Baseline and IES Performance of a Direct-Fired Desiccant Dehumidification Unit Under Various Environmental Conditions

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ABSTRACT

The use of on-site or near-site distributed electric power generation (DG), as part of an integrated energy system (IES), brings available waste heat closer to the end user's thermal loads. Heat-activated technologies such as desiccant dehumidification units are increasingly being viewed as an important element to effectively apply in IES designs that increase system efficiency, reduce fuel costs and consumption, and provide both electrical and thermal load energy.

The purpose of this study is to investigate both the baseline performance of a commercially available direct-fired desiccant dehumidification unit and its performance as one of the components of an IES. Desiccant dehumidification units, which are used to reduce the latent load (remove moisture) of the process (conditioned) air, are specified on the basis of grain depression and/or latent capacity (LC). Several operating parameters, such as process and regeneration air conditions (dry-bulb temperature and humidity), volumetric airflow rates, and desiccant loading affect the ability of the desiccant unit to remove moisture. This study investigates the impact of varying process and regeneration conditions on LC and latent coefficient of performance (LCOP) of heat-activated desiccant dehumidification units. The baseline performance of the desiccant unit with regeneration air heated by direct burning of natural gas is compared with an IES case in which the exhaust gas from a microturbine and its heat recovery unit are used as the regeneration energy source.

Baseline performance tests show that both LC and LCOP increased with inlet air dew point while keeping the other parameters (gas input and electrical parasitics) constant. The maximum baseline LCOP and LC were 0.58 and 103,246 Btu/h (30 kW), respectively. Using residual microturbine exhaust gas (what remains of the exhaust after going through an air-to-water heat recovery unit) as the regeneration heat source results in a 50% decrease in the latent cooling capacity of the desiccant dehumidification unit as compared to its baseline performance. However, adding the desiccant dehumidification unit to a microturbine/heat recovery unit in the IES increased system efficiency by 7% over the microturbine/heat recovery unit only. Emissions tests show that the most significant pollutant is carbon monoxide (CO). The average CO level in the regeneration outlet air (flue gas) was found to be ~13 ppm. In addition, the emissions tests did not show any significant cross-contamination between the process and regeneration airstream sides of the desiccant dehumidification unit.

INTRODUCTION

Energy concerns in the late 1970s led researchers to investigate the possibilities of using desiccant dehumidification systems in residential and commercial air conditioning (Vineyard et al. 2000, 2002). The primary functions of air-conditioning systems are to reduce the humidity of the conditioned airstream (latent cooling) and to lower the temperature of the conditioned airstream (sensible cooling). Conventional air conditioners perform latent and sensible cooling simultaneously by cooling the conditioned airstream to a temperature where sufficient moisture condenses out. Desiccant dehumidification systems, in contrast, can directly remove moisture from the conditioned air without cooling it. It should be noted that the dehumidification process may result in heating the process (conditioned) air. Some additional post-cooling of the dried process air may be required before it can be used for building ventilation. This process allows for separate control

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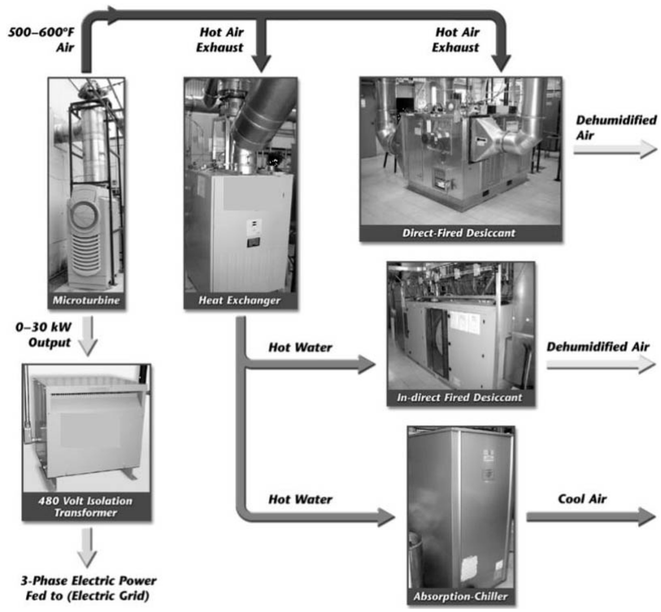

Figure 1 *IES test facility showing components presently under study.*

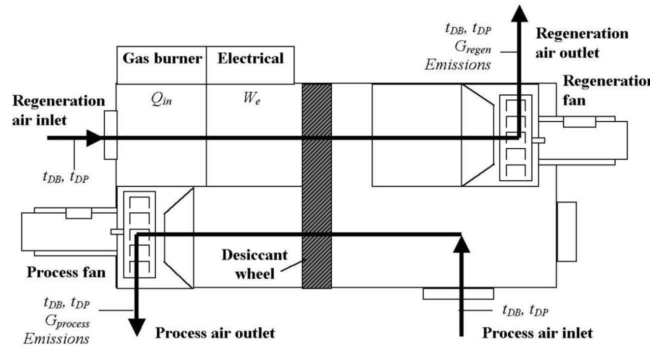

Figure 2 *Schematic diagram of the direct-fired desiccant dehumidification unit (*Q_{in} *= heat input,* t_{DB} *= dry-bulb temperature,* t_{DP} *= dew-point,* $G_{process}$ *= process airflow rate,* G_{regen} *= regeneration air flow rate).*

of humidity and temperature. Factors contributing to the acceptance of the desiccant dehumidification technology include effectiveness in reducing humidity, realization of the need for indoor humidity control, and potential economic benefits (Jalazadeh-Azar et al. 2000). Another motivation has been the implementation of building ventilation rate recommendations (ASHRAE 2001) requiring indoor humidity to be in the range of 50% to 60% to improve indoor air quality by reducing the growth of molds and fungi.

The use of on-site or near-site distributed electric power generation (DG), as part of an integrated energy system (IES), brings waste heat from fuel-fired DG sources close to the end user's thermal loads and permits engineers to substantially improve overall system energy efficiency and fuel economy. Heat-activated technologies such as desiccant dehumidification units are increasingly being viewed as an important element for the effective application of IES designs. However, extensive research and development is still needed in order to implement and accelerate the use of IES in the marketplace. As part of the U.S. Department of Energy's (DOE) research effort, work is being conducted on the performance and operation of a commercially available direct-fired desiccant dehumidification unit as part of an IES (Rizy et al. 2002). Utilizing the waste heat from local power generation yields combined resource efficiencies of 50% or more.

The IES research activity investigated the baseline performance and emissions of a commercially available direct-fired desiccant dehumidification unit over a wide range of conditions in a steady-state operating mode. The desiccant dehumidification unit is part of a flexible IES laboratory test bed (Figure 1) that allows for the connection of basic IES components into various configurations and the study of the characteristics of each component and the overall IES under various operating modes. The desiccant dehumidification unit, shown schematically in Figure 2, consists of a honeycomb desiccant wheel filled with titanium silicate and process and regeneration air circuits. As the process air flows through the desiccant wheel, the moisture that would normally be entering the building is removed from the airstream. The desiccant material is restored to its sorbent (dry) state by exposure to the heated regeneration airstream as the desiccant wheel rotates. After passing through the wheel, the outlet regeneration air is then discharged to the atmosphere.

The DG component of the IES under study includes a 30-kW[1] (102,433 Btu/h) natural gas-fired microturbine and its heat recovery unit (HRU), i.e., an air-to-water heat exchanger. Detailed descriptions of these units are given in earlier publications (Rizy et al. 2002; Petrov et al. 2002a, 2002b).

EXPERIMENTAL SETUP

Figure 2 shows the experimental setup used to collect the baseline performance data on the direct-fired desiccant dehumidification unit. The natural gas flow rate of the unit was monitored by a natural gas test meter equipped with a 0 to 20 in. wc (0 to 0.049 atm) pressure gauge. The desiccant unit is fully instrumented to measure dry-bulb and dew-point temperatures, process and regeneration airflow rates at the outlets, and total electrical power used by the unit. Sensors used for these measurements and associated accuracies are listed in Table 1. The required accuracy of the test instrumentation is in accordance with the ASHRAE Standard 139-1998 (ASHRAE 1998). Measurements for the process and regeneration airstreams include inlet and outlet dry-bulb and dew-point temperatures. Four chilled mirrors were used to measure the

1. The microturbine full-load power output is 28 kW (95,604 Btu/h); 2 kW (6,829 Btu/h) is auxiliary power consumed by the microturbine.

TABLE 1
Instrumentation Used in Direct-Fired Desiccant Dehumidification Unit Tests

Measurement	Sensor	Precision/Accuracy
Temperature	RTD	±0.2°F (±0.1°C) Range -328 to 1,562°F (–200 to 850°C)
Air flow	Fan evaluator*	±2% Range 500 to 5,000 scfm (14.2 to 141.6 m^3/min
Gas flow	Test meter	±0.2% Range 0 to 200 cfh (0 to 5.7 m^3/h)
Dew-point temperature	Chilled mirror	±0.2°F (±0.1°C) Range –40 to 140°F (–40 to 60°C)
Power	Watt transducer	±0.5% of full scale Range 0 to 40 kW (0 to 136,577 Btu/h)

* A multi-point, self-averaging Pitot traverse station with integral air straightener-equalizer honeycomb cell, capable of continuously measuring fan discharges or ducted airflow.

TABLE 2
Direct-Fired Desiccant Dehumidification Unit Test Conditions

Condition number	Process air inlet condition °F (°C)		Regeneration air inlet condition °F (°C)	
	Dry-bulb	Wet-bulb	Dry-bulb	Wet-bulb
1	95.0 (35.0)	75.0 (23.9)	95.0 (35.0)	75.0 (23.9)
2	95.0 (35.0)	76.2 (24.6)	95.0 (35.0)	76.2 (24.6)
3	85.0 (29.4)	75.8 (24.3)	85.0 (29.4)	75.8 (24.3)
4	85.0 (29.4)	78.1 (25.6)	85.0 (29.4)	78.1 (25.6)
5	80.0 (26.7)	67.0 (19.4)	95.0 (35.0)	75.0 (23.9)
6	80.0 (26.7)	67.4 (19.7)	80.0 (26.7)	67.4 (19.7)
7	80.0 (26.7)	75.0 (23.9)	80.0 (26.7)	75.0 (23.9)

dew-point temperatures of the airstreams. From these parameters, the wet-bulb temperatures, enthalpies, humidity ratios, latent capacity (LC), and latent coefficient of performance (LCOP) were calculated.

The inlet dry-bulb temperatures for the process and regeneration sides were maintained at ±1°F (±0.6°C) by using 10 and 30 kW (34,144 and 102,433 Btu/h) heaters, respectively. Dew-point temperatures were maintained at ±0.5°F (±0.3°C) by injecting steam into the inlet sections of the process and regeneration airstreams. Conditions under which the desiccant dehumidification unit was tested are listed in Table 2.

A flue gas analyzer was used to monitor the levels of oxygen (O_2), carbon monoxide (CO), carbon dioxide (CO_2), nitrogen oxides (NO, NO_2, NO_x), and sulfur dioxide (SO_2) from the desiccant dehumidification unit for both the regeneration and process airstreams. Also, it provided a monitor of any potential cross-leakage from the regeneration side to the process side. The accuracy of the emissions measurements is within ±2% of their readings. The detailed description of the emissions monitoring system is given by Petrov et al. (2002a, 2002b).

TEST PROCEDURES

Tests were performed to determine the effects of different air inlet conditions on the LC and LCOP of the direct-fired desiccant dehumidification unit with the gas burner activated (baseline tests). The LC is calculated using the following equation (Sand et al. 2002):

$$Q_{latent} = Q_{total} - Q_{sensible} \qquad (1)$$

where total cooling capacity Q_{total} and sensible cooling capacity $Q_{sensible}$ are as follows:

$$Q_{total} = \rho_{air} \cdot G_{process} \cdot (h_{process\ out} - h_{proccess\ in}) \quad (2)$$

$$Q_{sensible} = C_{pair} \cdot \rho_{air} \cdot G_{process} \cdot (t_{process\ out} - t_{process\ in}) \quad (3)$$

where ρ_{air} is the density of air at standard condition, $G_{process}$ is the volumetric flow rate of process air, $h_{process\ in}$ and $h_{process\ out}$ are the process inlet and outlet enthalpies, C_{pair} is the air heat capacity, and $t_{process\ in}$ and $t_{process\ out}$ are the process inlet and outlet dry-bulb temperatures.

The LCOP, a measure of the desiccant dehumidification unit's efficiency, is calculated by the ratio of the LC to the total energy input (thermal + electrical), including the gas input (based on the higher heating value or HHV of the gas) and electrical parasitics (desiccant wheel motor, fans, electronics, etc.). The tests were performed at the process and regeneration air inlet conditions listed in Table 2. Some of these conditions are listed in ARI Standard 940-98 (ARI 1998) and some were performed to compare with the manufacturer's data. During the tests, the unit was run in a steady-state operating mode (no cycling of the gas burner).

The airflow rates were found to be within the range of 2,700 to 2,850 scfm or 76.5 to 80.7 m^3/min (face velocity 862.6 to 911.2 ft/min or 262.9 to 277.7 m/min) for the process side and 750 to 850 scfm or 21.2 to 24.1 m^3/min for the regeneration side. The desiccant wheel diameter and speed were 2.46 ft (0.75 m) and 8 rph, respectively. The process air-side pressure drop across the wheel was 2.9 in. wc (0.007 atm), and the regeneration air-side pressure drop was 2.5 in. wc (0.006 atm). It should be noted that purge was not used on the desiccant wheel. During the tests the modulating function of the desiccant dehumidification unit that controls the gas input as a function of the regeneration outlet temperature was turned off, so the gas input was almost constant (154,000 to 160,000 Btu/h or 45 to 47 kW). The electrical parasitics were measured to be between 5.6 and 5.8 kW (19,120.8 and 19,803.7 Btu/h).

EXPERIMENTAL RESULTS

The baseline testing of the desiccant dehumidification unit was designed to get background performance information on the unit as it operated under different air inlet conditions. The performance results were used in the next series of testing to compare the overall IES performance (microturbine, heat recovery unit, and desiccant dehumidification unit) with the baseline performance of the desiccant dehumidification unit.

Comparison Between Manufacturer's Test Data and Current Test Results

A comparison of the test data supplied by the manufacturer and the test results produced for the same air inlet conditions is given in Table 3.

As evident from the table, there's relatively good agreement between the LCs provided by manufacturer and the LC produced by the laboratory tests. For the first two air inlet conditions, the LCs for the laboratory tests are within 1% and 5%, respectively, of the manufacturer's data while the LC for the last condition is within 13% of the manufacturer's data. The LCs for the laboratory tests were higher than the manufacturer's LC in the first and third case and slightly lower in the second case. It should be noted that the flow rates in the laboratory tests (*ca.* 2,700 to 2,850 scfm or 76.5 to 80.7 m^3/min) were higher than those reported by the manufacturer (*ca.* 2,400 to 2,500 scfm or 68.0 to 70.8 m^3/min). This resulted in lower process outlet temperatures and could also account for the differences in the LC.

TABLE 3
Comparison Between Manufacturer's Test Data and Laboratory Results

Process inlet test parameters	Process outlet Manufacturer's data				Process outlet Laboratory tests			
	DB °F (°C)	DP °F (°C)	Grains /lb of dry air (/kg of dry air)	LC Btu/h (kW)	DB °F (°C)	DP °F (°C)	Grains /lb of dry air (/kg of dry air)	LC Btu/h (kW)
DB 80°F (26.7°C) WB 67.4°F (19.7°C) DP 61.0°F (16.1°C) Grains 80	119.0 (48.3)	37.5 (3.1)	32.9 (72.5)	80,750.0 (23.6)	116.3 (46.8)	41.5 (5.3)	38.6 (85.1)	80,815.4 (23.7)
DB 85°F (29.4°C) WB 78.1°F (25.6°C) DP 75.8°F (24.3°C) Grains 135	137.0 (58.3)	57.8 (14.3)	71.3 (157.2)	108,460.0 (31.8)	123.9 (51.1)	60.6 (15.9)	79.0 (174.2)	103,246.3 (30.2)
DB 95°F (35.0°C) WB 76.2°F (24.6°C) DP 68.6°F (20.3°C) Grains 105	133.0 (56.1)	53.2 (11.8)	60.2 (132.7)	76,160.0 (22.3)	130.7 (54.8)	52.3 (11.3)	58.2 (128.3)	85,340.6 (25.0)

Notes: DB is the dry-bulb temperature; WB is the wet-bulb temperature; DP is the dew-point temperature; humidity is given in grains; and LC is the latent capacity.

TABLE 4
LC and LCOP Test Results (Direct-Fired Operation)

Process air inlet conditions °F (°C)			LC[1] Btu/h (kW)	LCOP[2] (%)
Dry-bulb	Wet-bulb	Dew-point		
80.0* (26.7)	67.0 (19.4)	60.2 (15.7)	74,110.3 (21.7)	41.9
80.0 (26.7)	67.4 (19.7)	61.0 (16.1)	80,815.4 (23.7)	45.0
95.0 (35.0)	75.0 (23.9)	66.5 (19.2)	81,198.1 (23.8)	46.7
95.0 (35.0)	76.2 (24.6)	68.6 (20.3)	85,340.6 (25.0)	48.9
85.0 (29.4)	75.8 (24.3)	72.4 (22.4)	96,646.6 (28.3)	54.0
80.0 (26.7)	75.0 (23.9)	73.1 (22.8)	99,609.9 (29.2)	55.1
85.0 (29.4)	78.1 (25.6)	75.8 (24.3)	103,246.3 (30.2)	58.0

* Inlet parameters of regeneration air: dry-bulb 95.0°F or 35.0°C and wet-bulb 75.0°F or 23.9°C.
[1] LC is the latent capacity.
[2] LCOP is the latent coefficient of performance (COP).

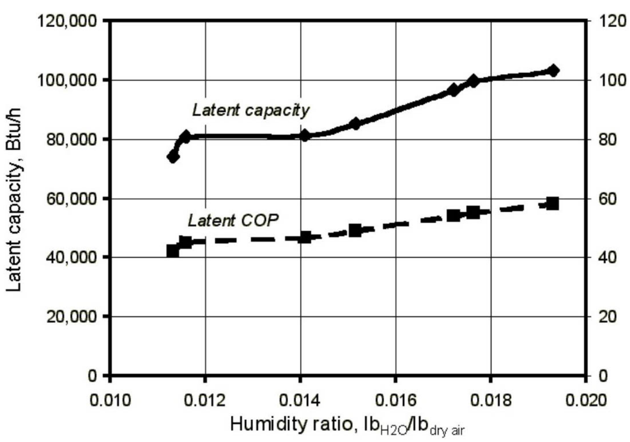

Figure 3 *Latent capacity and latent COP vs. humidity ratio.*

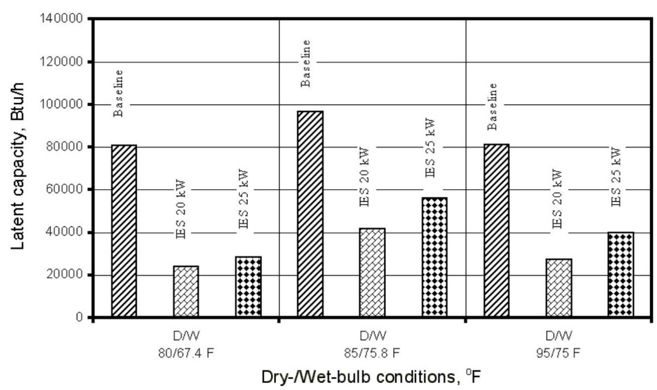

Figure 4 *Comparison between direct-fired and IES-based operation of desiccant unit.*

Effect of Operating Parameters on Latent Capacity and Latent COP

Baseline Direct-Fired Operation. The results of the baseline tests performed on the desiccant unit in the direct-fired mode under the conditions given in Table 2 are presented in Table 4 and Figure 3.

The data show that both the LC and LCOP increase with inlet air dew point while keeping the other parameters constant (gas input and electrical parasitics). The relationship between LC and LCOP versus humidity ratio is plotted in Figure 3 and also shows this increasing trend. Higher LC values at lower dry-bulb air inlet temperature (but at the same wet-bulb temperature) are reported in a previous study of an indirect-fired desiccant unit (Vineyard et al. 2002).

IES-Based Operation. The purpose of these tests was to study the operation of the desiccant dehumidification unit as a part of an IES, consisting of a natural gas-fired microturbine, an air-to-water HRU, and the desiccant dehumidification unit. The objective was to compare the desiccant dehumidification unit's performance as part of the IES against the unit's baseline results when the regeneration air is heated by a natural gas burner. In the IES, the exhaust gas from the microturbine passed through the HRU (where hot water was produced) and entered the regeneration inlet plenum of the direct-fired desiccant unit, where it was mixed with outside air that had the same inlet conditions as the process inlet air to give sufficient volume for the regeneration airstream. Temperature of the exhaust gas at the HRU outlet during these tests was 253.0 to 278.0°F (122.8 to 136.7°C). During the IES series of tests, the gas burner of the desiccant unit was not used and the desiccant unit's performance was evaluated at different microturbine power outputs. It should be noted that due to the high outdoor temperatures during the time of these tests, the microturbine power output (rated full-load power output of 28 kW or 95,604 Btu/h at ISO conditions of 59°F or 15°C at sea level) did not exceed 25 kW or 85,361 Btu/h.

The results for three different process air inlet conditions of Table 4 and two different microturbine power outputs (20

TABLE 5
Latent Capacity Test Results (IES-Based Operation)

Mode of operation	Process/outside air* inlet conditions °F (°C) DB[1]	WB[2]	DP[3]	Regeneration inlet plenum** conditions °F (°C) DB[1]	WB[2]	DP[3]	Latent capacity Btu/h (kW)
Direct-Fired	80.0 (26.7)	67.4 (19.7)	61.0 (16.1)	80.0 (26.7)	67.4 (19.7)	61.0 (16.1)	80,815.4 (23.7)
IES 20 kW				131.5 (55.3)	85.6 (29.8)	69.6 (20.9)	24,038.1 (7.0)
IES 25 kW				150.8 (66.0)	90.8 (32.7)	72.0 (22.2)	28.426.7 (8.3)
Direct-Fired	95.0 (35.0)	75.0 (23.9)	66.5 (19.2)	95.0 (35.0)	75.0 (23.9)	66.5 (19.2)	81,198.1 (23.8)
IES 20 kW				144.0 (62.2)	90.0 (32.2)	73.3 (22.9)	27,436.1 (8.0)
IES 25 kW				167.4 (75.2)	96.0 (35.6)	76.5 (24.7)	39,872.3 (11.7)
Direct-Fired	85.0 (29.4)	75.8 (24.3)	72.4 (22.4)	85.0 (29.4)	75.8 (24.3)	72.4 (22.4)	96,646.6 (28.3)
IES 20 kW				149.3 (66.2)	95.1 (35.1)	81.0 (27.2)	41,862.9 (12.3)
IES 25 kW				168.8 (76.0)	99.6 (37.6)	82.9 (28.3)	56,105.9 (16.4)

* Applicable in IES mode of operation. ** Condition after mixing of exhaust gas with outside air. [1]DB is the dry-bulb temperature. [2]WB is the wet-bulb temperature. [3]DP is the dew-point temperature.

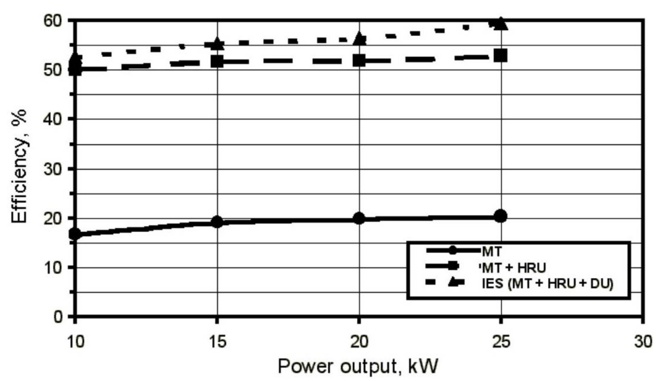

Figure 5 *Efficiencies of microturbine (MT), microturbine and heat recovery unit (MT+HRU), and overall IES (MT+HRU+DU).*

and 25 kW or 68,288 and 85,361 Btu/h) are shown in Table 5 and Figure 4. The test results show that the LC of the desiccant dehumidification unit under baseline conditions is 2.0 to 2.8 times greater than the unit's LC when it is operated with the above-mentioned IES components (microturbine output of 25 kW or 85,361 Btu/h). As expected, a higher microturbine output increases the unit's LC. The maximum LC was observed at the dry-/wet-bulb conditions of 85.0/75.8°F (29.4/24.3°C) and the minimum at 80.0/67.4°F (26.7/19.7°C). The baseline LC of the desiccant unit is 2.5 to 3.4 times greater than that of the IES arrangement when the microturbine power output is reduced by 20% (down to 20 kW or 68,288 Btu/h).

The overall IES efficiency is determined by the ratio of the sum of the electric power output generated by the microturbine, heat recovered by the HRU, and LC of the desiccant dehumidification unit to the total energy input, including the gas input (based on the HHV of the gas) to the microturbine and the electrical parasitics (all the power used by the fans, pumps, and electronics of the microturbine, desiccant, and HRU units). Analysis of the IES efficiency data (95.0/75.0°F or 35.0/23.9°C dry-/wet-bulb process air inlet conditions) indicates that addition of the desiccant unit (DU) into the system increased the overall IES efficiency (as compared to the microturbine + HRU efficiency). Also, the higher the microturbine kW output, the higher both the IES efficiency and the efficiency increment (Figure 5). At 25 kW (85,361 Btu/h) output, the IES efficiency increases by 7% from approximately 53% to 60% (based on the HHV of the natural gas).

Analysis of the test data indicates that the most efficient operation of the direct-fired desiccant dehumidification unit in the IES mode is with 100% of the microturbine's exhaust air through the HRU and with the HRU's outlet exhaust to the desiccant regeneration section. As indicated earlier, the gas burner of the desiccant dehumidification unit is deactivated for the IES mode. Analysis results also showed that the microturbine's 500 scfm or 14.2 m^3/min exhaust flow (at full output) is not sufficient for this direct-fired desiccant unit (900 scfm or 25.5 m^3/min regeneration air flow). A larger microturbine with an exhaust flow rate of at least 900 scfm (25.5 m^3/min) should yield much better results from the desiccant dehumidification unit with a deactivated gas burner.

Emissions Results

The outlets of the regeneration and process airstreams were continuously monitored for pollutants such as carbon monoxide (CO), carbon dioxide (CO_2), nitrogen oxides (NO_x), and sulfur dioxide (SO_2) at all test conditions. The emissions results are given in Table 6.

TABLE 6
Results of Emissions Tests of the Direct-Fired Desiccant Unit

Airstream outlet	Emissions parameters (average and range)				
	O_2,%	CO, ppmV	CO_2,%	NO_x, ppmV	SO_2, ppmV
Regeneration	20.2	13 (9–17)	0.5	1 (0–3)	0
Process	20.8	0	0.0	0	0

The results show that the most significant impurity emissions constituent is CO; the higher CO levels are basically attributed to lower regeneration outlet temperatures. This is in agreement with previous results of the gas microturbine study (Petrov et al. 2002), which showed higher CO emissions at lower combustion temperatures. However, the NO_x formation is minimized at lower combustion temperatures. NO_x and SO_2 levels were below sensitivity limits of the instrument used (reported as zero).

One of the most important findings of the emissions study is that the process airstream seems to be free of pollutants, i.e., there was no significant cross-contamination between process and regeneration airstreams (levels were below sensitivity limits of the instrument used).

CONCLUSIONS

Baseline performance and emissions testing of a commercially available direct-fired desiccant dehumidification unit, which is one of the main components of the IES Integration Laboratory, was conducted at various process and regeneration conditions. The maximum baseline LC and LCOP were found to be 103,246 Btu/h (30 kW) and 0.58, respectively.

In the IES tests, the use of the microturbine exhaust gas (what remains after going through the air-to water heat recovery unit) to drive the desiccant dehumidification unit at maximum microturbine power output results in a 50% decrease in the LC as compared with the desiccant unit's baseline data. However, integration of the desiccant unit into the IES, consisting also of a microturbine and HRU, increases the overall IES efficiency by as much as 7%. This results in an overall IES efficiency of 60%, based on the HHV of the natural gas.

Results of the emissions tests show that CO is the most significant pollutant in the flue gas. The average CO level in the regeneration air out (flue gas) was found to be approximately 13 ppm with a maximum level of 17 ppm. NO_x and SO_2 levels were found to be below the sensitivity limits of the instrumentation used. In addition, no cross-leakage between the process and regeneration sides was apparent from the composition of the process air outlet stream (levels were below sensitivity limits of the instrument used).

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