STUDY OF FLUE GAS EMISSIONS OF GAS MICROTURBINE-BASED CHP SYSTEM

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ABSTRACT

A number of Distributed Energy Resources (DER) such as gas microturbines as well as Combined Cooling, Heating and Power (CHP) systems have increased markedly over the last several years. Environmental issues (i.e. emissions, noise) are among of the most important aspects of operating these systems. This paper presents results of emissions study of a CHP Integration Test System (microturbine-based with heat recovery) that is located at the Oak Ridge National Laboratory (ORNL).

INTRODUCTION

The goal of the Combined Cooling, Heating and Power (CHP) for Buildings Program is to optimize the integration of Distributed Energy Resources (DER) equipment with energy efficient Heating, Ventilating, and Air-Conditioning (HVAC) systems. The objective is to maximize energy efficiency, reduce overall energy use and atmospheric emissions associated with energy production, increase the power available for critical loads by providing an option to central power generation/grid distribution, and improve electric power reliability and quality [1].

DER, such as microturbines, are small modular power generation systems located on or near the site where the energy generated is used [2]. Unlike centralized energy resources, such as large electric power plants, they provide an opportunity for local control of power generation and more efficient use of waste heat to boost overall plant efficiency and reduce emissions. In a CHP system, waste heat from these DER technologies can be used as input power for the generation of hot water, steam for space heating, and for driving heat-activated air conditioners, chillers, and desiccant dehumidifiers.

The goal of the CHP Integration Test Facility is to conduct experimental and theoretical studies of various CHP configurations to evaluate the optimal operational modes of these systems. Currently, CHP system configurations that are installed in the field are custom designed and consist of commercially available equipment originally developed for stand-alone use. One of the objectives of the CHP research is to determine how to integrate the hardware, controls, and operation of these separate pieces of equipment so that the system operates at optimum efficiency under both steady-state and transient conditions. Results of the testing will be used in optimizing the performance of the next generation integrated CHP packaged products with a single controller. Another important field of research at ORNL is the study of the flue gas emissions levels of the microturbine-based CHP system with variable electric and thermal loads and inlet parameters. An objective of the testing was to ensure that the emissions levels are within the limits specified by the EPA emissions regulations [3] and to verify the microturbine manufacturer's emissions specifications. In addition, increased levels of corrosive compounds in flue gases can result in acceleration of corrosion processes in power-generating equipment thus reducing its reliability and availability [4].

TEST EQUIPMENT

For the DER emissions tests, a CHP system consisting of a 30 kW* natural gas-fired microturbine and heat recovery unit was used. The microturbine, which is located outside of the CHP Integration Test Facility building, is a three-phase 480-VAC/30-kW rated unit that can operate at 50 or 60 Hz when connected to the grid. A stand-alone option, which allows the microturbine to start and generate power without electric utility service, is also available, although it was not employed or studied in these tests. The schematic diagram of the microturbine unit is shown in Figure 1. The gas microturbine and the electric generator are on the same shaft. The turbine generator, which is designed to operate at a maximum speed of 96,000 rpm, produces high-frequency AC power that is rectified to DC and converted to 50 or 60-Hz AC power by the power conditioning electronics of the digital power controller (DPC). In addition to power conversion functions, the DPC controls the microturbine operation and provides over/undervoltage and over/underfrequency protection.

In the CHP mode, the flue gas from the microturbine exhaust, which has a temperature of ~ 275 ^{o}C** is directed to the indoor-located heat recovery unit (HRU). It passes through the air-to-water heat exchanger tubes and transferes heat to water pumped through the tubes. After the heat exchanger the flue gas with a temperature of ~ 124 ^{o}C** is exhausted to the atmosphere. The nominal water flowrate through the HRU is 75.7 l/h. The schematic diagram of the CHP test rig is shown in Figure 2.

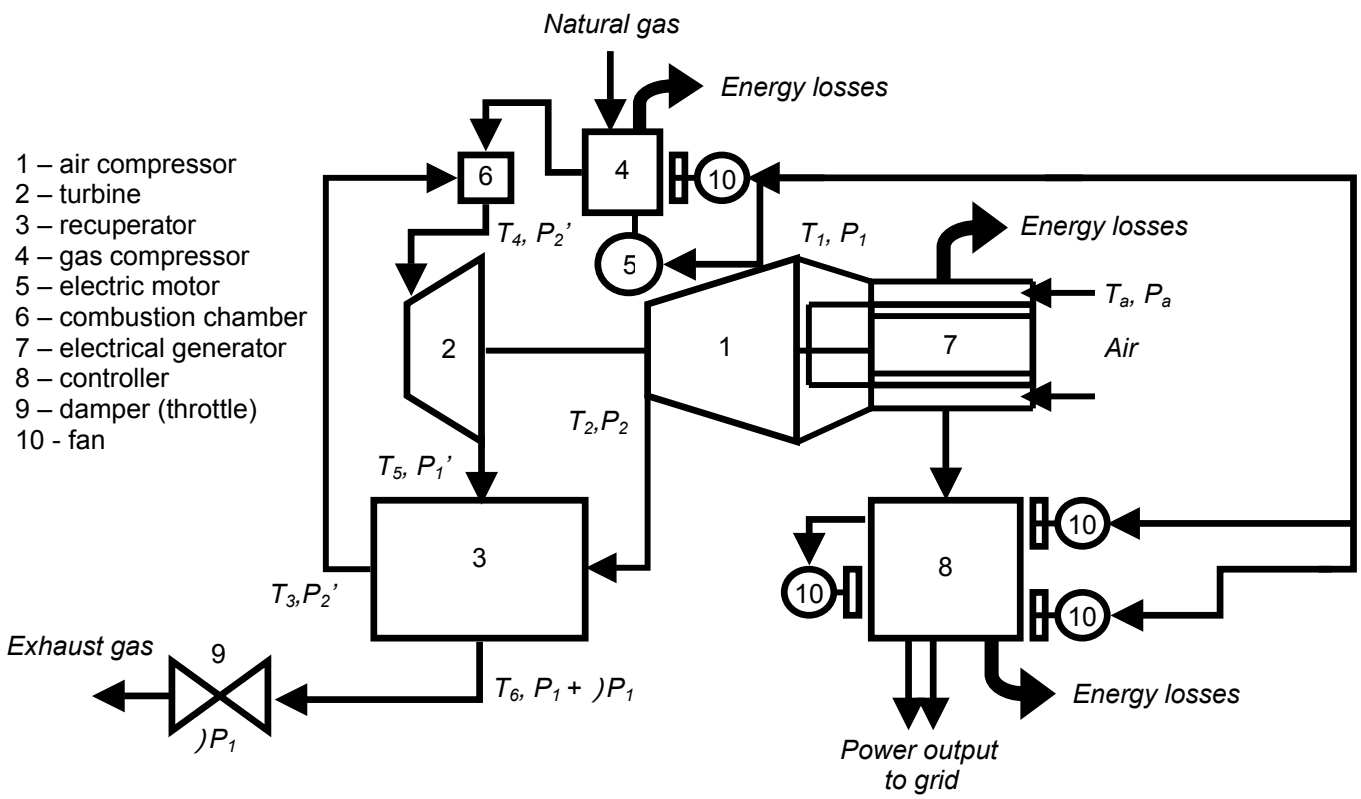

Figure 1. Schematic Diagram of the Gas Microturbine Unit.

* Microturbine full-load power output is 28 kW; 2 kW is auxiliary power consumed by the microturbine
** The temperature data are given for the microturbine full-load power output

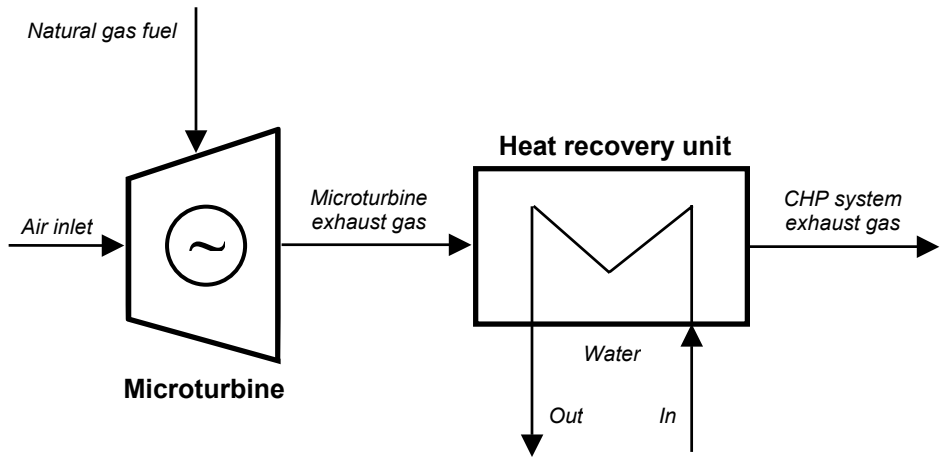

Figure 2. Schematic Diagram of the CHP System.

The thermodynamic cycle of the microturbine-based CHP system is shown in Figure 3. At point A, inlet air (ambient temperature T_a and ambient pressure P_a) enters the microturbine and goes to the inlet duct of the air compressor, where it is heated to temperature T_1 at point 1 with the heat from the electric generator. Disregarding the hydraulic losses between points A and 1, it may be assumed that P_1 is equal to P_a. The air from point 1 (T_1, P_1) goes to the air compressor, where it is compressed to point 2 (T_2, P_2).

After the air compressor, air goes to the recuperator, where heat of the flue gas heats it from T_2 at point 2 to T_3 at point 3. Due to the hydraulic resistance in the recuperator on the high-pressure side, the air pressure decreases to P_2' at point 3. After the recuperator the air goes to the combustion chamber, where it is heated from T_3 at point 3 to T_4 at point 4. After the combustion chamber, the hot gas is directed to the gas turbine, where it expands from point 4 (T_4, P_2') to point 5 (T_5, P_1'). After the turbine, the flue gas goes to the recuperator, where it is cooled from T_5 to T_6. Due to the hydraulic resistance of the recuperator on the low-pressure side, the pressure at point 6 is lower than P_1'. If the flue gas is released to the atmosphere, the pressure at point 6 is equal to P_1. If the flue gas is used to generate hot water in the heat recovery unit, the pressure at point 6 is higher than P_1 by the magnitude of the pressure loss in the heat recovery unit(s).

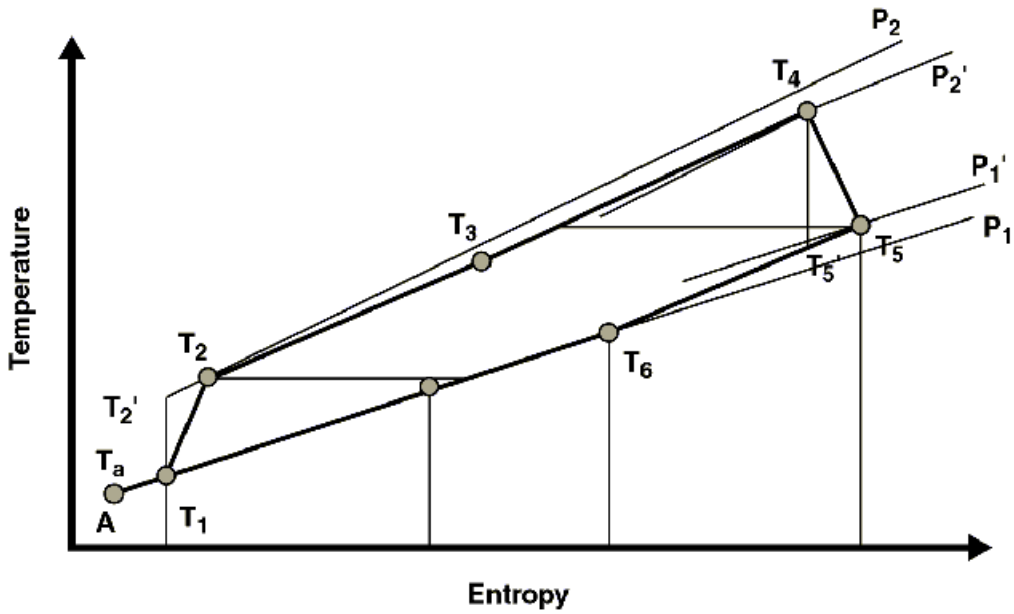

Figure 3. Thermodynamic Cycle of the CHP System.

The CHP system at the CHP Integration Test Facility includes sophisticated PC-based monitoring and control of the microturbine and PC-based monitoring of the heat recovery unit operating parameters (temperatures, pressures, flowrates etc.). Continuous emissions monitoring of the microturbine flue gas is performed with an Enerac 3000E flue gas analyzer which is supported by Enercom 2000 software [5, 6].

EMISSIONS MONITORING

The US Environmental Protection Agency lists six criteria air pollutants for which ambient air limits have been set [7, 8]. These air pollutants include nitrogen dioxide (NO_2), carbon monoxide (CO), sulfur dioxide (SO_2), lead (Pb), ozone (O_3) and particulates. Of these pollutants, NO_2 and CO are the most relevant for the operation of the gas microturbine-based CHP system. The most significant of the nitrogen oxides (NO_x) that are produced in high temperature combustion is nitric oxide (NO), which subsequently oxidizes in the atmosphere to produce nitrogen dioxide. CO is a poisonous gas formed when carbon based fuel is not fully burned. Both these gases can have a significant effect on the level of environmental pollution. Therefore, these two pollutants got the most of attention during the emissions studies in this project.

NO_x formation is minimized at lower combustion temperatures, but lower combustion temperatures also result in higher CO emissions [9, 10]. Thus, in order to achieve low emissions levels, operation at a high air to fuel ratio (excess air) within the primary combustion zone of the microturbine is required. The CO emissions, as well as carbon dioxide (a “Green House” gas), were calculated by the flue gas analyzer using the fuel data and oxygen concentration. The latter was measured with an oxygen electrochemical cell. The SO_2 concentration was also determined by the electrochemical method. The accuracy of the emissions measurements was within 2% of reading [5].

Excess air, concentrations of CO_2 and O_2 were expressed in %, while concentrations of NO_x, CO, and SO_2 were measured in ppm by volume (i.e. volume of gaseous pollutant per million volumes of ambient air) at the test oxygen concentration. Basically, the SO_2 concentration found in this research was very low (not exceeding 3 ppmV) and was excluded from further analysis. The levels of NO_x and CO were corrected to 15% O_2 (typical requirement for gas microturbines) using equations (1) and (2):

$$NO_{x_15\%} = (NO_x - NO_{x_a}) \cdot \left(\frac{5.9}{20.9 - O_2} \right) \cdot n \qquad (1),$$

where: $NO_{x_15\%}$ is the concentration of nitrogen oxides at 15% O_2, ppmV; NO_x is the concentration of nitrogen oxides measured during the tests, ppmV; NO_{x_a} is the ambient concentration of nitrogen oxides, ppmV; O_2 is the oxygen concentration measured during tests, %; and n is the ambient correction factor (available from [11]).

$$CO_{15\%} = (CO - CO_a - 0.088 \cdot THC_a) \cdot \left(\frac{5.9}{20.9 - O_2} \right) \qquad (2),$$

where: $CO_{15\%}$ is the carbon monoxide concentration at 15% O_2, ppmV; CO is the carbon monoxide concentration measured during the tests, ppmV; CO_a is the ambient carbon monoxide concentration, ppmV; THC_a is the ambient total hydrocarbon concentration, ppmV; and O_2 is the oxygen concentration measured during the tests, %.

Assuming that ambient levels of carbon monoxide, nitrogen oxides, and total hydrocarbons are equal or very close to zero, and that the ambient correction factor is close to 1, equations (1) and (2) may be written as:

$$NO_{x_15\%} = \frac{5.9 \cdot NO_x}{(20.9 - O_2)} \qquad (3),$$

$$CO_{15\%} = \frac{5.9 \cdot CO}{(20.9 - O_2)} \qquad (4).$$

These corrected values were then converted to mg/m^3, which is a typical unit for ambient air monitoring, with the following equation [12]:

$$C_{mg/m^3} = \frac{12.187 \cdot C_{ppmV_{15}} \cdot M}{(273.15 + t)} \qquad (5),$$

where: C_{mg/m^3} is the concentration of gaseous pollutant, mg/m^3; $C_{ppmV_{15}}$ is the concentration of gaseous pollutant, ppmV at 15% O_2 (from equations (1) and (2)); M is the molecular weight of gaseous pollutant, g/mole; and t is the temperature of conversion (in this case 25°C).

RESULTS

The emissions study of the CHP test system was performed over a wide range of microturbine power output and at different ambient temperatures. The basic results are shown in Figures 4-10.

Effect of Microturbine Power Output on Emissions Rate

The tests were performed over the microturbine power output range of 1/10 to full power output (3-28 kW). Figures 4 and 5 respectively present the dependencies of CO and NO_x emissions with power output in ppmV at 15% O_2 ($ppmV_{15}$) and mg/m^3. These results show the significant effect that power output has on emissions rate. The minimum cumulative rate of CO and NO_x is observed at full power output (28 kW): *ca.* 43 $ppmV_{15}$ (52 mg/m^3) CO and *ca.* 7 $ppmV_{15}$ (13 mg/m^3) NO_x. These data are close to, or within the limits specified by the manufacturer (40 $ppmV_{15}$ CO and 9 $ppmV_{15}$ NO_x) [8]. Decreasing the microturbine power output significantly increases the emissions rate of either NO_x or CO; the maximum CO and NO_x levels were observed at the power output levels of 20 and 15 kW, respectively. The cumulative CO + NO_x emissions rate shows a gradually increasing trend with reduction in the microturbine power output (Figure 5). The maximum cumulative emissions rate of 283 mg/m^3 is observed at 1/10 of the full power output (3 kW). Previous studies [13-16] have shown that the microturbine efficiency also depends on the power output rate and decreases with power output reduction from *ca.* 23% (based on higher heating value, HHV, of the natural gas) at 28 kW to *ca.* 9% at 3 kW. These combined results indicate that the microturbine-based CHP system operation at low electrical loads is not advisable from both emissions and microturbine unit efficiency aspect. The emissions results produced during these tests are in agreement with another emissions study performed with a different type of microturbine [17].

Figures 6 and 7 show the change of emissions rates during microturbine startup and power dispatch (transition to another power output). As indicated in the figures, peaks of emissions-relevant compounds of flue gases were observed in most cases of microturbine power output change. For example, during startup the concentration of CO in flue gas may reach 900-1000 ppmV (Figure 6).

Figures 8 and 9 show the change of excess air, oxygen and carbon dioxide concentrations with the microturbine power output. Oxygen content and excess air increase with the unit power output reduction, while CO_2 concentration decreases. It should be reiterated that excess air and the CO_2 concentration were not measured directly, but were calculated using fuel input data and the oxygen concentration in flue gas. By taking this into account, the inverse CO_2 dependence of oxygen is quite obvious.

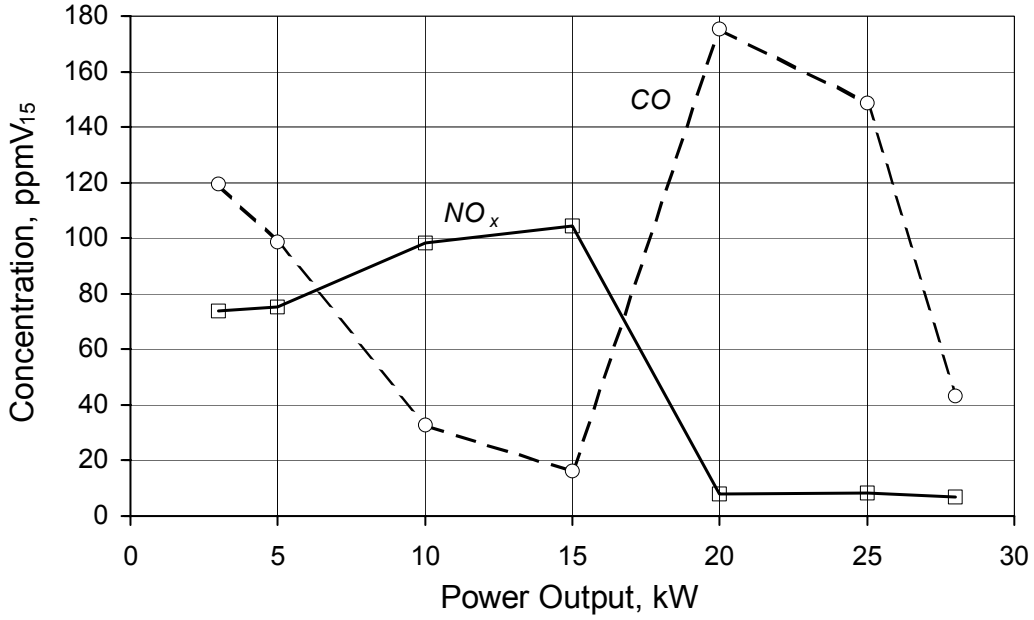

Figure 4. Concentration of CO and NO_x ($ppmV_{15}$) Versus Microturbine Power Output.

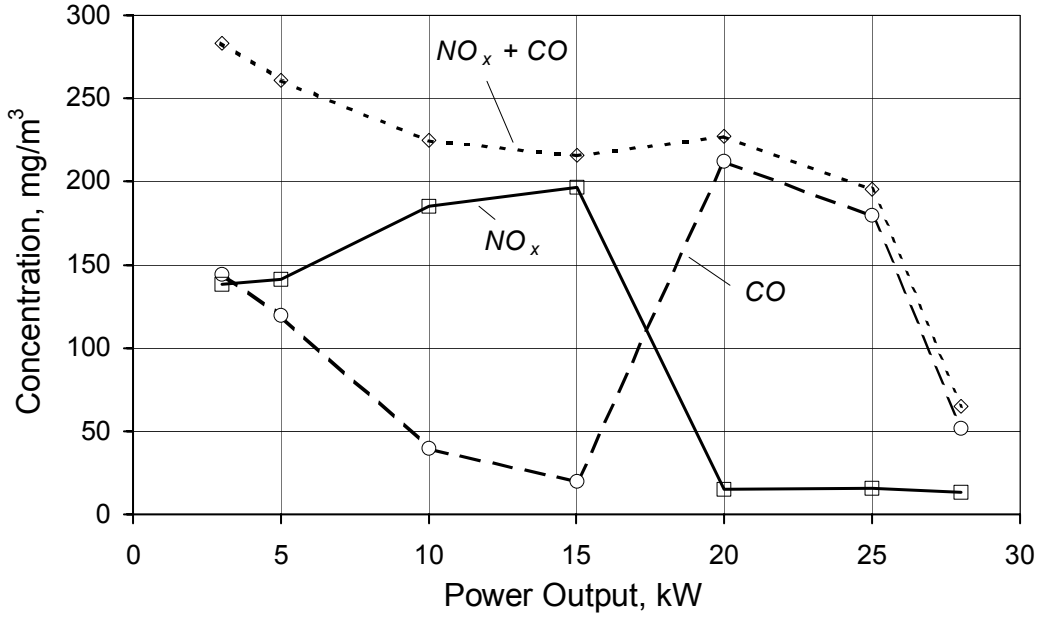

Figure 5. Concentration of CO and NO_x (mg/m^3) Versus Microturbine Power Output.

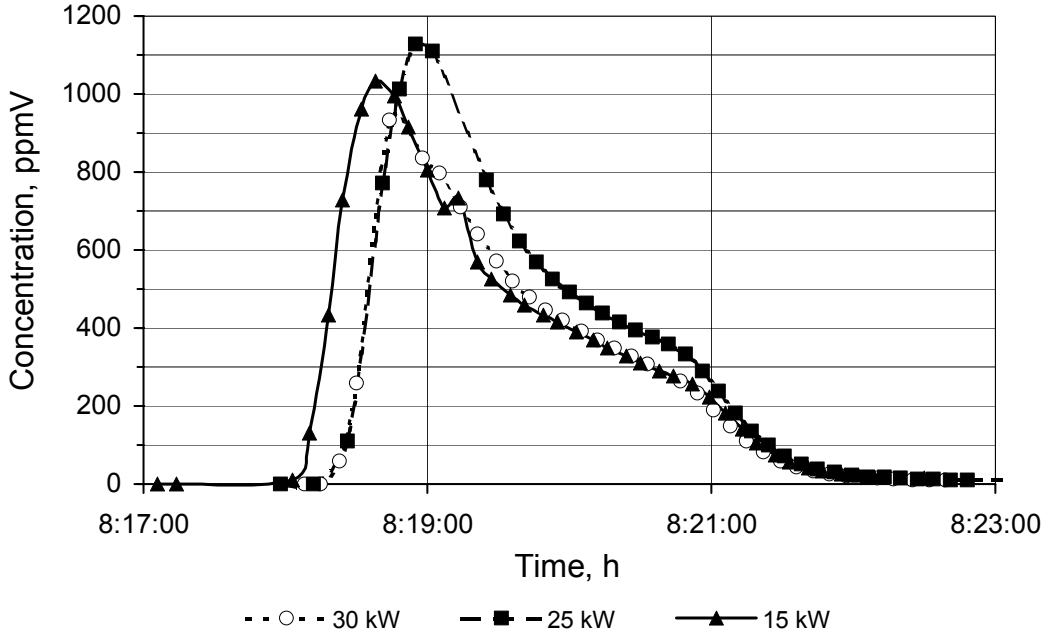

Figure 6. Concentration of CO During Microturbine Startup with Different Power Output Settings.

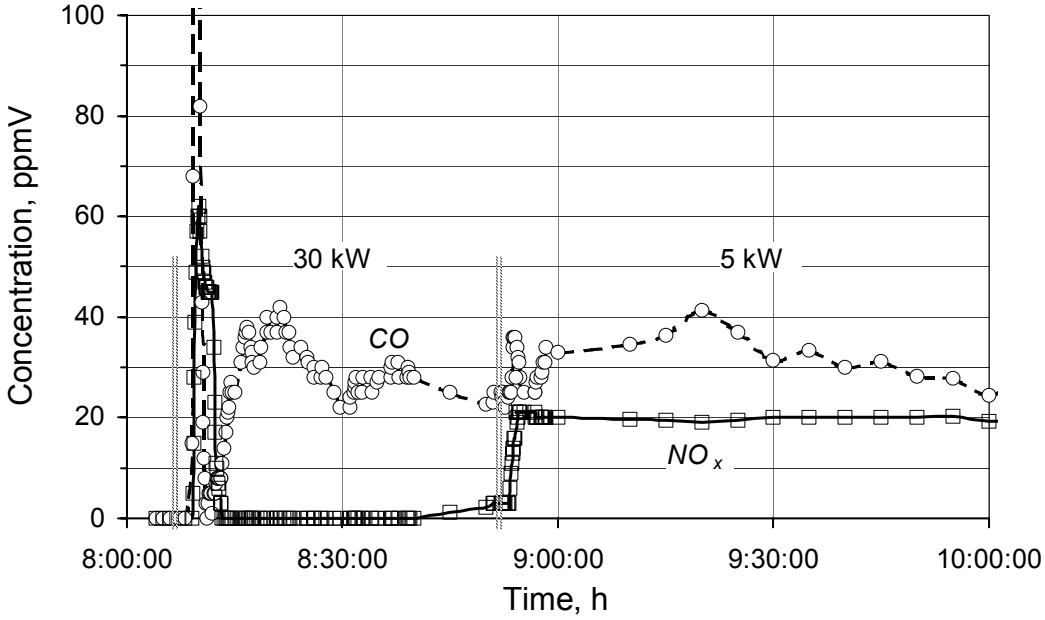

Figure 7. Concentration of CO and NO_x Charts During Microturbine Power Output Transitions (Power Dispatch). Dashed vertical lines show transition from one power output level to another.

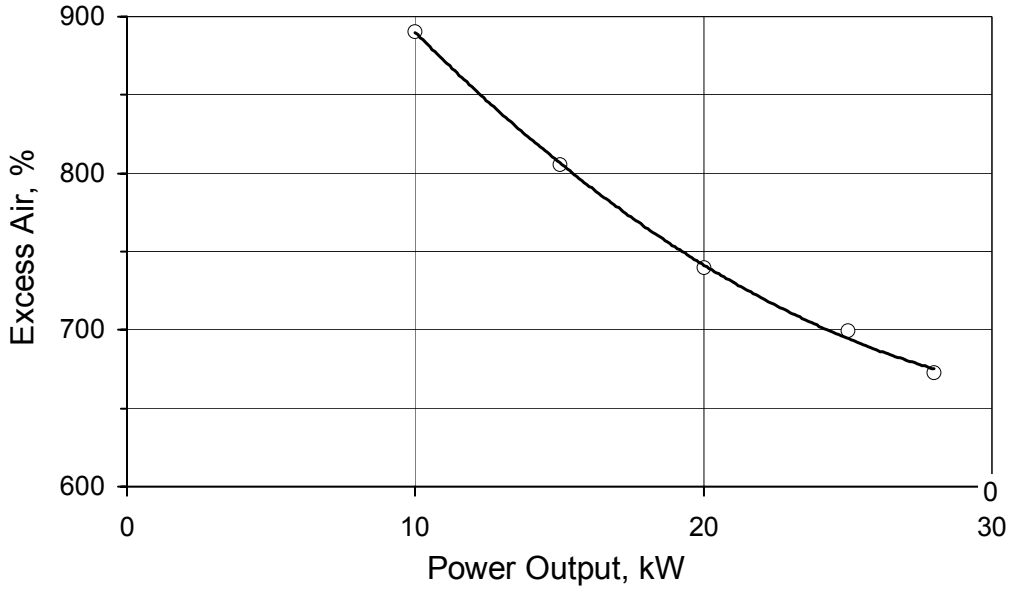

Figure 8. Excess Air Versus Microturbine Power Output.

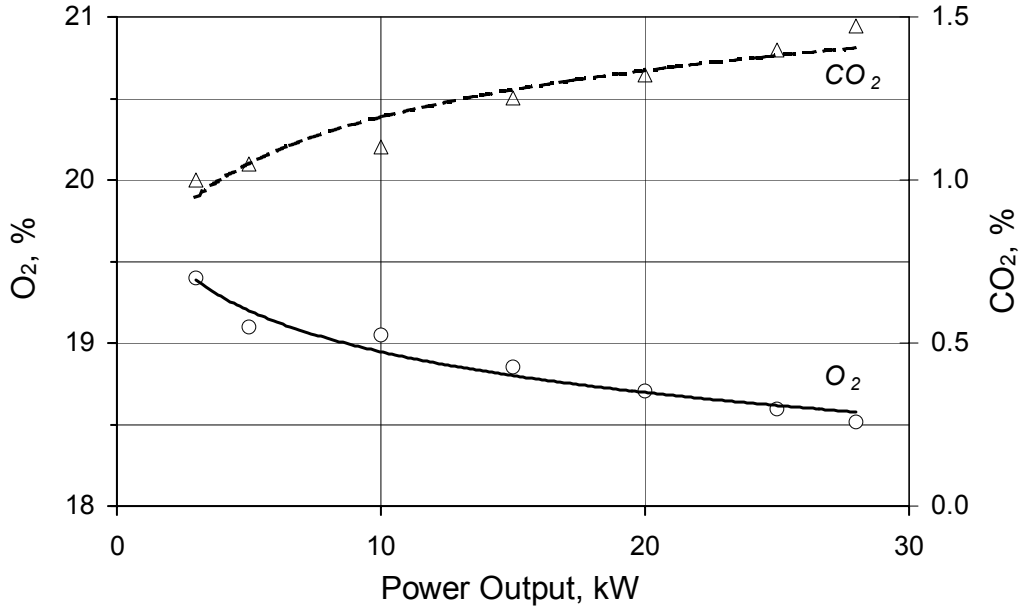

Figure 9. Concentration of O_2 and CO_2 Versus Microturbine Power Output.

Effect of Ambient Temperature on Emissions Rate

If the CHP system or part of it is located outdoors, ambient temperature may have some effect on the operating parameters of the system. In this particular case the microturbine is located outdoors, so the air inlet temperature of the microturbine is equal to the ambient air temperature, which varies throughout the day and from day to day and season to season depending on weather conditions. To study the effect of the air inlet temperature on the emissions rate of the microturbine-based CHP system, special tests were performed at power output settings of 15, 25, and 30 kW with varying ambient temperature, all other parameters being the same. The results indicate that most of the flue gas compounds studied, including NO_x, are almost unaffected by the change in air inlet temperature. However, CO is the exception. The CO dependence on the microturbine air inlet temperature is shown in Figure 10. As shown in the figure, there is a tendency for reduced CO levels in the microturbine flue gas with higher air inlet temperatures. Since the microturbine is located outside, the ambient temperature influences the combustion and stack temperatures of the microturbine thus affecting the level of CO concentration in the flue gas [9, 10]. The operation of the microturbine outside may pose a little challenge for CHP operators, because previous test results [13-16] show a decrease in the microturbine efficiency with increased air inlet temperature. For example, at full power output (28 kW) an increase in temperature from 5 to 24°C resulted in an efficiency drop from 23 to 21% (based on HHV). But the weather (ambient temperature in this case) is the "parameter" that can not be influenced or controlled by operators.

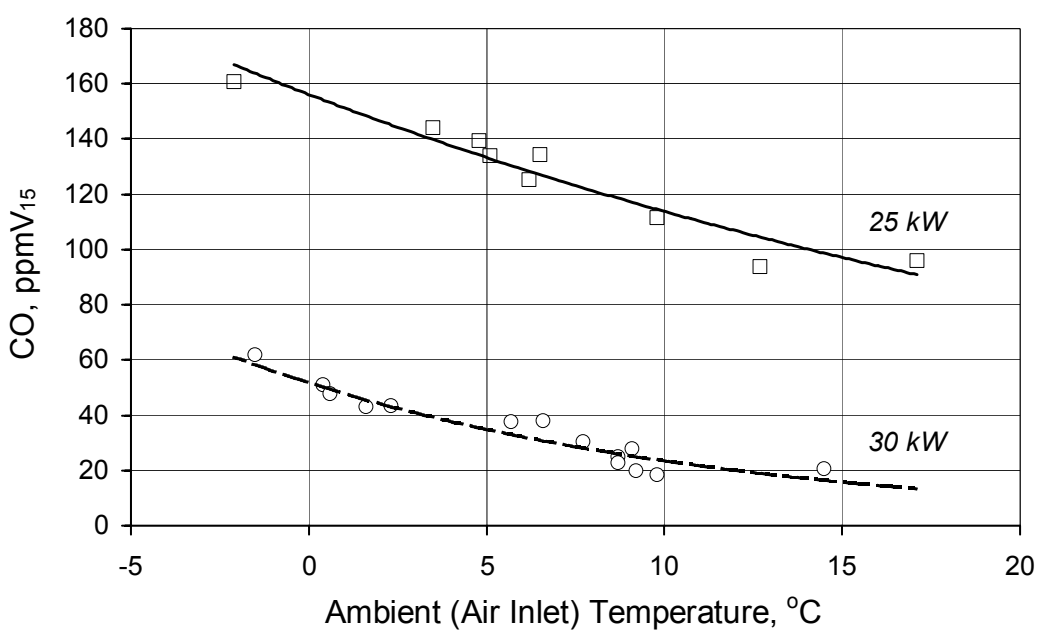

Figure 10. CO Concentration Versus Air Inlet Temperature with Different Microturbine Power Outputs.

CONCLUSIONS

In summary, emissions tests of the microturbine-based CHP test system (gas microturbine paired with the heat recovery systems) at ORNL have been conducted to determine emissions output for both steady-state and transient operations of the CHP system. The steady-state tests measured emissions at different microturbine power output levels and different air inlet temperatures (ambient temperatures) to the microturbine. The transient tests measured the emissions levels as the microturbine power output varied during startup and as the power output was changed to another level for power dispatching. Results showed that:

- Operation of the microturbine at full-load power output produces the lowest emissions of air pollutants (primarily CO and NO_x); the latter are within limits specified by the microturbine manufacturer.
- Operation at reduced microturbine power levels increases the cumulative emissions (CO + NO_x) of flue gas components.
- For a microturbine located outside, an increase in ambient, or air inlet temperature of the microturbine tends to reduce the CO levels in the flue gas.

ACKNOWLEDGEMENTS

The authors would like to thank the U.S. Department of Energy (DOE) for supporting this work. This work was conducted by the ORNL under DOE contract DE-AC05-00OR22725 with UT-Battelle, LLC.

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