DER PERFORMANCE TESTING OF A MICROTURBINE-BASED COMBINED COOLING, HEATING, AND POWER (CHP) SYSTEM

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Abstract

The Oak Ridge National Laboratory (ORNL) has established a research test facility for testing the performance and efficiency of a microturbine-based combined cooling, heating and power (CHP) system. Presently, the test facility incorporates a 30-kW microturbine for the distributed energy resource (DER), which uses inverter-based power conditioning to convert high-frequency AC to DC and then to 60-Hz AC. The exhaust waste heat from the microturbine is fed to various thermally activated technologies (TAT) to increase the overall system efficiency of the CHP power plant. The TAT devices include an air-to-water heat exchanger, direct and indirect-fired desiccant dehumidification systems and a 10-ton indirect-fired single-effect absorption chiller. Performance tests of the microturbine's response during startup, shutdown, and power dispatching (variable power) operations have been conducted as well as performance tests to determine possible exhaust backpressure effects of TAT on the microturbine's performance and efficiency. Initial CHP tests of integrating the microturbine with actual TAT devices have started and preliminary results are presented along with the findings for the microturbine performance both without and with external backpressure.

Keywords: Distributed Energy Resources (DER), Cooling, Heating and Power (CHP), and Microturbines.

1. Introduction

The goal of the CHP Integration Test Facility at ORNL is to optimize the integration of distributed electric power generation or distributed energy resource (DER) with thermally-activated heating, ventilating, and air-conditioning (HVAC) systems. The objective is to maximize energy efficiency, reduce energy use and emissions, increase the power available for critical loads by providing an option to central power generation, and improve electrical power reliability and quality.[1]

The traditional energy cycle in the United States and most other developed countries starts with the combustion of fossil fuels and/or the use of nuclear fuels in a large central power plant to generate electricity. The electricity is then delivered to users over a high-voltage transmission and lower-voltage distribution network. At least 50 to 70% of the energy content of the fuel is lost at the power plant alone through energy conversion inefficiencies and is discharged in the form of waste heat into the environment. Further losses (8 to 10%) occur in the electric power transmission and distribution network in the form of electric current losses and transformation losses (core and conductor losses from both step-up and step-down transformers).

Distributed energy resources (DER), such as microturbines, fuel cells, and advanced reciprocating engines, are small, modular power generation systems located on or near the site where the energy that is generated is used.[2,3,4] DER can also include energy storage, such as batteries and flywheels. Unlike centralized energy resources, such as large central power plants, they provide an opportunity for local control of power generation and more efficient use of waste heat to boost overall efficiency and reduce emissions. DER comprises a portfolio of technologies, both supply-side and demand-side. The DER technologies that can benefit the most from CHP include those that produce waste thermal heat such as gas turbines, reciprocating engines, microturbines, and fuel cells. In a CHP system, waste heat from these DER technologies can be used as input power for thermally activated technologies (TAT) such as air conditioners, chillers, and desiccant dehumidifiers; to generate steam for space heating; and/or to provide hot water. By making use of thermal energy that is normally wasted, CHP systems can meet a building's electrical and thermal loads with a lower input of fossil fuel, yielding resource efficiencies of 40 to 70% or more.

The United States Department of Energy (DOE) has initiated a Buildings Cooling, Heating, and Power Program (BCHP).[5] Its aim is to focus building industry research, development, and commercialization toward on-site and near-site fuel conversion, making it possible to combine and optimize the integration of electric power generation and thermally-activated heating, ventilating, and air-conditioning (HVAC) systems. These CHP systems can maximize energy efficiency and thus reduce energy use and reduce emissions, increase the power capacity to critical loads by providing an option to central power generation, and improve electric power reliability and quality.

Great new opportunities for CHP developed in the late 1990s with the emergence of 200-kW fuel cells and in 1999–2000 with the emergence of 30- to 75-kW microturbines. At the same time, heat recovery systems were introduced to use exhaust heat (waste heat) either directly or to heat water for use. The heated air or hot water can be used to drive TAT chillers and/or desiccant dehumidification systems. The new DER systems show promise for use in multiple-occupancy buildings, hotels, hospitals, offices, and commercial establishments such as restaurants and grocery stores. However, to expand DER market, it is necessary to conduct research to both understand and determine the optimal system configuration for seasonal operation, especially winter versus summer operation. This research will allow the industry to provide customers with highly efficient, reliable, cost-effective, and well-integrated CHP equipment and systems.

Within the scope of the BCHP Initiative, DOE has sponsored research on a natural-gas-fired microturbine-based CHP system at ORNL's CHP Integration Test Facility in Oak Ridge, Tennessee. The work provides both empirical and analytical assessment of CHP use in distributed, combined energy sources for buildings. In October 2000, the CHP Test Facility was commissioned and allows combining basic CHP functional components into various waste heat recovery configurations. It allows the study of the characteristics of each component and of the overall system under various operating modes. The configuration of the CHP test system is shown in Figure 1. Currently, a 30-kW microturbine is being tested with TAT at the facility.

The activity described in this article studied baseline performance and emissions of a 30-kW microturbine over a range of design and off-design conditions in steady-state operating mode at various microturbine exhaust backpressures. Also, preliminary CHP configurations of the microturbine combined with the heat exchanger and indirect-fired desiccant dehumidifier have been tested.

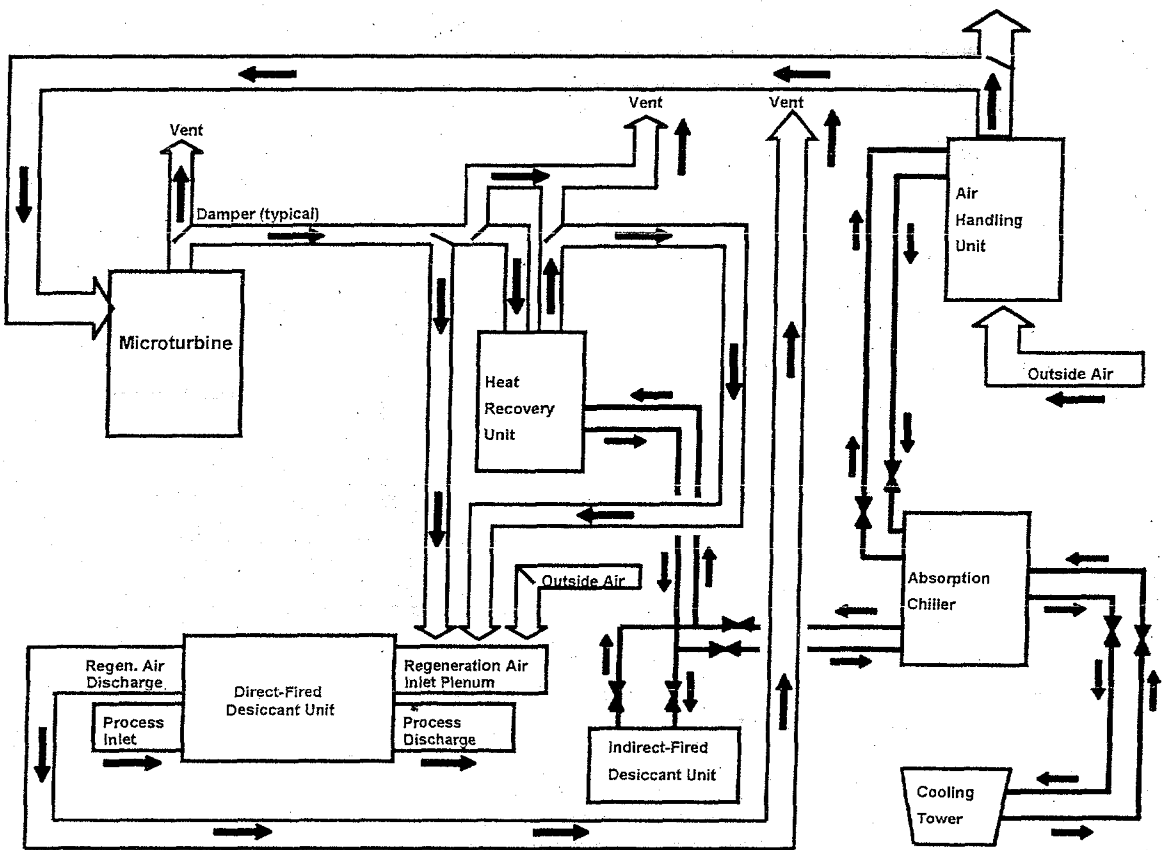

Figure 1. Schematic of CHP Integration Test Facility at ORNL.

2. CHP Integration Test Facility

The combined cooling, heating and power (CHP) test facility combines a natural gas-fired DER with thermally-activated heating, ventilating and air-conditioning (HVAC) and dehumidification systems. Normally, these thermally-activated technologies (TAT) use natural-gas firing to provide heated air or hot water as input to their process. In the CHP facility, the waste exhaust heat from the gas-fired microturbine, which is normally vented to environment, is instead captured and vented through an air duct system to either an air-to-water heat exchanger or mixed with outside air and then directed to one of our TAT units. Specific descriptions of the electric generator and the TAT devices are given in the next section.

To ensure the success of CHP systems, the interaction of the DER, such as the microturbine, and the heat exchanger or heat recovery unit (HRU) under steady-state modes of operation with various microturbine backpressures must be considered. One significant problem is that a heat exchanger creates hydrodynamic resistance, which results in a pressure increase at the microturbine's exhaust outlet that in turn decreases the microturbine's output power and efficiency. At the same time, hydrodynamic resistance depends on the flue gas flow rate through the working elements of the HRU (heat exchanger) and on the heat exchanger design. The greater the flue gas flow rate, the greater the hydrodynamic resistance and gas pressure from the microturbine. The increased flue gas flow rate results in a higher heat transfer coefficient and in smaller dimensions and lower weight and cost for the HRU. Thus, the optimal combined operation of a microturbine and a heat exchanger depends, in a complicated way, on the microturbine's backpressure.

2.1. Microturbine

The microturbine is a three-phase 480VAC/30kW rated unit that can operate at 50 or 60 Hz when connected to the electric grid. A stand-alone option that allows the microturbine to start and generate power without electric utility service is also available from the manufacturer, although this feature was not included with the unit employed in our tests. 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 unit's power conditioning electronics. The gas turbine and the electrical generator are on the same shaft and rotate rapidly to produce the correspondingly high-frequency AC current. Subsequently, the microturbine has a digital power controller (DPC) to control its operation and all power conversion functions. The DPC converts the variable-frequency power from the generator into grid-quality power at the output terminals. The variable-frequency power is converted to constant-voltage DC power, which is then inverted to constant-frequency AC power.

The unit is designed to produce a continuous phase current of 36 A at 480 VAC and to produce near unity power factor 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 480VAC/45kVA three-phase isolation transformer. The transformer is connected wye-delta with the wye-side connected to the microturbine. The delta connection provides an additional measure for preventing harmonics from entering the grid from the microturbine and protecting the microturbine from zero-sequence currents produced by faults. The microturbine acts as a current-source and thus has no direct affect on the grid voltage or frequency. The microturbine's DPC incorporates protection functions that 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 unit's DPC also includes over voltage, over/under frequency and rate of frequency protection functions to protect the microturbine and prevent it from islanding (continue to operate connected to the grid when a grid phase/phases have been lost). The 30 kW natural gas-fired microturbine was found to produce electricity with a maximum output power of ~28kW (full load).

The fuel (natural gas) is fed to the combustion chamber with the help of a gas compressor since the unit requires 3.7 atm (55 psig) rather than the 0.3 atm (5 psig) supplied by our gas distributor. The microturbine already employs some degree of heat recovery since it uses a recuperator to preheat the air entering the combustion chamber. The recuperator increases the maximum efficiency of the microturbine by ~10% from 13 to 23% based on the higher heating value (HHV) of the natural gas.

The test setup is designed so that the hot flue gas from the microturbine can be fed either directly to a direct-fired desiccant unit or to an air-to-water heat exchanger to provide hot water for heating or for input to an indirect-fired TAT. The temperature of the hot flue exhaust from the microturbine ranges from 250 to 293°C (482 to 560°F), and the temperature of the exhaust leaving the heat exchanger is ~120°C (~248°F). The flue exhaust from the heat exchanger can be either fed to the direct-fired desiccant unit or vented to the atmosphere. Hot water from the heat exchanger, which will be in the range of 85 to 95°C (185 to 203°F), can be fed either to the indirect-fired absorption chiller or to the indirect-fired desiccant unit. Dried and/or cooled air goes to the conditioned space or is used to cool the inlet air of the microturbine to increase its power output and efficiency.

2.2. Thermally-Activated Technologies

Thermally-activated technologies (TAT) at the CHP Integration Test Facility include an absorption chiller and two desiccant dehumidifiers. The facility has an indirect-fired single-effect 10-ton absorption chiller, and direct-fired and indirect-fired desiccant dehumidifiers. The direct-fired unit uses the hot exhaust from the microturbine along with outside air mixed in directly and the indirect-fired unit uses heated water from the air-to-water heat exchanger.

Desiccant Dehumidifiers: Desiccant systems provide a means of drying outside air before it enters a conditioned space, i.e., an office building or restaurant. The desiccant dehumidifier uses a wheel of desiccant material that adsorbs moisture. The liquid or solid desiccant material becomes saturated as moisture is absorbed, but dries out and can be used again when heated. Natural gas combustion or other heat sources are used to regenerate the desiccant material. In our test facility, the waste heat from the DER (microturbine) is used.

Absorption Chillers: Absorption chillers are used to generate chilled water (~44°F or ~7°F) from a heat source to provide building air conditioning. The chilled water from the absorption chiller is circulated to air handlers in the air duct distribution system of the building to provide this air conditioning. The direct-fired absorption chillers contain natural gas-fired burners to provide the heat source. Indirect-fired units use hot water or steam from a separate heat source, such as a boiler or heat recovery unit.

Absorption chillers are classified as single-, double- or triple-effect. For low quality heat, indirect-fired single-effect absorption chillers are best since they provide cooling using low temperature hot water, i.e., 88°C (190°F), or low pressure steam, i.e., 0.68 atm (10 psig). Indirect-fired double-effect chillers provide increased efficiency but also need higher pressure steam, i.e., > 6.8 atm (100 psig), or high temperature water, i.e., > 177°C (350°F).

3. Microturbine Baseline Characterization

The testing at the CHP Integration Test Facility started with the baseline characterization of the microturbine. The instrumentation was set up to collect both electric and thermal performance for the microturbine. Electrical data included the microturbine's DC voltage, and single and three-phase AC power output, voltage, and current as well as its single-phase values. The thermal data included the microturbine's input temperature, exhaust temperature, internal temperatures at the compressor and turbine, and emissions. The startup and power dispatch characteristics of the microturbine are shown in Figures 2 and 3. The shutdown of the unit that isn't shown in this paper required more than twice as long as the startup (520 s or 8 min 40 s). Also, although the power output dropped off fairly linearly, the turbine speed stayed at 45,000 rpm for nearly all this time to cool down the turbine. The energy efficiency and heat output of the microturbine as it varies with power output are shown in Figure 4 and its electrical losses (including an isolation transformer) and potential thermal heat recovery are shown in Figure 5.

The emissions (NO_x and CO) of the flue gas from the microturbine versus its power output (at steady-state) are shown in Figure 6. The microturbine was found to produce low emissions at full power of ~3 ppm NO_x measured at 18.5% O_2 or ~8 ppm NO_x when corrected to 15% O_2.

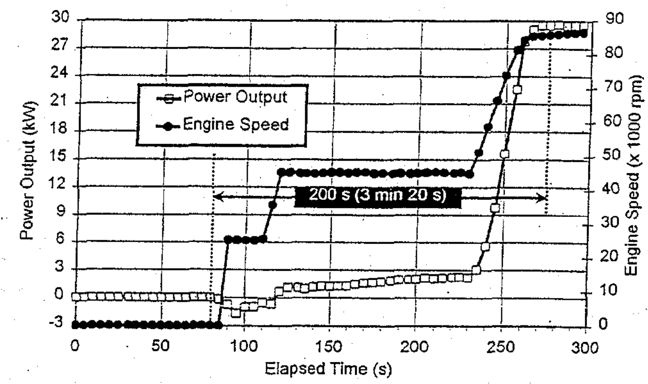

Figure 2. Startup Performance (power output and turbine speed) of the 30-kW Microturbine.

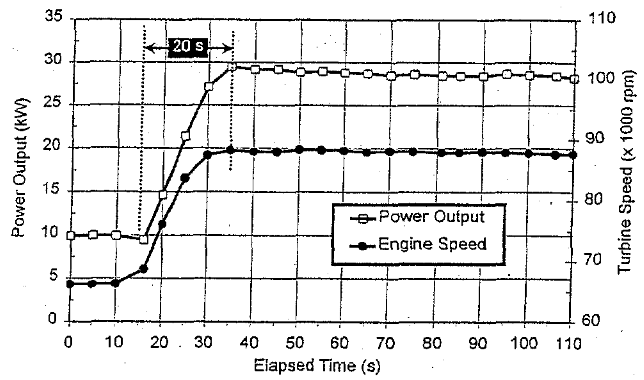

Figure 3. Power Dispatching Response (power output and speed dynamics) of the 30-kW Microturbine.

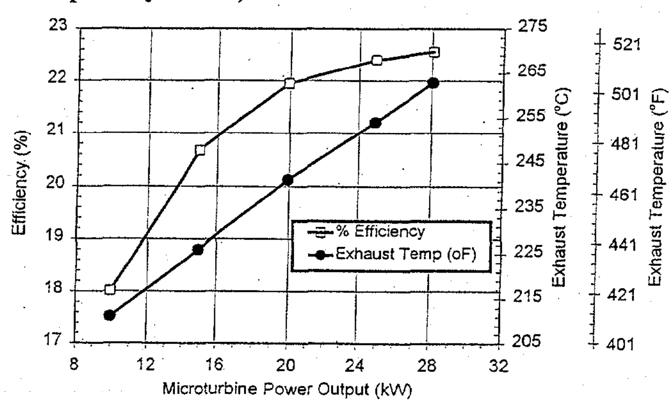

Figure 4. Efficiency and Exhaust Heat Temperature of the Microturbine vs. its Power Output.

4. CHP Testing

The next step in the testing process was to determine the impact of exhaust backpressure on the microturbine's operating performance. The recovery of thermal waste heat from the microturbine involves additional pressure on the unit's exhaust. Even without the presence of any thermal recovery at the unit's exhaust, there is some degree of backpressure (~$8.0x10^{-4}$ atm or 0.3 in wc) although this is quite low.

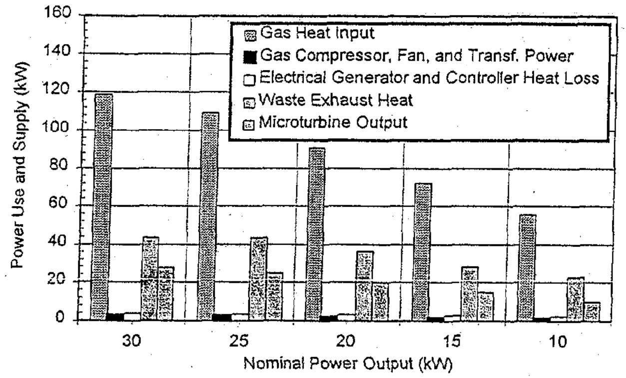

Figure 5. The Electrical and Thermal Energy Power Losses of the Microturbine Along with Its Input and Output Power.

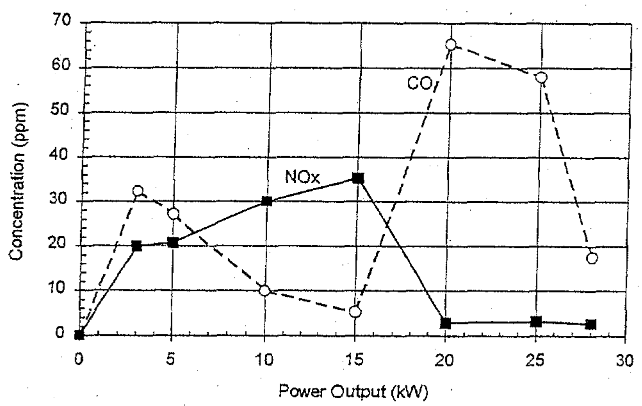

Figure 6. Emissions (NO_X and CO) in the Microturbine Flue Gas vs. its Power Output.

The backpressure on the unit was adjusted by a slide damper on the exhaust duct and monitored by a pressure transducer. A flue gas analyzer was used to monitor the unit's emissions. The other parameters — monitored via the manufacturer's monitoring hardware and software built into the microturbine — include the unit's power output; engine speed; and voltage, current, and power in each phase.

The total power output demand of the microturbine was varied in increments of 5 kW from 10 to 30 kW (one-third to full power settings), and the backpressure ranged from ($8.0x10^{-4}$ to $1.7x10^{-2}$ atm or 0.3 to 7.5 in. wc). Series of tests on the microturbine were conducted while constant output power demand was maintained, and then while constant turbine speed was maintained at various backpressures. It should be noted that because the microturbine was located outdoors, the microturbine's air inlet temperature was dictated by outdoor conditions. The results of these tests are shown in Figure 7.

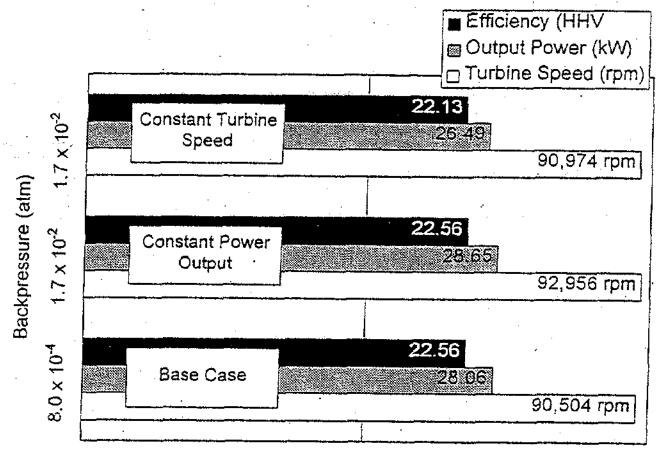

Figure 7. Results of Backpressure Tests on Microturbine to Emulate CHP Heat Recovery.

Most recently, the microturbine was paired with an air-to-water heat exchanger to feed hot water to an indirect-fired desiccant dehumidifier. The heat recovery in the heat exchanger at a water flow rate of 4.3 m^3/h (19 gpm) was found to be ~23 kW (or ~75,000 Btu/h) with the microturbine at one-third power up to ~44 kW (or ~150,000 Btu/h with the unit at full power as shown in Figure 8. Figure 9 shows a relatively constant CHP system efficiency of ~55% (based on HHV) over the microturbine's power output range.

5. Conclusions

A test facility has been developed at the ORNL for testing combined power generation and thermal recovery components. The testing to date has included assessing the performance of a microturbine with increasing external backpressure applied to its exhaust to emulate the application of thermal recovery systems as well as the use of an air-to-water heat exchanger to recover the waste heat. In parallel with these tests, the data measurements have been used to develop a semi-empirical model for the microturbine in order to determine how its power output and efficiency would vary with thermal recovery.

The series of baseline tests on the microturbine show that the unit's efficiency drops off significantly with power output level. At full power, the microturbine can produce over 28 kW at an efficiency of ~23% when the outside temperature is below 18°C (65°F). Due to the rpm limits on the turbine, the power output drops off significantly when the outside temperature exceeds this value. This is most apparent when the unit is operating at full power. At one-third power, the microturbine only has an efficiency of ~18%. Most recent tests have shown that this drops off to ~8% at a power output level of 3 kW.

The performance tests on the microturbine indicate that the unit has slow startup and shutdown capabilities (requiring several minutes). However, once up and operating, the unit can vary (dispatch) its power output level within several seconds once a new power setting is selected. Quite consistently, it was found that it took ~20 seconds to vary the microturbine's power output and this seems to be independent of the unit's current setting and new setting or amount of change.

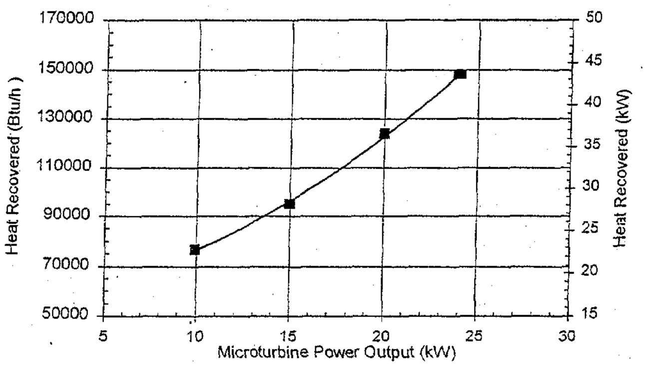

Figure 8. Results of Heat Recovery in the Heat Exchanger at a Water Flow rate of 4.3 m^3/h or 19 gpm

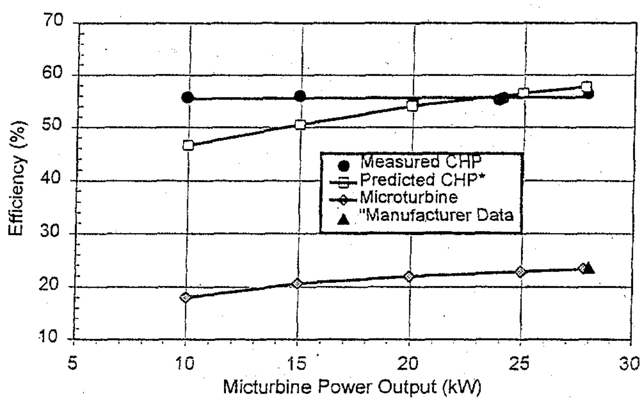

Figure 9. CHP Power Plant Efficiency vs. Efficiency of Microturbine without Heat Recovery.

The only major problems that we have experienced with the microturbine relate to the natural gas compressor which boosts the incoming pressure of the utility gas from 0.3 atm (5 psig) to 3.7 atm (55 psig). We have experienced two failures of the ball-bearing rotary flow compressor (RFC); the original unit and its replacement at ~90 and ~200 hours of operation each, respectively. We have since replaced the second failed ball-bearing RFC with a new foil-bearing RFC and are re-benchmarking the baseline characteristics of the microturbine. In addition, CHP performance and emission tests will continue with indirect and direct-fired desiccant dehumidifiers and with indirect-fired single effect absorption chiller.

The microturbine was found to produce low emissions at all power levels, especially at full power. The unit at full power produces ~3 ppm NO_x measured at 18.5% O_2 or ~8 ppm NO_x when corrected to 15% O_2. Although, the emissions were found to consistently peak (~10 to 12 times greater) at the one-third to two-thirds (10 to 20-kW) power output level settings.

6. Acknowledgements

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