

ENVIRONMENTAL ASPECTS OF OPERATION OF A GAS-FIRED MICROTURBINE-BASED CHP SYSTEM

Andrei Yu. Petrov, Abdolreza Zaltash, D. Tom Rizy, and Solomon D. Labinov

Cooling, Heating and Power (CHP) Group

Engineering Science and Technology Division (ESTD)

Oak Ridge National Laboratory (ORNL), Oak Ridge, Tennessee

ABSTRACT

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

For the DER emissions tests, a CHP system consisting of a 30-kW natural gas-fired microturbine located outside the test building and an air-to-water heat recovery unit for capturing the exhaust heat located inside were used. Three basic emissions components – carbon monoxide (CO), nitrogen oxides (NO_x), and sulfur dioxide (SO₂) – were given particular attention. The steady-state tests with the microturbine output maintained at a near steady power output measured emissions at different power output levels (10–30 kW with 1 kW increment) and different air inlet (ambient) temperatures (-2–17°C or 28–63°F) although we did not have direct control of the inlet temperature. The transient tests measured the emission levels as the microturbine power output varied during startup and shutdown and as the power output was increased or decreased from one output level to another for power dispatching. Results show that operation of the microturbine at full power (~28 kW) produces the lowest emissions of air pollutants. The CO and NO_x levels were found to be within limits specified by the microturbine manufacturer while the maximum SO₂ concentrations will not cause dewpoint corrosion of the CHP equipment. Operation of the microturbine at reduced power output increases the cumulative emission levels of the flue gas. The microturbine air inlet temperature increase (our unit was located outside) tends to reduce the CO levels in the flue gas.

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 by the site loads [2]. Unlike centralized energy resources, such as large electric power plants, they provide an opportunity for local control of power generation with improved power quality and reliability especially when supplemented by the electric grid, as well as having the capability to support

the grid (*i.e.*, voltage and capacity support) when interconnected with the grid and more efficient use of waste heat to boost overall plant efficiency and reduce emissions on a overall basis. In a CHP system, waste heat from these DER technologies can be used for the generation of hot water for domestic use or for indirectly driving heat-activated systems, steam for space heating, and directly 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 equipment configurations to evaluate the optimal operational modes of CHP systems. Currently, CHP systems that are installed in the field are custom designed and consist of individual commercially available equipment originally developed for independent 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 our testing will be used to develop data and models for optimizing the performance of the “next generation” of 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 variable weather conditions that impact inlet conditions of the microturbine. An objective of the testing was to ensure that the emission levels are within the limits specified by the EPA emissions regulations [3] and to verify the microturbine manufacturer’s emissions specifications. In addition, the purpose of these tests was to measure the levels of corrosive compounds in the flue gases which if high enough can accelerate the corrosion of metal components in the power-generating equipment thus reducing its reliability and availability [4].

TEST EQUIPMENT

The CHP Integration Test Facility is a flexible test bed consisting of a 30-kW* microturbine configured and instrumented to operate either without or with waste heat recovery from the microturbine exhaust. The thermal heat recovery components consist of an air-to-water heat exchanger, both an indirect-fired and a direct-fired desiccant dehumidifier, and an indirect-fired 10-ton single-effect absorption chiller (Figure 1). An air duct network from the microturbine exhaust to the heat exchanger and/or to the direct-fired thermal equipment, a water loop from the heat exchanger to the indirect-fired thermal equipment, and an air mixer chamber leading to the air duct network (for mixing outside air with exhaust air) provide for flexible testing of various waste heat recovery conditions and loadings.

For the DER emissions tests, the CHP system was configured only with the 30-kW natural gas-fired microturbine and the air-to-water heat recovery unit (HRU). The microturbine, which is located on the 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 2 [5]. 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).

The microturbine unit is designed to produce a continuous phase current of 36 A at 480 VAC and to produce unity power factor (the amount of real power divided by the total power) when the unit is grid connected. The unit’s nominal phase-to-neutral voltage is 277 VAC. The microturbine is connected to the grid (through a 480-VAC electrical panel which is connected to the local distribution system) via a 480-VAC/45-kVA three-phase isolation transformer. The microturbine power controller incorporates protection functions that

* Microturbine full-load power output is 28 kW; 2 kW is auxiliary power consumed by the microturbine

will shut down the unit if the phase-to-neutral voltage sags (or drops) to less than 208 VAC for more than 10 seconds. Islanding of the microturbine (or separation of the unit from the grid) is detected within milliseconds from the loss of current control. The microturbine also includes over-voltage, over/under frequency, and rate of frequency protection functions to protect the unit and to prevent islanding of the unit.

In the CHP mode, the flue gas from the microturbine exhaust, which has a temperature of $\sim 275^{\circ}\text{C}^{**}$ ($\sim 527^{\circ}\text{F}$) is directed to the indoor-located heat recovery unit (HRU). The exhaust passes through the air-to-water heat exchanger tubes and transfers heat to the water that is pumped through the tubes. The flue gas leaving the heat exchanger and exhausted to the atmosphere has a temperature of $\sim 124^{\circ}\text{C}^{**}$ ($\sim 255^{\circ}\text{F}$). The nominal water flowrate through the HRU is 75.7 L/min (~ 20 gpm). The schematic diagram of the CHP test rig is shown in Figure 3.

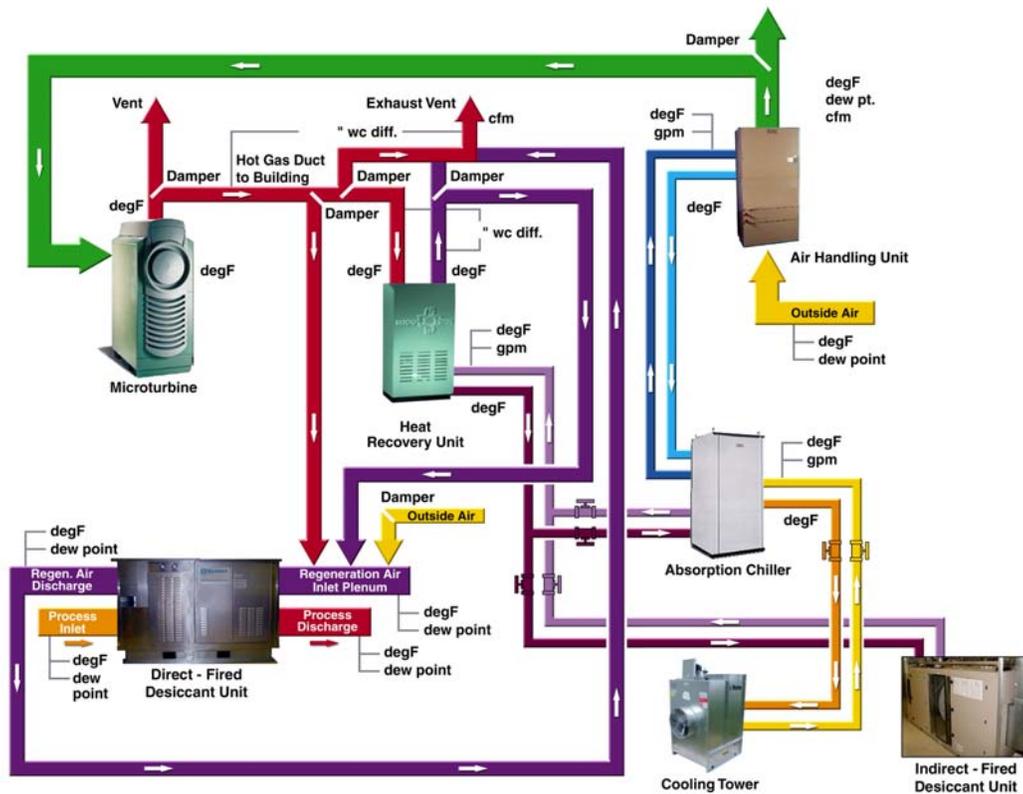


Figure 1. CHP Integration Test Facility at ORNL.

The thermodynamic cycle of the gas microturbine is shown in Figure 4. 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).

** The temperature data are given for the microturbine full-load power output

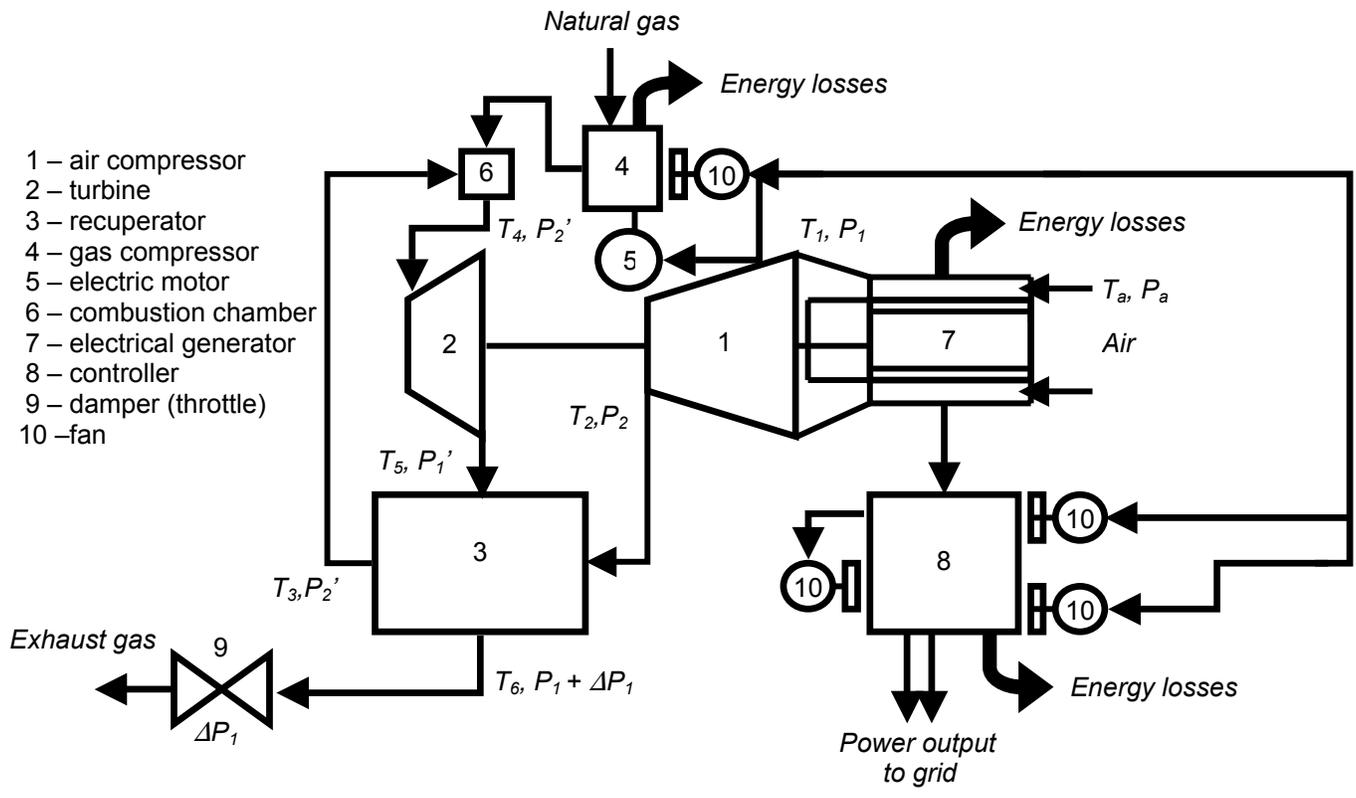


Figure 2. Schematic Diagram of the Gas Microturbine Unit.

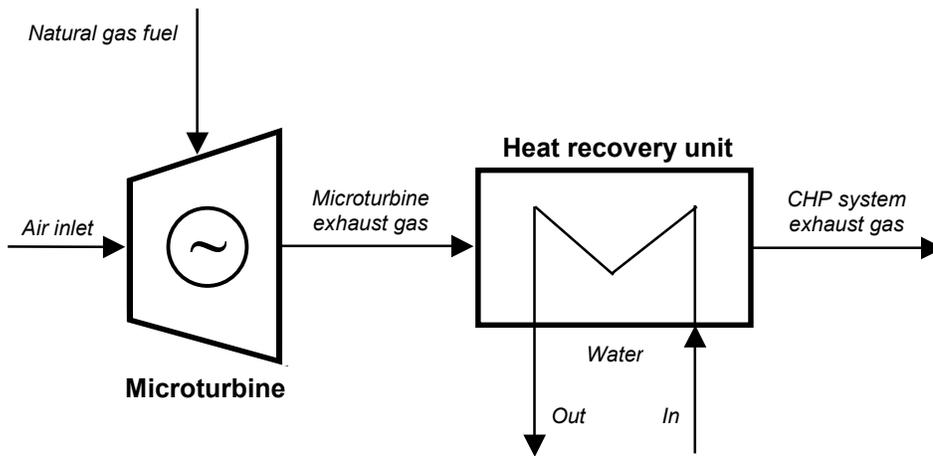


Figure 3. Schematic Diagram of the Microturbine and HRU (CHP System).

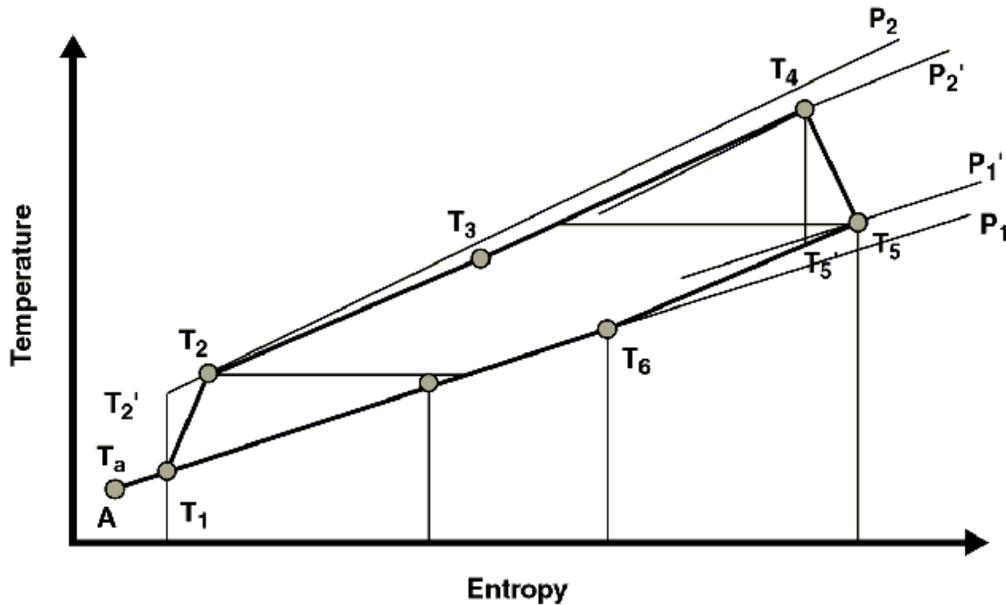


Figure 4. Thermodynamic Cycle of the Gas Microturbine.

After the air compressor, the air goes to the recuperator, where 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).

The CHP system at the CHP Integration Test Facility includes sophisticated PC-based monitoring and control of the microturbine and PC-based instrumentation and monitoring of the HRU's 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 [6, 7].

EMISSIONS MONITORING

The U.S. Environmental Protection Agency (EPA) lists six criteria air pollutants for which ambient air limits have been set [8, 9]. 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 , CO, and SO_2 are the most relevant for the operation of the gas-fired 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 NO_2 . CO is a poisonous gas formed when carbon based fuel is not fully burned. SO_2 is formed at high combustion temperatures [10]. As gas temperature decreases, a portion of SO_2 is converted into SO_3 , which reacts with water vapor contained in the flue gas to form sulfuric acid. This may result in corrosion of low-temperature sections of the CHP system. All these gases can have a significant effect on the level of environmental pollution and were given most of the attention during this project's emissions studies.

NO_x formation is minimized at lower combustion temperatures, but lower combustion temperatures also result in higher CO emissions [11, 12]. Thus, in order to achieve low emissions levels, the microturbine needs to be operated at a high air to fuel ratio (excess air) within the primary combustion zone of the unit. The excess air and carbon dioxide (CO₂, a “Green House” gas) emissions were calculated by the flue gas analyzer from the fuel data and oxygen concentration. The latter was measured with an oxygen electrochemical cell. The SO₂ concentration was also determined by the electrochemical cell method. The accuracy of the emissions measurements was within ±2% of the reading [6].

Excess air, concentrations of CO₂ and O₂ were expressed in %, while concentrations of NO_x, CO, and SO₂ were measured in ppm by volume (*i.e.* volume of gaseous pollutant per million volumes of ambient air) at the test O₂ concentration. The latter were corrected to 15% O₂ (typical requirement for gas microturbines) using equations (1)-(3):

$$\text{NO}_{x_15\%} = (\text{NO}_x - \text{NO}_{x_a}) \cdot \left(\frac{5.9}{20.9 - \text{O}_2} \right) \cdot n \quad (1),$$

where: NO_{x_15%} is the concentration of nitrogen oxides at 15% O₂, 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; O₂ is the oxygen concentration measured during the tests, %; and n is the ambient correction factor (available from [13]).

$$\text{CO}_{15\%} = (\text{CO} - \text{CO}_a - 0.088 \cdot \text{THC}_a) \cdot \left(\frac{5.9}{20.9 - \text{O}_2} \right) \quad (2),$$

where: CO_{15%} is the carbon monoxide concentration at 15% O₂, 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 O₂ is the oxygen concentration measured during the tests, %.

$$\text{SO}_{2_15\%} = (\text{SO}_2 - \text{SO}_{2_a}) \cdot \left(\frac{5.9}{20.9 - \text{O}_2} \right) \quad (3),$$

where: SO_{2_15%} is the sulfur dioxide concentration at 15% O₂, ppmV; SO₂ is the sulfur dioxide concentration measured during the tests, ppmV; SO_{2_a} is the ambient sulfur dioxide concentration, ppmV; and O₂ is the oxygen concentration measured during the tests, %.

Assuming the ambient levels of carbon monoxide, nitrogen oxides, sulfur dioxide, and total hydrocarbons are equal or very close to zero, and that the ambient correction factor is close to unity, equations (1)-(3) may be written as:

$$\text{NO}_{x_15\%} = \frac{5.9 \cdot \text{NO}_x}{(20.9 - \text{O}_2)} \quad (4),$$

$$\text{CO}_{15\%} = \frac{5.9 \cdot \text{CO}}{(20.9 - \text{O}_2)} \quad (5),$$

$$SO_{2_15\%} = \frac{5.9 \cdot SO_2}{(20.9 - O_2)} \quad (6).$$

These corrected values were then converted to mg/m^3 , which is a typical unit for ambient air monitoring, with the following equation [14]:

$$C_{mg/m^3} = \frac{12.187 \cdot C_{ppmV_{15}} \cdot M}{(273.15 + t)} \quad (7),$$

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)-(3)); M is the molecular weight of the gaseous pollutant, g/mole; and t is the temperature of conversion (in this case $25^\circ C$).

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 5-11.

Effect of Microturbine Power Output on Emissions Rate

The tests were performed over the microturbine power output range of 1/3 to full power output (10-28 kW). Figures 5 and 6 present the dependencies of CO , NO_x , and SO_2 emissions with power output in ppmV at 15% O_2 ($ppmV_{15}$) and mg/m^3 respectively. These results show the significant effect that power output has on emissions rate. The minimum rate of emissions is observed at full power output (28 kW): *ca.* 36 $ppmV_{15}$ (41 mg/m^3) CO , *ca.* 4 $ppmV_{15}$ (8 mg/m^3) NO_x , and *ca.* 0.6 $ppmV_{15}$ (1.5 mg/m^3) SO_2 . These data are within the limits specified by the microturbine manufacturer (40 $ppmV_{15}$ CO and 9 $ppmV_{15}$ NO_x) [9]. Concentration of 9 $ppmV_{15}$ NO_x for a 30 kW microturbine translates into a NO_x concentration of approximately 0.24 kg/MWh. This is much lower than the 100 $ppmV_{15}$ NO_x or 21.2 kg/MWh NO_x reported for a reciprocating engine slightly larger than three times in capacity (100 kW) [15].

However, decreasing the microturbine power output significantly changes the emission rate of the above-mentioned contaminants. It was found that CO had two concentration peaks at lower power output: at 16 and 20 kW. The 16-kW peak was not detected during the first series of emission tests with 5 kW increment in power output [5]. In addition, in the output range of 19-20 kW, a certain fluctuation in CO levels was observed between *ca.* 210 and 500 $ppmV_{15}$.

The SO_2 emissions trend basically followed that for CO with maximum peak SO_2 levels of *ca.* 50 $ppmV_{15}$. Taking into account that with gas-fired units only 10% of SO_2 is converted to SO_3 , and no significant damage occurs when the SO_3 concentration is less than 10 $ppmV_{15}$ [10], it may be deduced that in this case SO_2 will not cause corrosion in the low-temperature path of the CHP unit. The maximum NO_x level was observed at a power output of 15 kW. The cumulative $CO+NO_x+SO_2$ emissions rate reached the maximum values of 630 and 650 mg/m^3 at the turbine power output of 16 and 20 kW respectively (Figure 6). Below 15 kW output the cumulative emissions rate is still high enough reaching 250 mg/m^3 . Previous studies [16-19] 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.* 17.5% at 10 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 aspects. Also, the results show high CO emissions over the most common operational range of the microturbine (15-25 kW). The emission

trends produced during these tests are generally in agreement with another emissions study performed with a different type of microturbine [20].

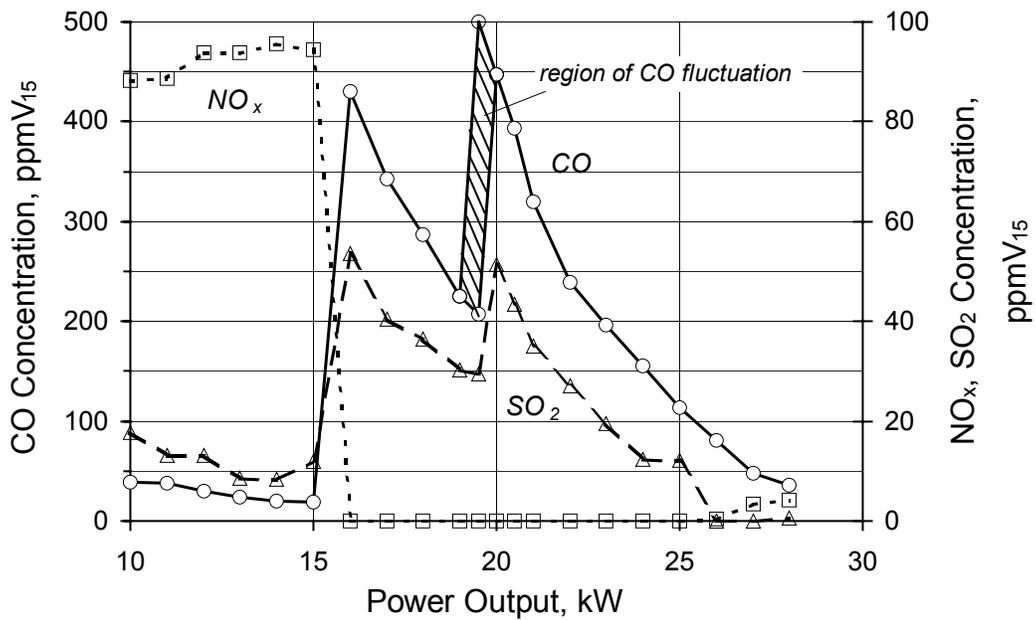


Figure 5. Concentration of CO, NO_x, and SO₂ (ppmV₁₅) Versus Microturbine Power Output.

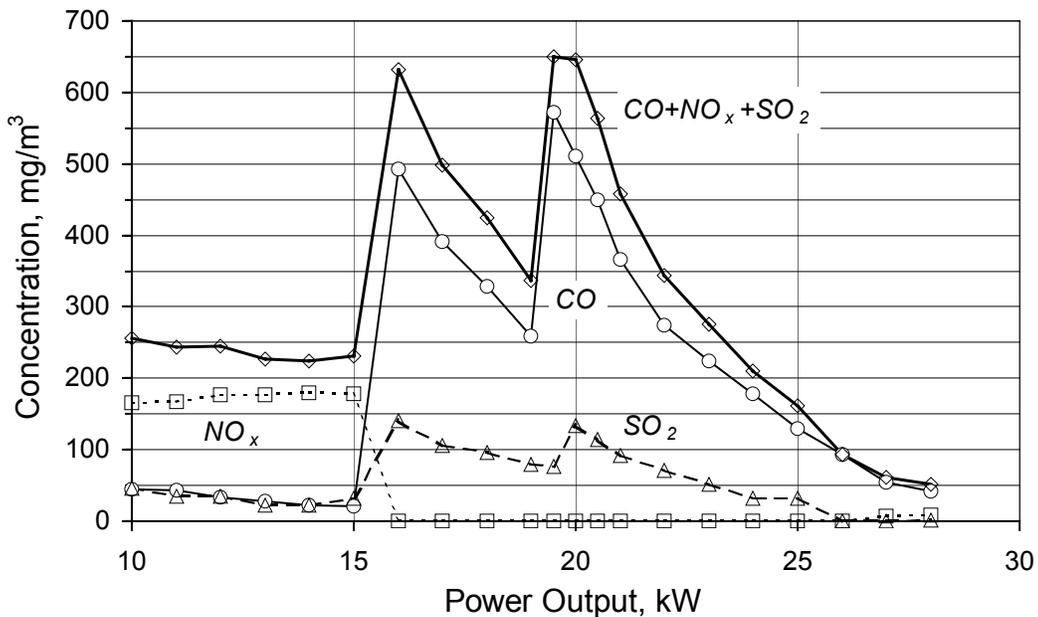


Figure 6. Concentration of CO, NO_x, and SO₂ (mg/m³) Versus Microturbine Power Output.

Figures 7 and 8 show the change of emissions rates during microturbine startup and power dispatch (transition to another power output level). As indicated in the figures, peaks of emissions-relevant compounds in flue gases were observed in most cases of microturbine power output change. For example, during startup the concentration of CO in flue gas can reach 900-1000 ppmV (Figure 7).

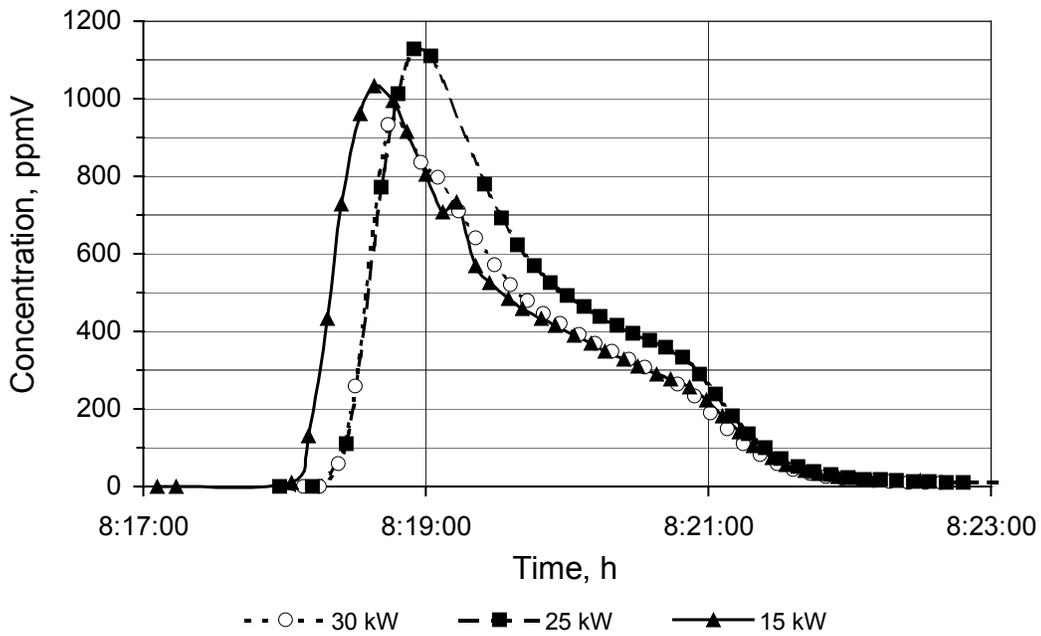


Figure 7. Concentration of CO During Microturbine Startup at Three Different Nominal Power Output Settings.

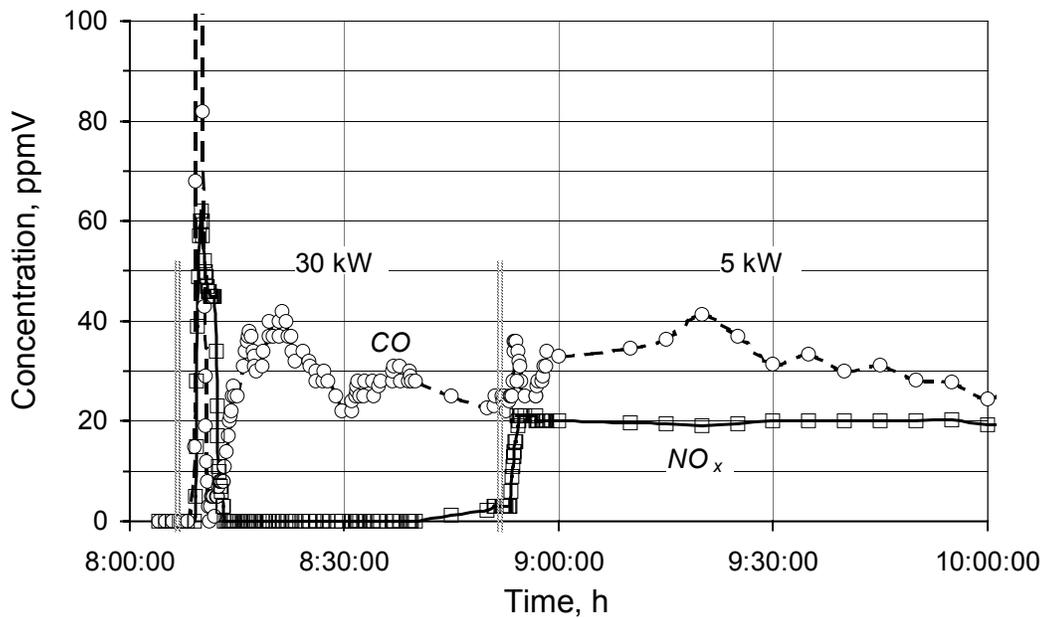


Figure 8. Concentrations of CO and NO_x During Microturbine Power Output Transitions (Power Dispatch). Dashed vertical lines show transition from one power output level to another.

Figures 9 and 10 show the change of excess air, O₂ and CO₂ concentrations with the microturbine power output. Oxygen content and excess air increase as the unit's power output is reduced, while the CO₂ concentration decreases. It should be reiterated that excess air and the CO₂ concentration were not measured directly, but were calculated using fuel input data and the oxygen concentration in the flue gas. By taking this into account, the inverse CO₂ dependence of oxygen is quite obvious.

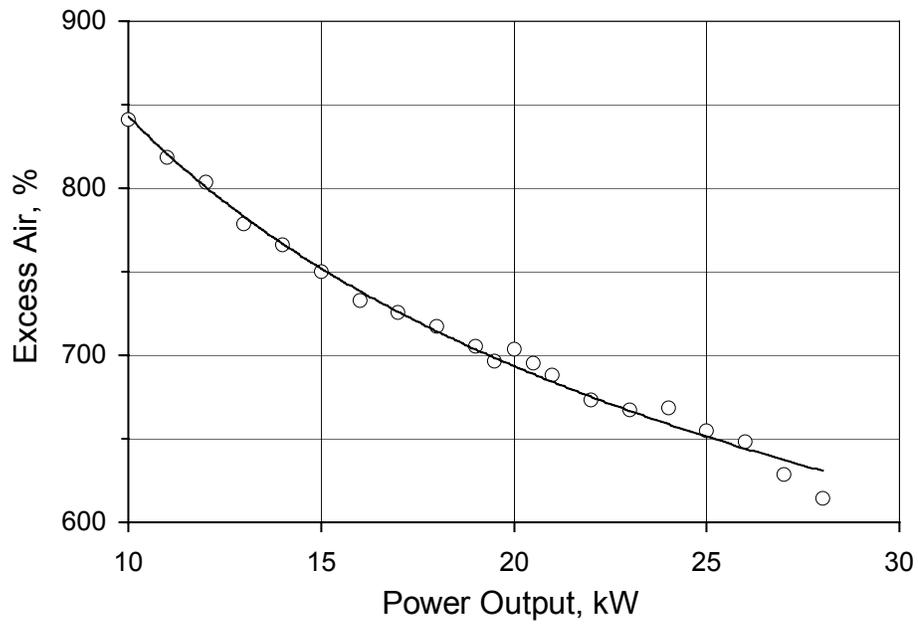


Figure 9. Excess Air Versus Microturbine Power Output.

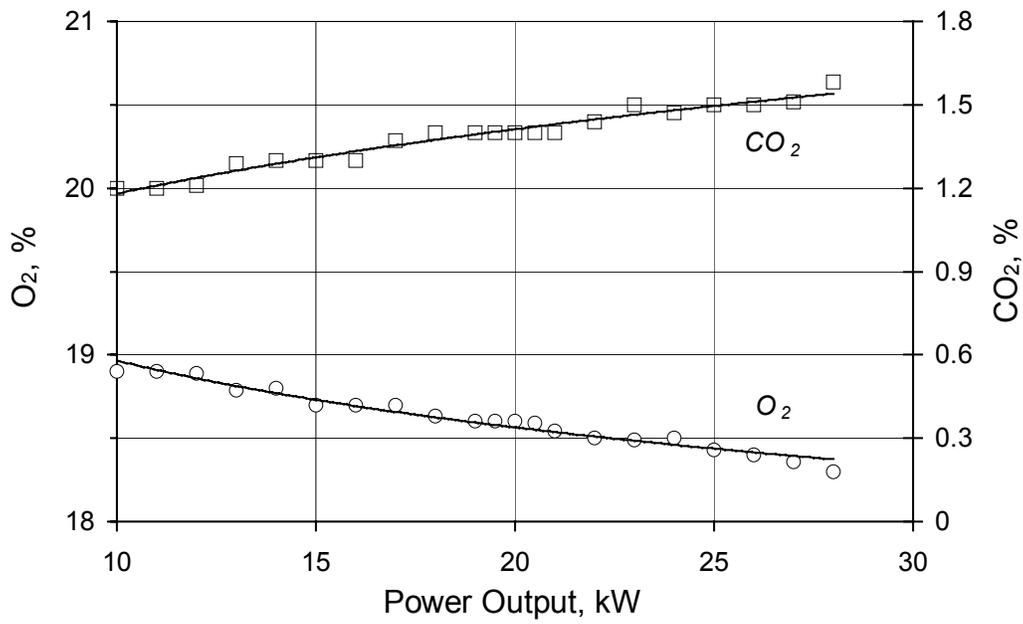


Figure 10. Concentration of O₂ and CO₂ Versus Microturbine Power Output.

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 microturbine air inlet temperature 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 25 and 30 kW with varying ambient temperature, while keeping other parameters constant. The results indicate that most of the flue gas compounds studied are not significantly affected by the change in air inlet temperature, except CO. The CO dependence on the microturbine air inlet temperature is shown in Figure 11. 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 [11, 12]. The operation of the microturbine outside may pose a little challenge for CHP operators, because previous test results [16-19] showed 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 (41 to 75°F) resulted in an efficiency drop from 23 to 21% (based on HHV). But the weather (ambient temperature in this case) is the "parameter" that cannot be influenced or controlled by operators.

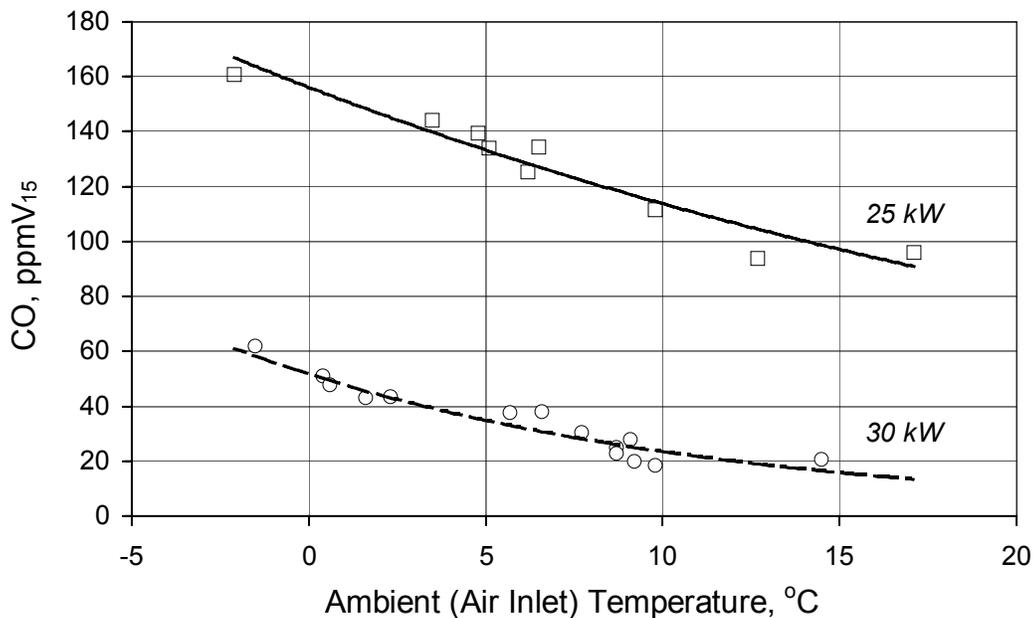


Figure 11. CO Concentration Versus Air Inlet Temperature at Two Nominal Power Output Settings of 25 and 30 kW.

CONCLUSIONS

In summary, emissions tests of the microturbine-based CHP test system (gas microturbine paired with heat recovery systems) at Oak Ridge National Laboratory have been conducted to determine emissions output for both steady-state and transient operations of a microturbine-based 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 emission levels as the microturbine power output was varied during startup and changed from one output level to another during power dispatching.

At full power output, the 30-kW microturbine was found to produce 36 ppmV₁₅ (41 mg/m³) CO, 4 ppmV₁₅ (8 mg/m³ NO_x), and 0.6 ppmV₁₅ (1.5 mg/m³) SO₂. The measured NO_x emissions at full power output were found to be less than the manufacturer's specified value. The manufacturer-specified concentration of NO_x (9 ppmV₁₅) for full power output translates into a NO_x concentration of approximately 0.24 kg/MWh. For the sake of comparison this is much lower than 21.2 kg/MWh reported for a much larger reciprocating engine (three times larger).

The results of the emission tests with the microturbine operated at various power output levels (1/3 to full power) and at various ambient temperatures (microturbine was located outside) showed that:

- Operation of the microturbine at full-load power output produces the lowest emissions of air pollutants (primarily CO, NO_x, and SO₂); the first two are within limits specified by the microturbine manufacturer.
- Maximum levels of SO₂ emissions encountered in this study cannot cause dewpoint corrosion of low-temperature path of the CHP system.
- Operation at reduced microturbine power levels increases the cumulative emissions (CO+NO_x+SO₂) 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.
- CO concentration peaks (~440 and ~500 ppmV₁₅) were measured at lower microturbine power output levels: at 16 and 20 kW.
- Much greater levels of CO concentration can be reached during startup of the microturbine. The particular case given in this paper shows the CO concentration in the flue gas reaching ~1000 ppmV.
- Oxygen content and excess air increase as the microturbine's power output is reduced, while the CO₂ concentration decreases. Both excess air and the CO₂ concentration were not measured directly, but were calculated using fuel input data and the oxygen concentration in the microturbine's flue gas.

In regards to CHP operation where the electric efficiency of the microturbine is of primary concern, operation of a microturbine-based CHP where the unit is located on the outside of buildings may pose a challenge for CHP operators since the test results show a decrease in microturbine efficiency with increased inlet ambient air temperature. Although in most cases it will probably be the overall energy input (or plant efficiency) of a CHP system that will be of primary concern to CHP operators/owners rather than the individual component efficiencies.

ACKNOWLEDGEMENTS

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

REFERENCES

1. Banetta S., Paganucci F., and Giglioli R., "System Description and Test Planning For a Combined Heat and Power (CHP) Plant Composed by a Micro Gas Turbine and an Absorption Chiller/Heater," Proceedings of ASME TURBO EXPO 2001, 2001-GT-0102, June 4-7, 2001, New Orleans, LA, pp. 1-5. Available from http://www.asme.org/igt/events/te2001/papers_purch_01.html.
2. Strategic Plan For Distributed Energy Resources, Office of Energy Efficiency and Renewable Energy and Office of Fossil Energy, U.S. Department of Energy, Washington, D.C., 2000. Available from http://www.eren.doe.gov/der/documents_resources.html.
3. 1990 Clear Air Act Amendments. Published by Office of Air & Solutions, U.S. Environmental Protection Agency. Available from <http://www.epa.gov/oar/caa/contents.html#ia>.
4. Goncharov V.I. and Goncharov D.V., "The Problem of Reducing SO₂ Emissions from Thermal Power-Generating Plants." Thermal Engineering, 1990, vol. 37, No. 6, pp. 288-289.
5. Petrov A.Yu., Zaltash A., Rizy D.T., and Labinov S.D., "Study of Flue Gas Emissions of Gas Microturbine-Based CHP System." PowerPlant Chemistry, 2002, vol. 4, No. 4, pp. 235-239.
6. ENERAC Integrated Emissions System, Model 3000E. Instructions Manual. Energy Efficiency Systems, Westbury, NY, USA, 1998. Available from <http://www.enerac.com/>.
7. ENERCOM 2000, Version 8.1. User's Guide. Energy Efficiency Systems, Westbury, NY, USA, 2000. Available from <http://www.enerac.com/software.htm>.
8. 1997 National Air Quality: Status and Trends. Published by Office of Air & Solutions, U.S. Environmental Protection Agency. Available from <http://www.epa.gov/oar/aqtrnd97/brochure>.
9. Capstone Low Emissions Microturbine Technology. Capstone Turbine Corporation, Chartsworth, CA, USA, 2000. Available from <http://www.microturbine.com>.
10. Gabrielli F., Goodstine S., and Mastronarde T, "Cold-End Corrosion in HRSGs". PowerPlant Chemistry, 2002, vol. 4, No. 3, pp. 148-153.
11. Brewster B.S., Cannon S.M., Farmer J.R., and Meng F., "Modeling of Lean Premixed Combustion in Stationary Gas Turbines." Progress in Energy and Combustion Science, 1999, vol. 25, pp. 353-385.
12. Sarkisov A.A., Rudakov O.A., Salivon N.D., Sigalov Yu.V., and Mitrofanov V.A., "The Generalized Emissions Characteristic of a Gas-Turbine Engine as a Function of the Design and Operating Parameters of the Combustion Chamber." Thermal Engineering, 2000, vol. 47, No. 4, pp. 352-355.

13. Code of Federal Regulations, Title 40: Protection of Environment; Chapter 1: Environmental Protection Agency; Part 60: Standards of Performance for New Stationary Resources; Paragraph 335: Test Methods and Procedures, 1999. Available from http://www.access.gpo.gov/nara/cfr/waisidx_99/40cfr60_99.html.
14. Beychok M.R. Fundamentals Of Stack Gas Dispersion. Newport Beach, CA, USA, 1995.
15. Foley G. and Sweetser R., "Emerging Role for Absorption Chillers in Integrated Energy Systems in America." Paper to be presented at the International Mechanical Engineering Congress and Exposition Emerging and New Technologies for Heat Pump and Refrigeration Cycles and CHP (Combined Cooling, Heating and Power), November 17-22, 2002, New Orleans, LA, USA.
16. Fairchild P.D., Labinov S.D., Zaltash A., and Rizy D.T., "Experimental and Theoretical Study of Microturbine-Based BHP System." Proceedings of the 2001 International ASME Congress and Exposition, IMECE 2001 / AES-23622, November 11-16, 2001, New York, NY, USA, pp. 1-12.
17. Zaltash A. and Rizy D.T., "Operating Experiences at ORNL CHP Integration Test Facility." Presentation at the DOE/CETC/CANDRA Workshop on Microturbine Applications, January 17-18, 2002, College Park, MD, USA. Available from http://www.nrcan.gc.ca/es/etb/cetc/cetc01/htmldocs/ces_rbrandon_e.html.
18. Labinov S.D., Zaltash A., Rizy D.T., Fairchild P.D., DeVault R.C., and Vineyard E.A., "Predictive Algorithms for Microturbine Performance for BHP Systems." Paper presented at the ASHRAE Annual Meeting, June 22-26, 2002, Honolulu, HI, USA. Available at the 2002 ASHRAE Annual Meeting CD.
19. Rizy D.T., Zaltash A., Labinov S.D., Petrov A.Yu., and Fairchild P.D., "DER Performance Testing of a Microturbine-Based Combined Cooling, Heating, and Power (CHP) System." Paper presented at the Power System 2002 Conference "Impact of Distributed Generation", March 13-15, 2002, Clemson, SC, USA. See <http://www.ces.clemson.edu/powsys2002/main.htm> for availability of papers and presentations.
20. Masemore S., "Performance Verification of Microturbines: Instrument Selection, Installation, and Field Operation." Presentation at the DOE/CETC/CANDRA Workshop on Microturbine Applications, January 17-18, 2002, College Park, MD, USA. Available from http://www.nrcan.gc.ca/es/etb/cetc/cetc01/htmldocs/ces_rbrandon_e.html.