. The engine model was fueled by the blends of biodiesel and petrodiesel, with the concentration of biodiesel from 10% to 30%. The results of the modeling indicated that most system operational parameters varied, to some extent, when the biodiesel concentration was increased. These effects should be considered for the fuel switching of micro gas turbines and designing factory-made micro gas turbine engines. For future work, this model will be used to predict the system performance when fueled by the blends with higher portion of biodiesel.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the financial support provided by the Natural Sciences and Engineering Research Council of Canada (NSERC) and National Science Council of Taiwan (NSC) through Summer Program in Taiwan, Natural Sciences and Engineering Research Council of Canada (NSERC) through Discovery Grants (DG), and Ontario Graduate Scholarship Program (OGS). Also the supports provided by National Tsing Hua University and research students at the Turbogenerator lab are appreciated.

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