INTEGRATION OF DISTRIBUTED ENERGY RESOURCES AND THERMALLY-ACTIVATED TECHNOLOGIES

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Abstract

A new CHP Integration Test Facility has been commissioned at the Oak Ridge National Laboratory (ORNL) for the testing of distributed energy resources (DER) combined with thermally-activated technologies for combined cooling, heating, and power (CHP). Presently, it has been set up to test a 30-kW microturbine with both direct and indirect-fired desiccant dehumidification systems and a 10-ton indirect-fired single-effect absorption chiller. The first phase of testing has been completed which examined both the startup and shutdown capabilities and limitations of the microturbine and its load following performance. The performance testing determined the variability of the microturbine's operating performance variables, such as power output, voltage, current, and heat output as well as its power output ramping characteristics for load following. Nominally, the microturbine's maximum power output and efficiency without waste heat recovery are 28 kW and 23%, respectively. The efficiency of the microturbine drops as the power output and turbine speed are reduced. The efficiency of the microturbine at one-third rated power output or 10 kW is 18%. Once up and running the microturbine can vary its power output such as from 10 to 20 kW in 20 s although it requires 200 s or close to 3.5 minutes for cold startup. The goal of the DER/CHP test facility at ORNL is to increase the efficiency of the DER/CHP electric and thermal power plant by optimally integrating both the packaging and operation of the various components. Nominally the exhaust heat from the microturbine at full output is ~500°F (~260°C). The exhaust heat can be used directly by mixing it with outside air to get the correct inlet temperature (~220°F or 105°C) for the direct-fired dehumidifier or fed to an air-to-water heat exchanger to obtain hot water (~180°F or 82°C) for an indirect-fired dehumidifier or absorption chiller. At the ORNL DER/CHP test facility, the hot air ducting and hot water plumbing have been completed and various waste heat recovery tests are underway. Prior to these tests, a series of exhaust backpressure tests were conducted to determine the performance impacts on the microturbine for expected backpressure of the thermally-activated technologies. It has been found that exhaust backpressures of up to ~1.7×10^{-2} atm or 7 inches of water column (in wc) can be applied without producing any significant reduction in the energy efficiency or power output of the microturbine. In fact, the speed of the turbine increases as the backpressure is applied which consequently does not significantly impact the power output or efficiency of the microturbine. In this paper, the microturbine's performance results for startup/shutdown, load variation, and backpressure testing are provided and discussed. Also, preliminary results of testing the microturbine with indirect-fired thermally-activated technologies, which were conducted this winter are presented and discussed.

1. Introduction

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 externally applied backpressure.

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.[2,3,4,5] 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).[6] 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.

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 the 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[7] 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.

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 the environment, is instead captured and vented through an insulated air duct system to either an air-to-water heat exchanger or mixed with outside air and then directed to the TAT units. Specific descriptions of the microturbine generator and the TAT devices are given in the next section.

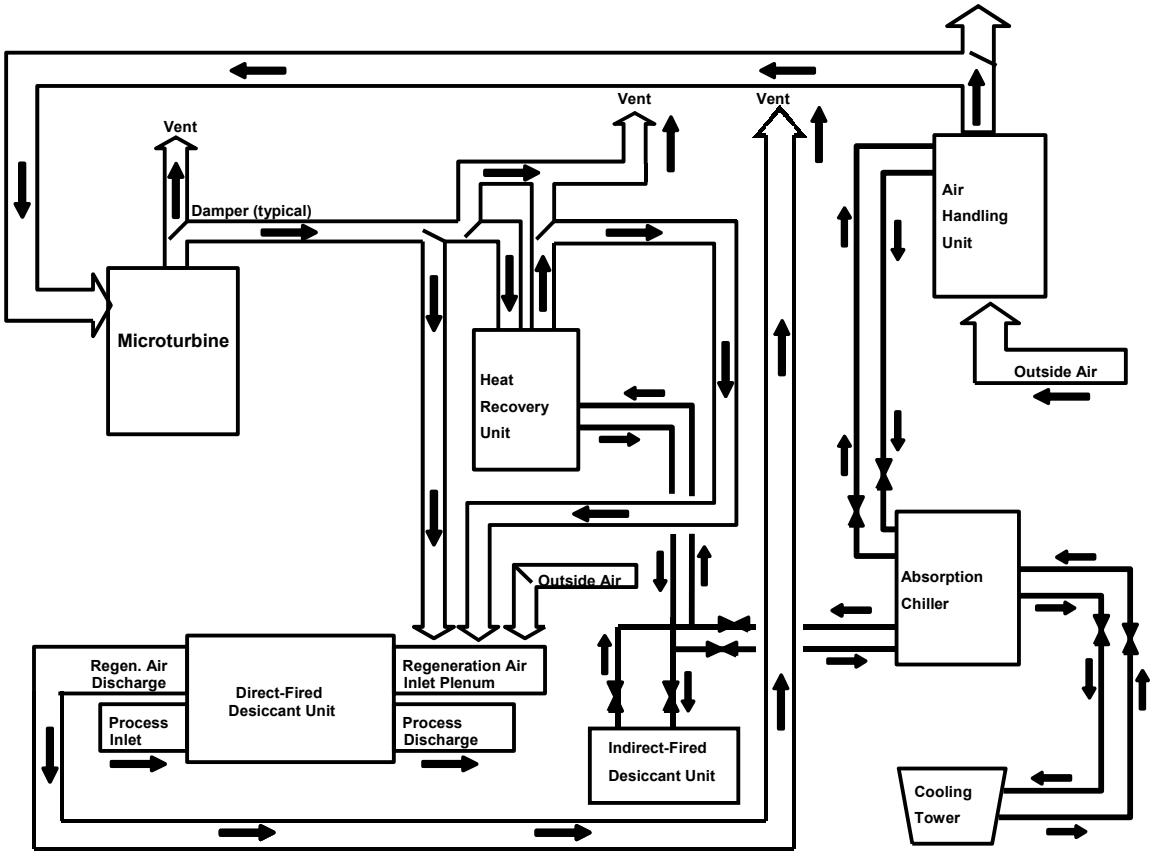


Figure 1. Schematic Of CHP Integration Test Facility At ORNL.

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 (microturbine exhaust) 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 digital power controller (DPC). The DPC controls the microturbine's operation and all its power conversion functions. The gas turbine and the electrical generator are on the same shaft and rotate rapidly to produce the correspondingly high-frequency AC current. The DPC converts the variable-frequency power from the generator into grid-quality power at the output terminals.

The unit is designed to produce a continuous phase current of 36 A at 480 V_{AC} (line-to-line voltage) and to produce near unity power factor when the unit is grid connected. The unit's nominal phase-to-neutral voltage is 277 V_{AC}. The microturbine is connected to the grid (through a 480 V_{AC} electrical panel which is connected to the local distribution system) via a 480V_{AC}/45kVA three-phase isolation transformer. The transformer is connected grounded wye-delta with the grounded-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 effect 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 V_{AC} for more than 10 s. Islanding of the microturbine (or separation of the unit from the grid) is detected within milliseconds from the loss of current control. In addition to providing undervoltage protection, the microturbine'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 natural 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 or exhaust 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 482 to 560°F (250 to 293°C), and the temperature of the exhaust leaving the heat exchanger is ~248°F (~120°C). 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 185 to 203°F (85 to 95°C), 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°C) 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 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., 190ºF (88ºC), 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., > 350ºF (177ºC).

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. The thermal data included the microturbine's input temperature, exhaust temperature, internal temperatures at the compressor and turbine, and emissions. The startup, shutdown and power dispatch characteristics of the microturbine are shown in Figures 2 through 4. As shown in Figure 2, the startup of the unit requires 200 s or more than 3 minutes from when it starts motoring to bring the turbine up to operating speed until it starts generating full output power. The characteristic is basically the same regardless of what power output setting the unit is set at for startup. As shown in Figure 3, the shutdown of the unit requires more than twice as long or nearly three times the startup time. The shutdown requires 520 s or more than 8 minutes. 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 variability of the microturbine's power output at the full power setting (30-kW) is shown in Figure 5. As indicated in Table 1, the standard deviation of the power output at this setting is ±237 W.

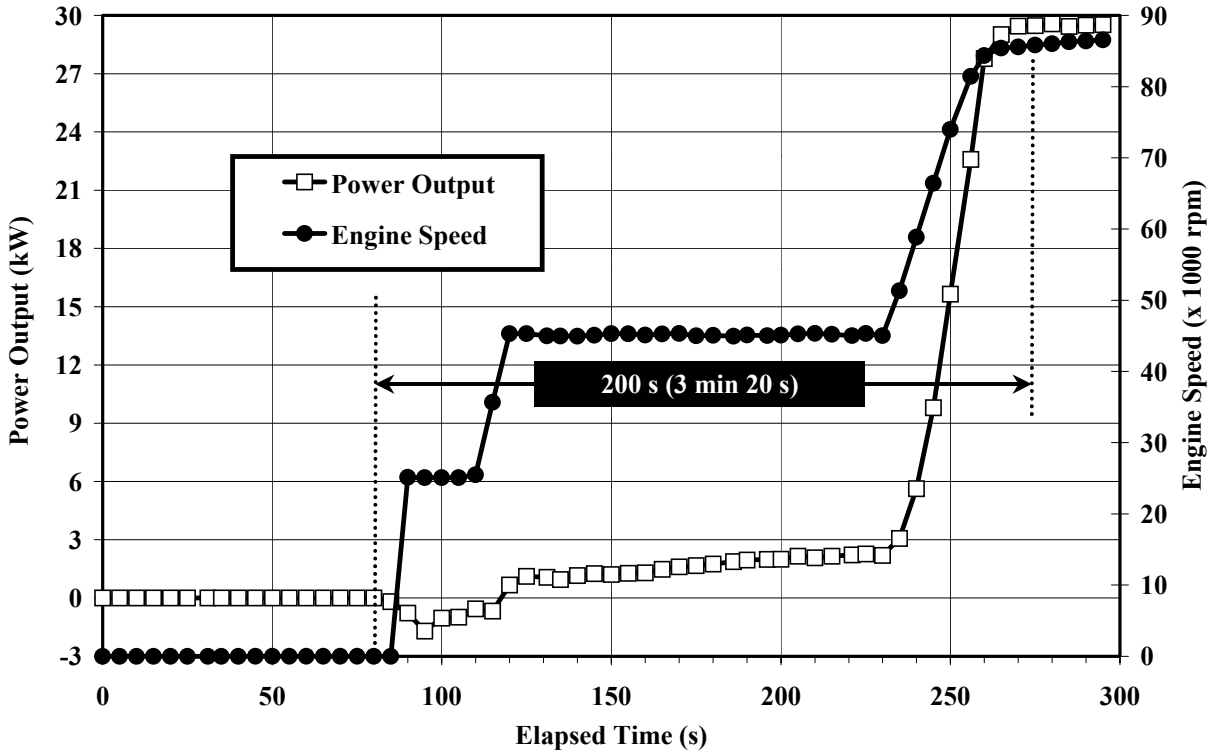


Figure 2. Startup Performance (Power Output And Turbine Speed) Of The 30-kW Microturbine.

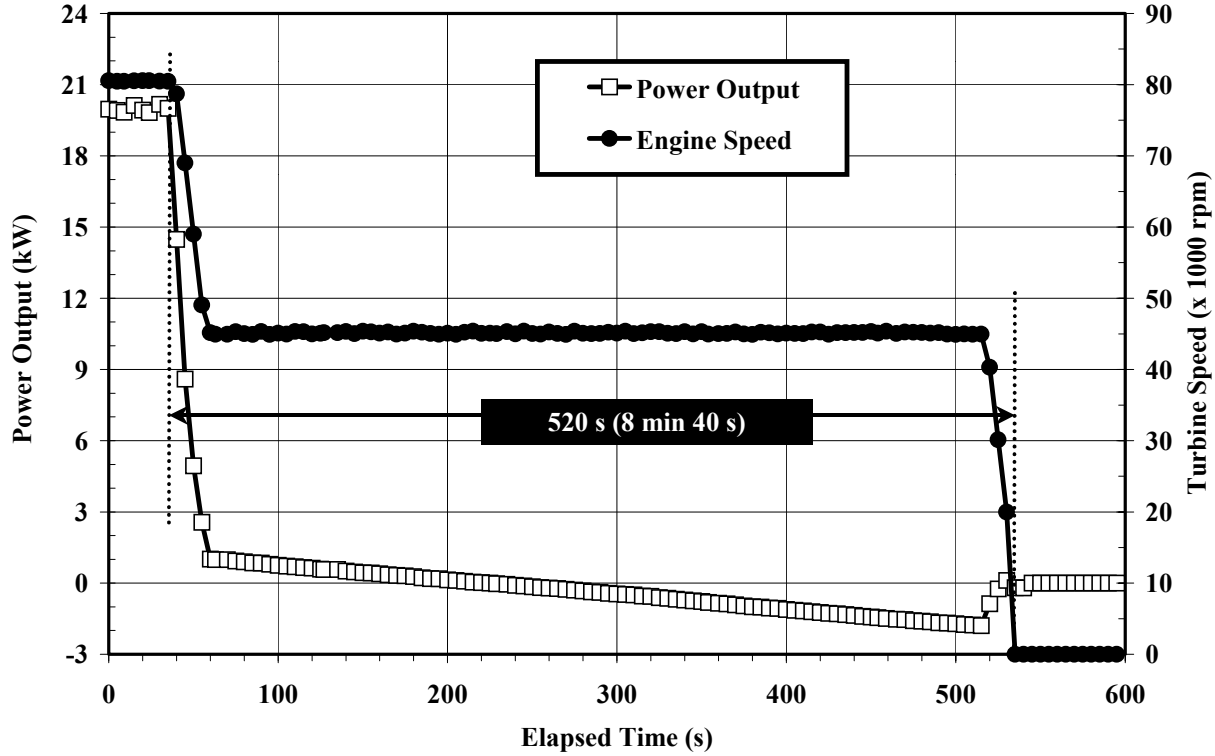


Figure 3. Shutdown Performance (Power Output And Turbine Speed) Of The 30-kW Microturbine.

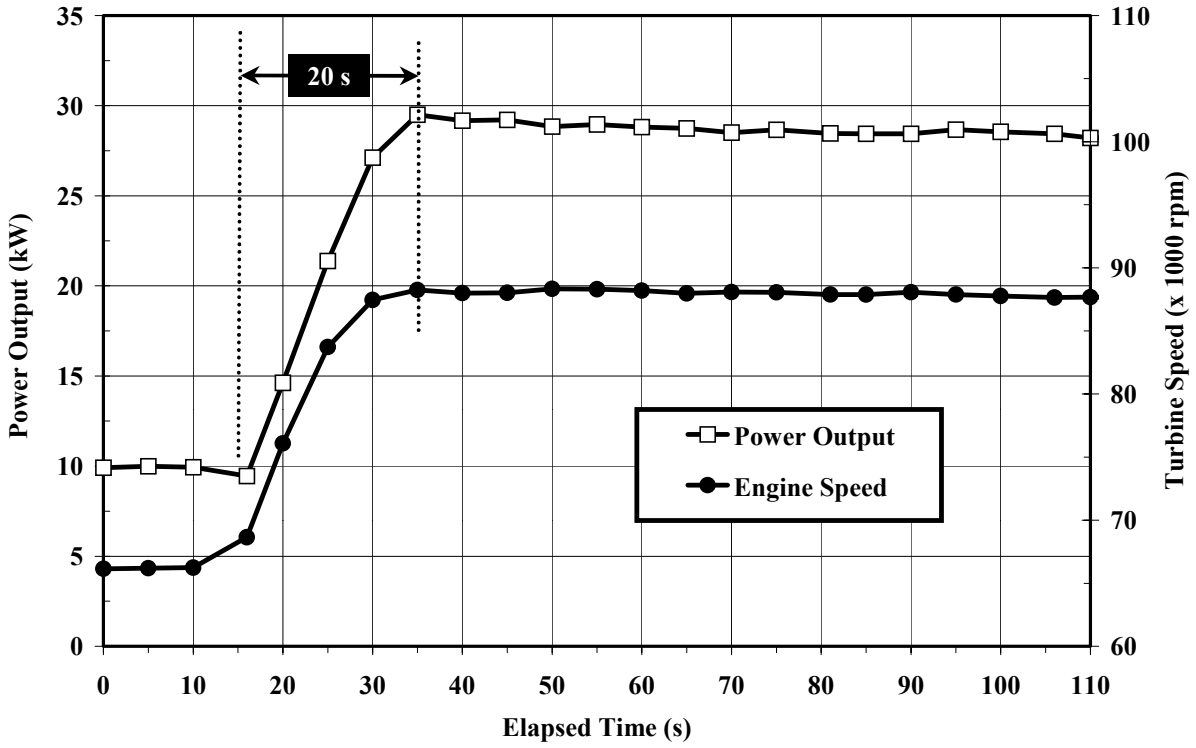


Figure 4. Power Dispatching Response (Power Output And Speed) Of The 30-kW Microturbine.

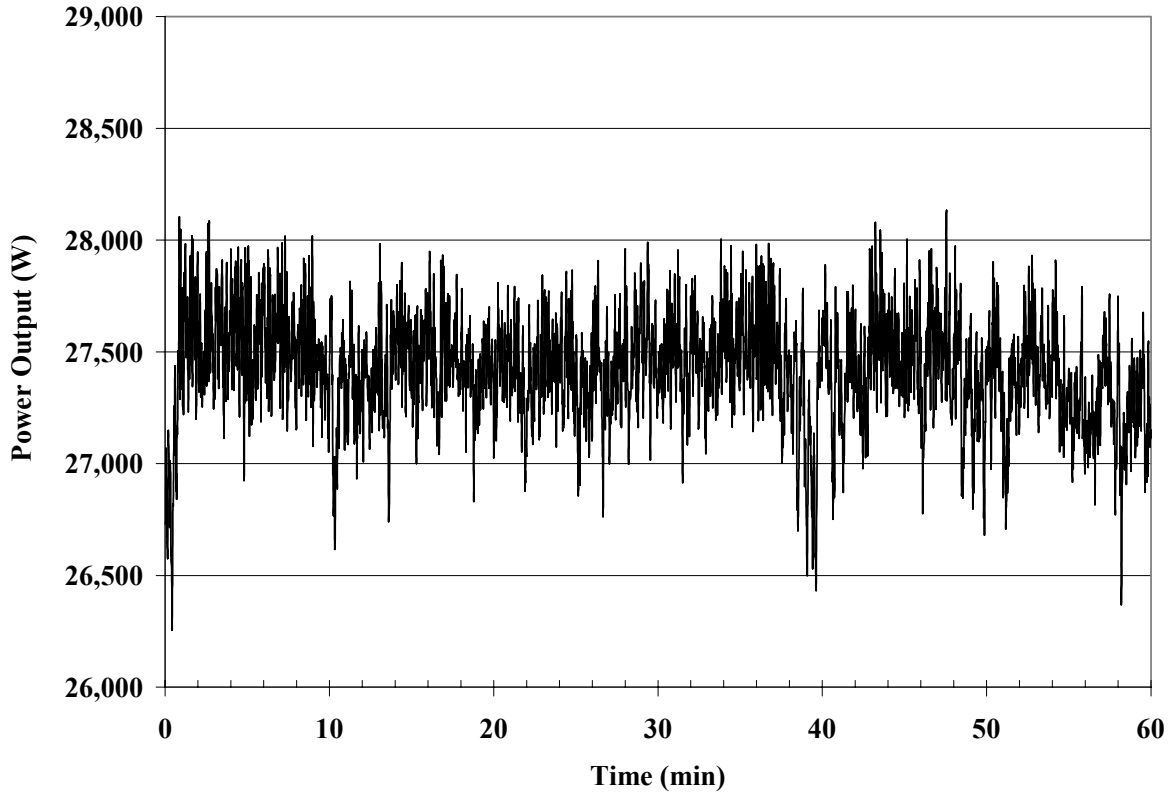


Figure 5. Microturbine Power Output Variation For One-Hour Of Operation At The 30-kW Setting.

Table 1 shows the microturbine's performance variations for power settings from full output (30-kW) to one-sixth power (5-kW) in 5-kW increments. It shows the microturbine's measured power output, turbine speed, phase voltages and currents (a, b, and c) and rectified DC voltage along with standard deviations for some of these values. The measured emissions at these various power settings are also shown. The microturbine, which is set up to operate in a grid-dependent (grid-connected) mode only at the test facility, was found to operate at a power factor of 98% with a ± 0.86% standard deviation for the power range 30 to 20 kW and at 97% with a standard deviation of ± 0.80% for 15 to 5 kW. In a parallel effort additional steady-state and dynamic testing of the microturbine in both grid-dependent and grid-independent (standalone) modes of operation have been conducted.[8]

Table 1. Microturbine Performance Characteristics At Various Power Settings*.

Power Setting (kW)	Power output (W)	% Efficiency (HHV)[8]	$T_{exhaust}$ (EF)	Engine speed (RPM)	DC Voltage (V_{dc})	Phase Voltage (V_{rms})	Phase Current (A_{rms})	CO** (ppm)	NO_x** (ppm)	CO_2 (%)	O_2 (%)
30	27421 ± 237	22.57 ± 0.06	507.5 ± 0.6	91,735 ± 159	759.7 ±0.4	289.0 286.8 286.9	32.0 32.0 32.0	16	4	1.5	18.5
25	24658 ± 187	22.15 ± 0.14	493.2 ± 0.7	88,496 ± 175	759.7 ±0.4	289.3 286.9 287.1	28.3 28.3 28.1	51	3	1.4	18.5
20	19775 ± 189	21.63 ± 0.07	471.8 ± 0.6	81,796 ± 116	759.6 ±0.4	287.3 285.1 285.4	23.0 23.0 23.0	68	3	1.3	18.7
15	14792 ± 146	20.47 ± 0.06	443.5 ± 0.5	74,928 ± 123	759.9 ±0.5	287.0 284.9 285.2	17.0 17.0 17.0	5	35	1.2	18.9
10	9785 ± 101	17.51 ± 0.08	419.4 ± 0.3	67,684 ± 72	759.6 ±0.2	286.1 284.2 284.4	11.1 11.0 11.0	10	30	1.1	19.1
5	4,982 ± 84	12.34 ± 0.07	384.2 ± 1.0	57,793 ± 84	759.5 ±0.0	284.4 282.5 282.6	6.0 6.0 6.0	22	22	1.1	19.2

**All performance measurements were taken at similar outside temperature conditions, between 39°F (3.9°C) and 34°F (1.1°C). Sixty-eight percent or more of the measurements fall within one standard deviation, which is shown as the ± range. **Actual CO and NO_x measurements are shown and have not been corrected to 15% O_2.*

The energy efficiency and heat output of the microturbine as they vary with power output are shown graphically in Figure 6 and the microturbine's electrical losses (including an isolation transformer) and unrecoverable exhaust heat are shown in Figure 7.

The emissions (NO_x and CO) of the flue gas or exhaust from the microturbine versus its power output (at steady-state) are shown in Figure 8. The emissions shown in this figure are all corrected to 15% O_2 rather than at the different O_2 levels of the actual measurements shown in Table 1. The microturbine was found to produce low emissions at full power of ~8 ppm NO_x when corrected to 15% O_2.

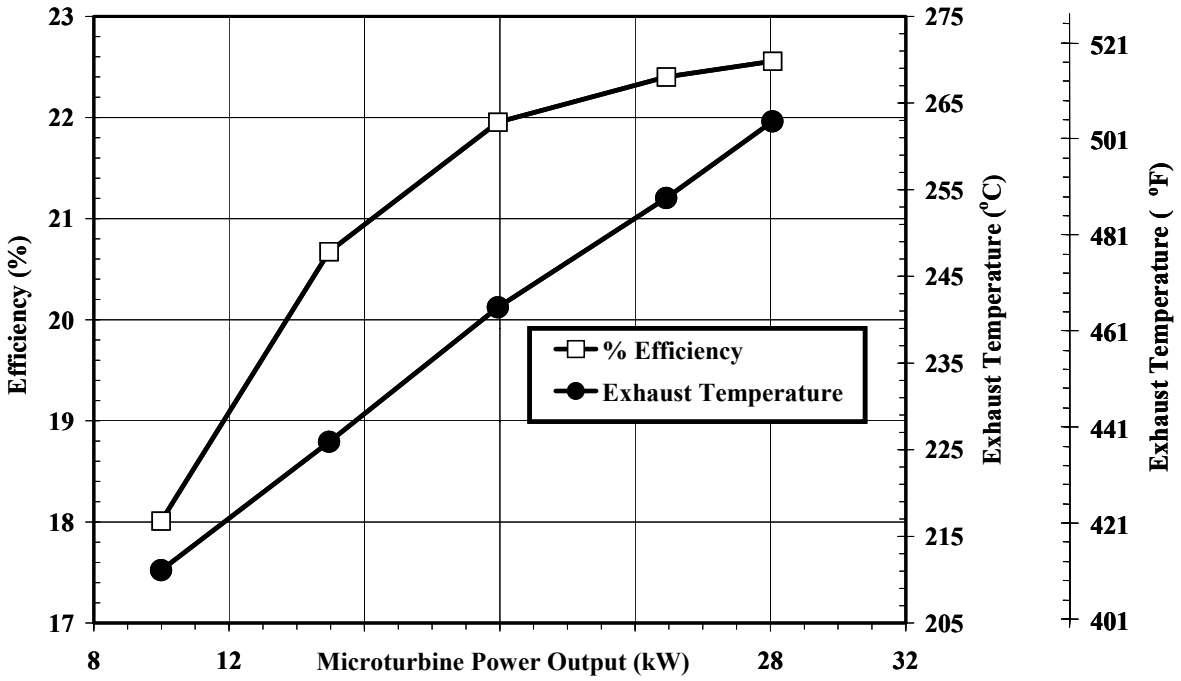
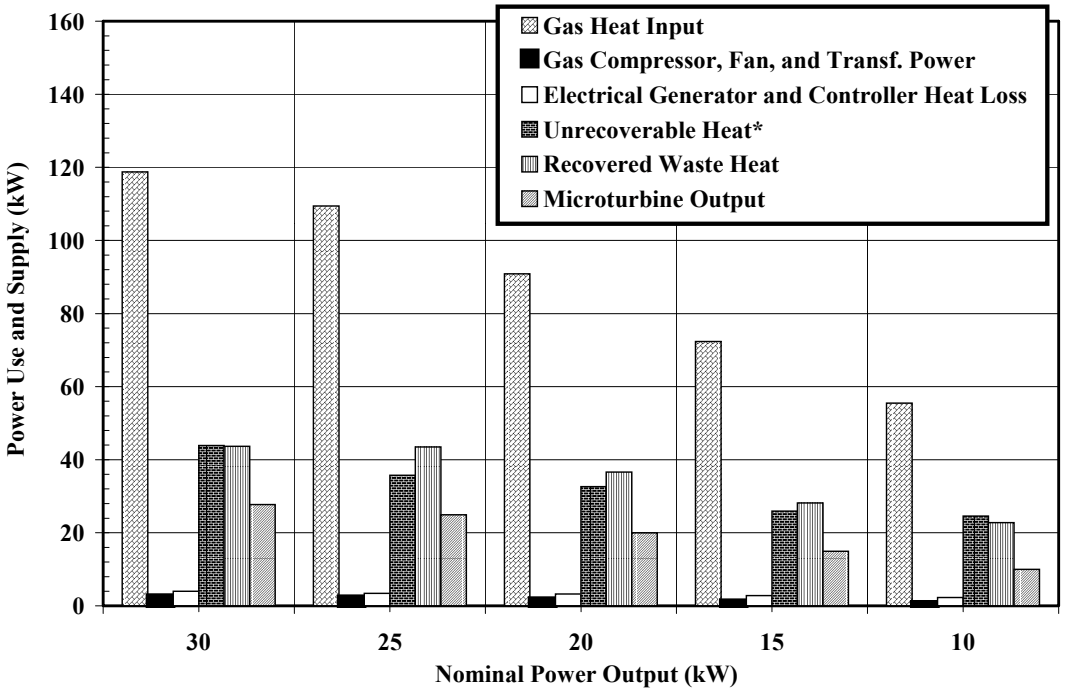


Figure 6. Efficiency And Exhaust Heat Temperature Of The Microturbine vs. Its Power Output.



**Not recovered due to the limited efficiency of the air-to-water heat exchanger (HRU). An HRU of higher efficiency is needed to recover a greater amount of exhaust waste heat.*

Figure 7. The Electrical And Thermal Energy Power Losses Of The Microturbine Along With Its Input And Output Power And Recoverable Waste Heat for Thermally-Activated Technologies.

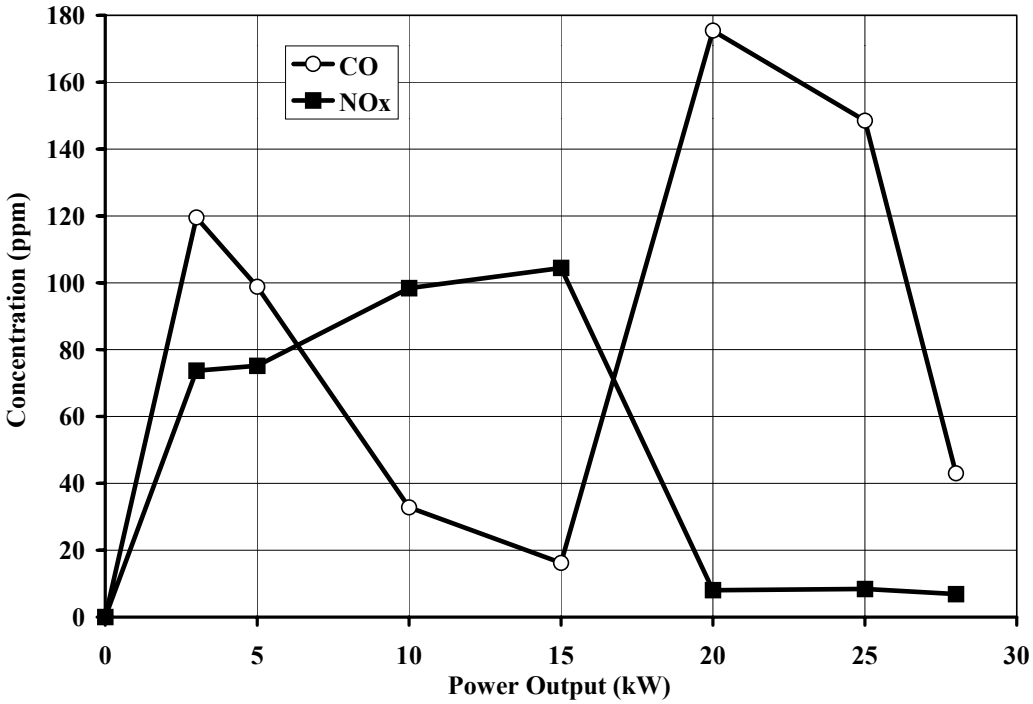


Figure 8. Emissions (NO_x And CO Corrected To 15% O_2) In The Microturbine Flue Gas vs. Its Power Output.

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 (~8.0×10^{-4} atm or 0.3 in wc) although this is quite low.

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 and external power recorders — 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 (8.0×10^{-4} to 1.7×10^{-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 9.

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 (10 kW) up to ~44 kW (or ~150,000 Btu/h) with the unit at full power (30 kW) as shown in Figure 10.

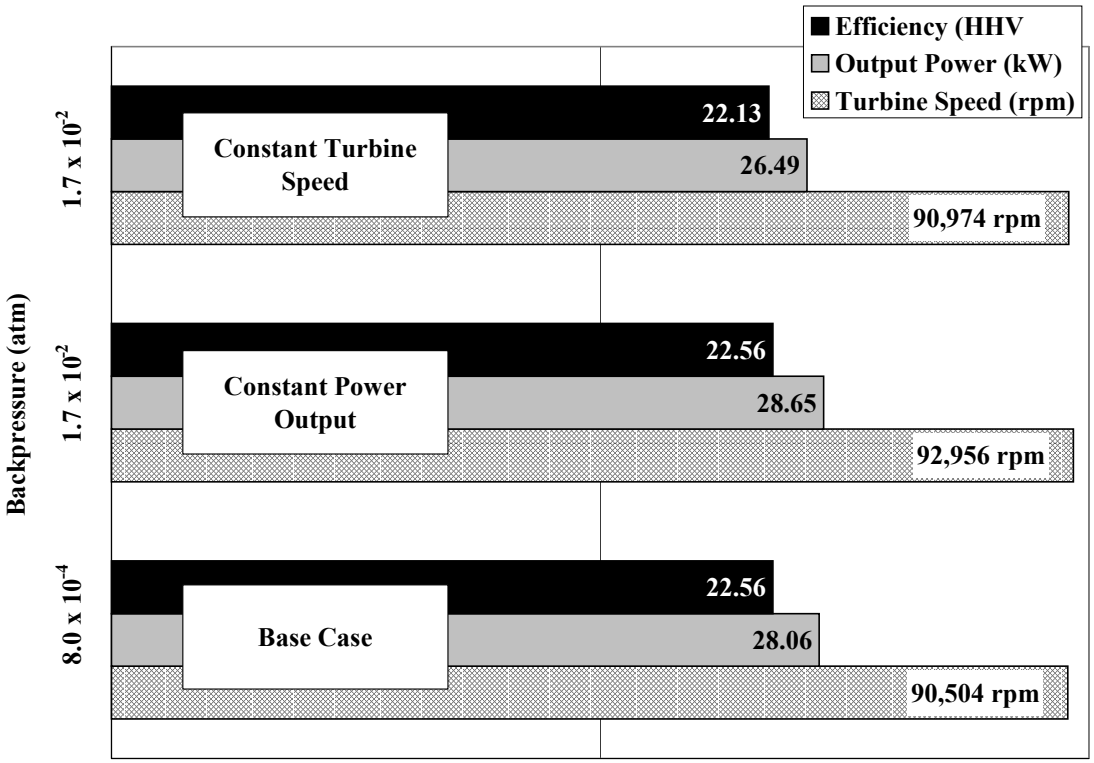


Figure 9. Results Of Backpressure Tests On Microturbine To Emulate CHP Heat Recovery.

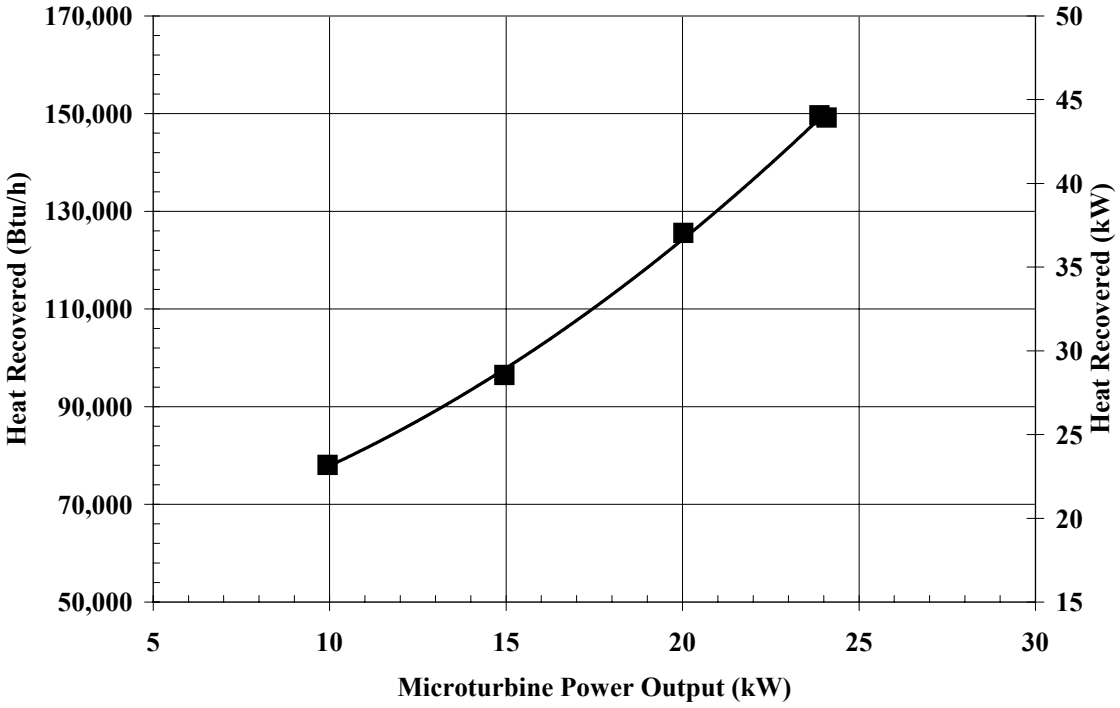
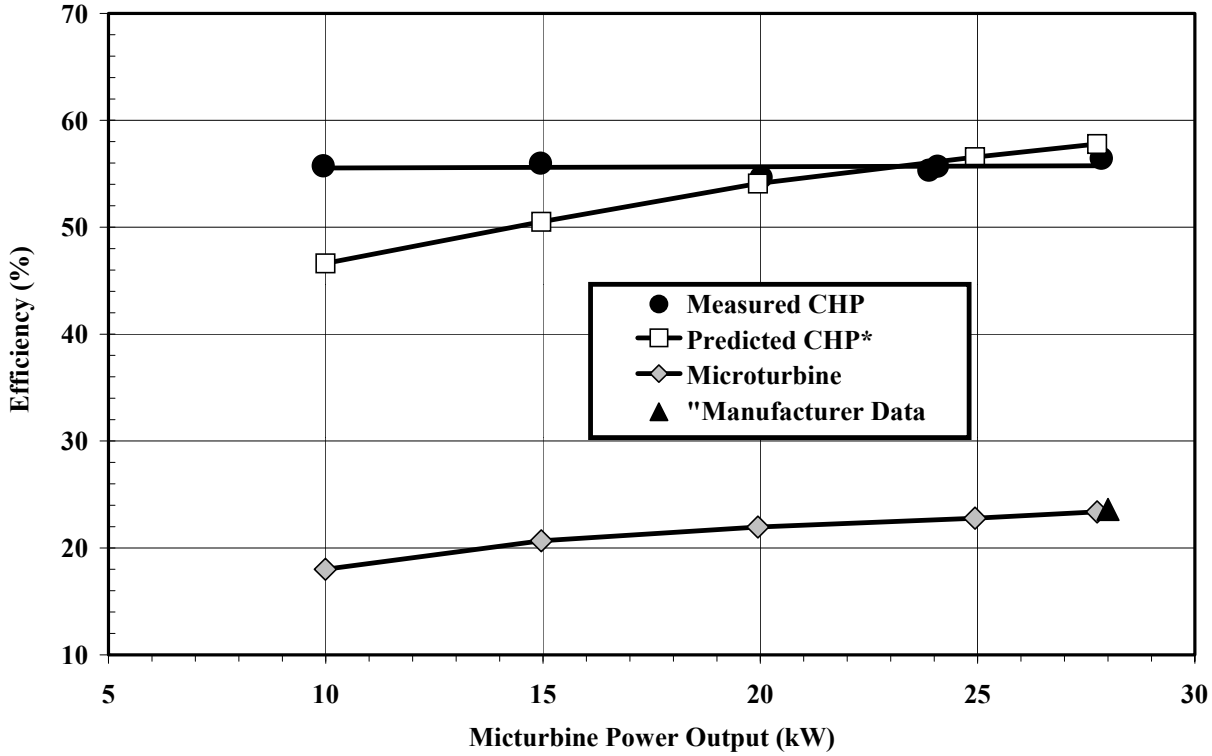


Figure 10. Results Of Heat Recovery In The Heat Exchanger At A Water Flow Rate Of 4.3 m^3/h Or 19 gpm.

Figure 11 shows a relatively constant measured CHP system efficiency of ~55% (based on a higher heating value or HHV for the natural gas) over the microturbine's power output range. Predicted CHP efficiencies are based on 260°F (400K or 127°C) flue gas or exhaust heat temperature rejected to the atmosphere. It should be noted that the measured exhaust temperature from the microturbine to the atmosphere was ~260°F at full power, however, at one-third power the exhaust temperature was ~200°F (366K or 93°C).



**Based on 260°F (400K or 127°C) flue gas or exhaust waste heat temperature rejected to the atmosphere.*

Figure 11. CHP Power Plant Efficiency vs. Efficiency Of Microturbine Without Heat Recovery.

5. Conclusions

A DER/CHP integration test facility has been developed at 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 (HRU) to recover the waste exhaust 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[7].

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 ~28 kW at an efficiency of ~23% when the outside temperature is below 65°F (18°C). 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 (10 kW), the microturbine only has an efficiency of ~18% and at one-sixth power (5 kW) it decreases rather drastically to ~12% or about half of the efficiency at full power. Most recent tests have shown that at 3 kW it drops off to ~9% (~one-third of the full power efficiency).

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 tens of seconds once a new power setting is selected. Quite consistently, it was found that it took ~20 s to vary the microturbine's power output and this seems to be independent of the unit's current setting, new setting and amount of change.

There is a slight variability in the electrical performance characteristics of the microturbine as it is operated, such as the power output which was found to vary ± 100 W more or less over an hour of operation depending upon the unit's power setting. The turbine's speed was also found to vary ± 100 rpm more or less again depending upon the unit's power setting. The microturbine was found to maintain phase voltages of between 289 to 282 V_{rms} over its power range settings while its phase currents range from 32 to 6 A_{rms} for full power to one-sixth power.

The microturbine was found to produce low emissions at all power levels, especially at full power output. The unit at full power produces ~4 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 25 times greater) at the one-third to one-half (10 to 15-kW) power output level settings.

As shown earlier, the overall CHP plant efficiency of the microturbine paired with an air-to-water heat recovery unit (HRU) was found to be ~55% over the entire range of the unit's power output range. At full power output the microturbine's efficiency and exhaust heat output are at their maximum. At lower power settings the microturbine's heat output temperature drops off (i.e., by ~88°F or 49°C from full to one-third power), however its efficiency does as well which helps to offset the loss in heat output temperature. The measured plant efficiency of the microturbine-based CHP falls fairly close to the efficiency predicted by the CHP model that was developed in a parallel effort. The measured CHP efficiency is fairly flat even though the exhaust heat temperature drops off because at lower power output (1) the quantity of exhaust heat produced by the microturbine on a relative basis is greater, and (2) the heat exchanger is more efficient at lower temperatures. The reason that the predicted efficiency curve is not as flat is because it assumes a constant exhaust temperature of 260°F (400K or 127°C) to the atmosphere. CHP performance and emission tests will continue with indirect and direct-fired desiccant dehumidifiers and with an indirect-fired single effect absorption chiller.

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 have re-benchmarked the baseline characteristics of the microturbine with this new RFC.

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