EFFECT OF MICROTURBINE INLET AIR COOLING AND HUMIDIFICATION ON IES PERFORMANCE

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ABSTRACT

The scope of the Integrated Energy Systems (IES) Program directed by the U.S. Department of Energy (DOE)'s Distributed Energy Program is to provide R&D and testing of distributed generation (DG) combined with thermally-activated technologies (TAT) for waste heat recovery. The goal is to improve the overall performance and efficiency of IES technology and accelerate its use by industry. One of the key parameters that exert an influence on IES performance is ambient inlet air condition. The R&D currently performed at the Oak Ridge National Laboratory's (ORNL) IES Test Laboratory, a National User Facility, is focused on the operational (electrical and thermal) and emissions performance of a 30-kW microturbine generator (MTG)-based IES system. Specifically, this paper addresses the use and effectiveness of MTG inlet cooling and humidification.

Results of testing at the IES Laboratory reveal that, although inlet cooling with and without moisture injection can result in performance improvement in some IES components, there is no overall gain in IES efficiency. In the case of inlet cooling with moisture injection (for humidification), much higher evaporative cooling and subsequently moisture levels is needed at the input of the MTG in order to produce any significant gain in IES performance. However, these increased moisture levels could potentially be harmful to the MTG unit. These tests indicate that inlet cooling is not recommended for this size MTG if the goal is to achieve either IES efficiency gains or reduction of emissions from the MTG exhaust. These findings do not, however, completely rule out inlet cooling for larger microturbines or for other types of distributed generators (i.e., reciprocating engines). Future testing is needed to determine effects of inlet cooling on the performance characteristics of larger microturbines and other generators.

INTRODUCTION

The scope of the Integrated Energy Systems (IES) Program directed by the U.S. Department of Energy (DOE)'s Distributed Energy Program is to provide R&D and testing of distributed generation (DG) combined with thermally-activated technologies (TAT) for waste heat recovery. The goal is to improve the overall performance and efficiency of IES in order to accelerate its implementation in the market place. The R&D currently performed at the Oak Ridge National Laboratory's (ORNL) IES Test Laboratory, a National User Facility, focuses on assessing the operational (electrical and thermal) and emissions performance of current DG and TAT devices operated individually and in combination as part of an IES. The results from the testing are being used to develop and verify mathematical models of the individual DG and TAT devices and to be able to simulate and analyze more extensively IES configurations and operating modes. IES development includes identifying component and system improvements for the "next generation" IES products and applications; supporting projects that are developing packaged IES prototype systems; and providing data and calculation results to support rating and certification standards for IES products.

TEST EQUIPMENT AND PROCEDURES

As expected, one of the key operational parameters influencing IES performance is the environmental operating condition, specifically inlet ambient air temperature [1]. Higher ambient temperatures (usually >15°C or 59°F) have been found to result in lower net electric power output from microturbine generators (MTGs). In order to study the effect of air cooling on the inlet of a 30-kW MTG and subsequently an MTG-based IES System, a number of tests have been performed on the MTG combined with various thermally-activated IES equipment (Figure 1). The IES Test Laboratory has a 30-kW MTG located outside of the building with TAT equipment located inside. An air duct system vents heated exhaust from the MTG to inside the building where it can be directed to various TAT equipments. It should be noted that the MTG uses a recuperator so the exhaust temperature is approximately 500°F (260°C) instead of 1000°F (538°C).

The TAT equipment included: an air-to-water heat recovery unit (HRU) with an average effectiveness of 92%; and a 35-kW (10-ton) LiBr/water hot water-fired (indirect-fired) single-effect absorption chiller (AC) with cooling tower (CT) and air handling unit (AHU). The exhaust gas from the MTG was used to heat water in the HRU; the hot water, in turn, was used to produce chilled water in the AC, and, consequently, cool air in the AHU. The cool air outlet of the AHU was extended to outside of the IES laboratory building where the MTG is located and connected to the cooling chamber installed directly in front of the turbine inlet of the MTG (Figures 2 and 3). The incoming cool air was distributed evenly along the MTG inlet in order to provide adequate cooling for the power electronics of the MTG too. After the cool air inlet tests, the cooling chamber was removed from the MTG inlet and the testing continued with ambient air supplied to the MTG. Since the MTG is located outside the ambient air is a function of the weather's temperature and humidity.

A final environmental condition that was tested involved moisture or steam injection into the gas turbine for efficiency improvement and/or reduction of pollutant emissions as outlined in the literature [2-4]. In order to investigate the effectiveness of this method for IES, special tests were conducted. Prior to these tests, a moisture injection system at the MTG inlet was assembled and calibrated (Figure 3). Six misting nozzles were located circumferentially inside the MTG cooling chamber to provide additional evaporative cooling of the pre-cooled MTG inlet air. The mass flowrate of water through this system at maximum pressure (4 bar, or 60 psi) was 0.29 kg/min (0.63 lb/min), which corresponds to approximately 1.8-2.0% of mass air flowrate.

All the tests were performed at constant hot, chilled, and cooling water flowrates and constant speed of CT fan. The ambient temperature during these tests was nearly constant allowing a direct comparison of results without correction for the ambient temperature. The first series of tests was performed at a constant MTG power output of 20 kW with varying engine speed while changing from cool to ambient air inlet. A second series of tests was performed at maximum available MTG power output (resulting in varying actual power output and constant engine speed). A summary of the test parameters and results are given in Tables 1 and 2. Data readings were recorded at steady-state conditions.

Figure 1. IES Test Arrangement for MTG Inlet Air Cooling/Humidification (the turbine inlet cooling/humidification chamber is removed but is shown below).

Figure 2. General View of the MTG Inlet Air Cooling/Humidification System.

Table 1. The Basic Performance Parameters during MTG Inlet Air Cooling.

Parameter	Constant MTG power output		Constant MTG engine speed	
	Ambient inlet	Cool inlet	Ambient inlet	Cool inlet
Environmental				
Ambient temperature, ^oC (^oF)	31.3 (88.4)	31.3 (88.4)	32.2 (89.9)	30.9 (87.7)
Relative humidity, %	40.4	45.6	39.4	51.4
MTG				
Power Output, kW	20.0	20.0	21.8	25.5
Engine Speed, rpm	92,670.3	87,530.3	95,933.0	95,761.6
Air flow, kg/s (lb/h)	0.250 (1980.3)	0.238 (1,887.0)	0.264 (2,094.3)	0.275 (2,183.6)
Exhaust flow, m^3/min (scfm)	11.6 (410.4)	11.2 (394.9)	11.8 (415.8)	12.7 (447.2)
Air inlet temperature, ^oC (^oF)	33.7 (92.6)	19.5 (67.1)	34.0 (93.2)	19.6 (67.3)
Air inlet RH, %	35.0	81.4	37.0	82.4
Exhaust temperature, ^oC (^oF)	285.9 (546.6)	266.2 (511.2)	293.9 (561.1)	285.5 (545.9)
Natural gas input, kW (Btu/h)	107.7 (367,541.3)	100.4 (342,451.3)	117.0 (399,257.1)	126.0 (430,016.9)
HRU				
Heat recovered, kW (Btu/h)	44.4 (151,627.2)	36.9 (126,063.7)	48.2 (164,520.5)	47.9 (163,508.8)
Heat recovered at AC side, kW (Btu/h)	42.6 (145,248.4)	35.2 (120,087.9)	47.2 (161,090.9)	44.8 (152,927.7)
Hot water flowrate, kg/min (lb/min)	138.9 (306.3)	140.5 (309.7)	138.4 (305.2)	137.7 (303.5)
Inlet hot water temperature, ^oC (^oF)	76.7 (170.0)	72.9 (163.2)	79.6 (175.3)	79.9 (175.9)
Outlet hot water temperature, ^oC (^oF)	81.3 (178.4)	76.8 (170.2)	84.7 (184.4)	84.8 (184.7)
Inlet exhaust gas temperature, ^oC (^oF)	274.3 (525.8)	252.5 (486.5)	283.7 (542.7)	273.1 (523.6)
Outlet exhaust gas temperature, ^oC (^oF)	99.0 (210.2)	94.1 (201.4)	101.6 (214.8)	100.6 (213.0)
AC and AHU				
Cooling capacity at AC side, kW (Btu/h)	30.6 (104,311.3)	28.3 (96,587.2)	31.3 (106,740.6)	32.8 (111,757.2)
Cooling capacity of AC at AHU side, kW (Btu/h)	27.8 (94,721.0)	25.8 (88,087.8)	28.2 (96,386.7)	30.4 (103,808.2)
Chilled water flowrate, l/min (gpm)	104.5 (27.6)	104.9 (27.7)	104.1 (27.5)	104.9 (27.7)
Inlet chilled water temperature, ^oC (^oF)	13.3 (55.9)	15.2 (59.4)	13.3 (55.9)	15.0 (59.0)
Outlet chilled water temperature, ^oC (^oF)	9.1 (48.4)	11.3 (52.4)	8.9 (48.1)	10.5 (50.9)
Total AHU cooling capacity (air side), kW (Btu/h)	24.5 (83,517.9)	23.0 (78,523.8)	23.5 (80,071.7)	27.2 (92,947.3)
Total AHU useful cooling capacity (air side), kW (Btu/h)*	24.5 (83,517.9)	19.5 (66,388.1)	23.5 (80,071.7)	22.4 (76,465.4)
Air inlet (DB) temperature, ^oC (^oF)**	31.3 (88.3)	30.8 (87.5)	31.2 (88.2)	30.6 (87.0)
Air inlet (WB) temperature, ^oC (^oF)**	21.2 (70.2)	21.9 (71.4)	20.9 (69.7)	22.8 (73.0)
Air outlet (DB) temperature, ^oC (^oF)**	17.6 (63.7)	19.2 (66.5)	17.7 (63.8)	19.2 (66.5)
Air outlet (WB) temperature, ^oC (^oF)**	15.9 (60.7)	17.4 (63.4)	16.0 (60.8)	17.7 (63.9)
Air flowrate, m^3/min (scfm)	73.2 (2,584.8)	78.3 (2,764.8)	75.4 (2,662.1)	79.2 (2,796.0)
Electric Consumption				
Total power use, kW	6.7	6.8	6.8	6.8
Efficiencies *(based on the higher heating value (HHV) of natural gas)*				
MTG, %	18.5	19.9	18.6	20.2
MTG+HRU, %	58.7	55.6	58.8	57.3
MTG+HRU+AC, %	44.6	45.6	43.2	44.2
MTG+HRU+AC+AHU, %	38.8	36.8	36.5	36.0
AC COP, %	72.0	80.8	66.3	73.2
Emissions				
CO, ppmV	5	5	60	17
CO_2, ppmV	1.8	1.8	2	1.9
O_2, %	17.9	17.9	17.6	17.6
Excess air, %	516	526	465	484
SO_2, ppmV	0	0	0	0
NO_x, ppmV	37	35	3	3
NO, ppmV	32	31	3	3

**Total AHU useful cooling capacity (air side) = total AHU cooling capacity (air side) – cooling capacity required for MTG inlet air cooling, **DB and WB are =dry bulb and wet bulb temperatures, respectively.*

Table 2. The Basic Performance Parameters during MTG Inlet Air Humidification.

Parameter	Constant MTG power output		Constant MTG engine speed	
	No moisture	0.29 kg/min (0.63 lb/min)	No moisture	0.25 kg/min (0.56 lb/min)
Environmental				
Ambient temperature, ^oC (^oF)	29.6 (85.2)	29.4 (84.9)	29.8 (85.6)	30.0 (86.0)
Relative humidity, %	44.3	45.0	67.3	64.1
MTG				
Power output, kW	20.0	20.0	24.8	25.2
Engine speed, rpm	87,325.5	86,845.0	95,907.1	95,866.6
Air flow, kg/s (lb/h)	0.239 (1,896.6)	0.238 (1,888.8)	0.276 (2,187.2)	0.277 (2,198.0)
Exhaust flow, m^3/min (scfm)	10.6 (374.8)	10.8 (381.5)	12.3 (433.5)	12.2 (430.0)
Air inlet temperature, ^oC (^oF)	17.4 (63.4)	15.4 (59.8)	21.0 (69.8)	18.7 (65.7)
Air inlet RH, %	79.2	97.6	83.5	96.4
Exhaust temperature, ^oC (^oF)	264.3 (507.8)	262.3 (504.1)	286.1 (546.9)	285.3 (545.5)
Natural gas input, kW (Btu/h)	101.5 (346,246.8)	101.1 (344,865.6)	126.0 (430,081.5)	127.3 (434,223.5)
HRU				
Heat recovered, kW (Btu/h)	37.4 (127,496.8)	37.3 (127,431.8)	48.4 (165,125.3)	48.5 (165,341.0)
Heat recovered at AC side, kW (Btu/h)	36.0 (122,773.7)	35.1 (119,857.8)	44.9 (153,293.1)	45.5 (155,291.2)
Hot water flowrate, l/min (gpm)	144.6 (38.2)	144.6 (38.2)	141.6 (37.3)	141.6 (37.4)
Inlet hot water temperature, ^oC (^oF)	72.4 (162.4)	71.9 (161.4)	82.6 (180.6)	81.9 (179.5)
Outlet hot water temperature, ^oC (^oF)	76.2 (169.2)	75.7 (168.2)	87.6 (189.6)	86.9 (188.5)
Inlet exhaust gas temperature, ^oC (^oF)	251.2 (484.2)	249.8 (481.6)	277.1 (530.8)	276.6 (529.9)
Outlet exhaust gas temperature, ^oC (^oF)	93.4 (200.1)	93.1 (199.6)	105.1 (221.1)	104.6 (220.2)
AC and AHU				
Cooling capacity at AC side, kW (Btu/h)	24.8 (84,512.2)	25.5 (86,866.9)	33.0 (112,660.5)	35.0 (119,678.3)
Cooling capacity of AC at AHU side, kW (Btu/h)	22.3 (76,217.1)	22.6 (76,871.7)	30.6 (104,245.1)	32.5 (110,925.7)
Chilled water flowrate, l/min (gpm)	106.4 (28.1)	106.4 (28.1)	104.1 (27.5)	104.1 (27.5)
Inlet chilled water temperature, ^oC (^oF)	12.8 (55.1)	12.8 (55.0)	16.7 (62.0)	15.6 (60.1)
Outlet chilled water temperature, ^oC (^oF)	9.5 (49.1)	9.4 (48.9)	12.1 (53.8)	10.8 (51.5)
Air inlet (DB) temperature, ^oC (^oF)	28.4 (83.1)	28.7 (83.6)	29.5 (85.1)	30.1 (86.2)
Air outlet (DB) temperature, ^oC (^oF)	16.9 (62.4)	16.8 (62.3)	20.6 (69.1)	19.9 (67.8)
Air flowrate, m^3/min (scfm)	75.9 (2,680.8)	75.4 (2,661.3)	77.1 (2,723.7)	76.6 (2,703.9)
Electric Consumption				
Total power use, kW	6.7	6.7	6.8	6.8
Efficiencies *(based on the higher heating value (HHV) of natural gas)*				
MTG, %	19.7	19.8	19.7	19.8
MTG+HRU, %	56.2	56.4	57.2	57.6
MTG+HRU+AC, %	41.8	42.6	44.0	45.4
AC COP, %	68.8	72.8	73.5	77.0
Emissions				
CO, ppmV	5	0	21	18
CO_2, ppmV	1.7	1.8	1.9	1.9
O_2, %	17.6	17.9	17.7	17.6
Excess air, %	544	516	484	473
SO_2, ppmV	0	3	0	4
NO_x, ppmV	35	35	0	0
NO, ppmV	31	31	0	0

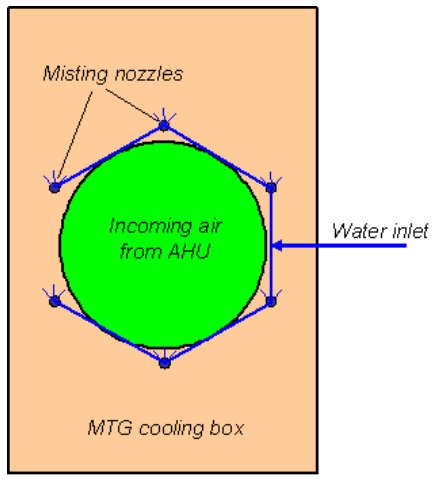

Figure 3. Diagram of Moisture Injection System at the MTG Inlet.

The test instrumentations and their precisions are given in Table 3.

Table 3: Instrumentation Used in IES Tests.

Parameter	Instrumentation	Range	Precision
Temperature	RTD	-200 to 850°C (-328 to 1,562°F)	±0.1°C (±0.2°F)
Air flow	Fan evaluator	14.2 to 141.6 m^3/min (500 to 5,000 scfm)	±2%
Water flow	Flow meter	0 to 0.38 m^3/min (0 to 100 gpm)	±1%
Natural gas flow	Pulse count test meter	0 to 11.8 m^3/h (0 to 415 cf/h)	±0.2%
Natural gas pressure	Pressure transducer	0 to 49.77 kPa (0 to 15 in wc)	±0.5% of full scale
Dew-point temperature	Chilled mirror	-40 to 60°C (-40 to 140°F)	±0.1°C (±0.2°F)
Relative humidity	Humidity sensor	0 to 100% RH	±3%
Power	Watt transducer	0 to 40 kW	±0.5% of full scale

The heat recovered by the HRU or cooling capacity produced by the AC (Q_w) is defined as:

$$Q_w = C_{pw} \cdot \rho_w \cdot G_w \cdot \Delta t_w \quad (1),$$

where ρ_w is the density of water at the average temperature; G_w is the volumetric flow rate of hot or chilled water; C_{pw} is the water heat capacity at the average temperature; and

Δt_w is the difference in temperature between the input and output hot water of the HRU or AC. The uncertainty in Q_w determination is approximately ± 3.3%.

The total cooling capacity of the AHU (Q_{AHU}) is defined as:

$$Q_{AHU} = \rho_{air} \cdot G_{air} \cdot \Delta h_{air} \quad (2),$$

where ρ_{air} is the density of air at standard condition; G_{air} is the volumetric flow rate of air through the AHU; and Δh_{air} is the difference in enthalpies of input and output air of the AHU. The enthalpies are determined from the corresponding dry- and wet-bulb air temperatures. The uncertainty in Q_{AHU} determination is approximately ± 4.4%.

The main advantage of the IES Laboratory facility is the capability to study the operation of various IES combinations of individual DG and TAT units. The various IES arrangements, include:

1. MTG (electric power only with no heat recovery),
2. MTG+HRU (electric power and hot water by recovery of the MTG exhaust heat),
3. MTG+HRU+AC (electric power and chilled water),
4. MTG+HRU+AC+AHU (electric power and cool air).

The efficiencies for each of these IES combinations were calculated based on the higher heating value (HHV) of natural gas using the Equations (3)-(6).

The MTG efficiency is defined as:

$$E_{MTG} = (W_e/Q_{in\ HHV}) \cdot 100, \% \quad (3),$$

where W_e is the net electric power generated by the MTG and $Q_{in\ HHV}$ is the gas input. The uncertainty in E_{MTG} determination is approximately ± 1.0%.

The MTG+HRU efficiency, which is the IES efficiency consisting of the MTG and HRU, is defined as:

$$E_{MTG+HRU} = (W_e + Q_{HRU})/(Q_{in\ HHV} + W_{par}) \cdot 100, \% \quad (4),$$

where Q_{HRU} is the heat recovered by the HRU and W_{par} is the parasitic electric power consumed by the HRU and the HRU booster pump. The uncertainty in $E_{MTG+HRU}$ determination is approximately ± 2.2%.

The MTG+HRU+AC efficiency, which is the IES efficiency consisting of the MTG, HRU, and AC, is defined as:

$$E_{MTG+HRU+AC} = (W_e + Q_{AC})/(Q_{in\ HHV} + W_{par}) \cdot 100, \% \quad (5),$$

where Q_{AC} is the AC cooling capacity and W_{par} is the parasitic electric power consumed by the HRU, AC, CT, and pumps. The uncertainty in $E_{MTG+HRU+AC}$ determination is approximately ± 2.2%.

The MTG+HRU+AC+AHU efficiency, which is the total IES efficiency consisting of the MTG, HRU, AC, and AHU, is defined as:

$$E_{MTG+HRU+AC+AHU} = (W_e + Q_{AHU})/(Q_{in\ HHV} + W_{par}) \cdot 100, \% \quad (6),$$

where Q_{AHU} is the AHU cooling capacity and W_{par} is the total parasitic electric power consumed by the IES. The uncertainty in $E_{MTG+HRU+AC+AHU}$ determination is approximately ± 2.9%.

In all these calculations the equal energy value of electric, thermal, chilled and cooling power output is assumed. Thus, to convert kW to Btu/h, the conversion factor of 3412.14 (Btu/h)/kW was used.

The coefficient of performance (COP) of the AC, a measure of the AC efficiency, was calculated using the following equation:

$$COP_{AC} = (Q_{AC} / Q_{HRU\ (AC)}) \cdot 100, \% \quad (7),$$

where $Q_{HRU\ (AC)}$ is the heat supplied by the HRU to the AC. It should be noted that this value may be 2-7% less than the heat recovered by the HRU due to heat losses in the water distribution loop from the HRU to the AC. The uncertainty in COP_{AC} determination is approximately ± 6.1%.

DISCUSSION OF RESULTS

The test results of the IES performance with MTG inlet air cooling and humidification at two different modes - constant MTG power output and constant engine speed (maximum output) - are discussed below.

MTG Inlet Air Cooling Tests

Constant MTG Power Output. The cooling of the MTG air inlet temperature from 33.7°C (92.6°F) to 19.5°C (67.1°F), which also increased the inlet relative humidity from 35 to 81.4%, as shown in Figure 4, resulted in an ~5,000 rpm or 5.5% decrease in MTG engine speed and no change in MTG power (Figure 5). In addition, this resulted in a decrease in natural gas consumption and a 1.4% increase in MTG efficiency from 18.5 to 19.9% (Figure 6). This also resulted in a 6.9% and 4.9% reduction in the MTG and HRU exhaust gas temperatures (Table 1 and Figure 7), respectively, and a decrease in the HRU heat recovery (Figure 8) and temperature of hot water supplied to the AC (Figure 7) by approximately 7.4 kW (25,160 Btu/h) and 4.5°C (8°F) respectively. The reduction in the HRU heat "outweighs" the positive effect of the reduction in the MTG fuel consumption, and results in a MTG+HRU efficiency of ~3% lower then as compared to the case of

operating the IES with no inlet cooling, i.e. ambient air inlet of 33.7°C or 92.6°F (Figure 6). But the resulting AC chilled capacity with the cool MTG air is only 2.3 kW (7,700 Btu/h) lower than the similar parameter for the ambient air inlet (Figure 8). This is apparently due to the increase in air flow rate through the AHU during inlet air cooling tests (78.3 m^3/min or 2,765 scfm) as compared to the ambient air inlet tests (73.2 m^3/min or 2,585 scfm) as a result of additional driving force created by the MTG air compressor. The AC COP with the MTG inlet air cooling (80.8%) is almost 9% higher than that with the ambient MTG inlet (Figure 6). This is due to the higher chilled water temperature leaving the AC unit.

Regarding the overall IES efficiency (production of electricity and cool air), it should be noted that in the case of inlet air cooling, the total cooling produced by the AHU should be divided into space cooling and MTG inlet air cooling (Figure 9). The split used for MTG inlet air cooling was 16% of the AHU total air flowrate. There was slight improvement in efficiencies with the exception of the MTG+HRU+AC+AHU which decreased from 38.8 to 36.8%. In addition, inlet air cooling did not result in any significant change in the concentration of exhaust gas emissions. There was only slight reduction in NO_x and NO which decreased from 37 to 35 and 32 to 31 ppmV, respectively

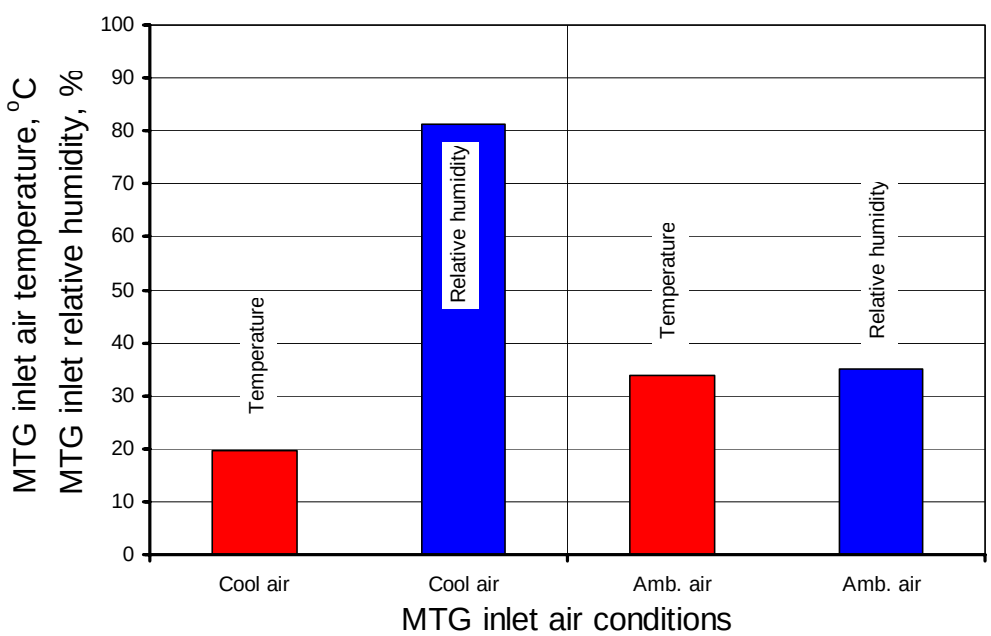

Figure 4. Constant MTG Power Output: MTG Inlet Air Temperature and Relative Humidity with and without Inlet Air Cooling (see Table 1).

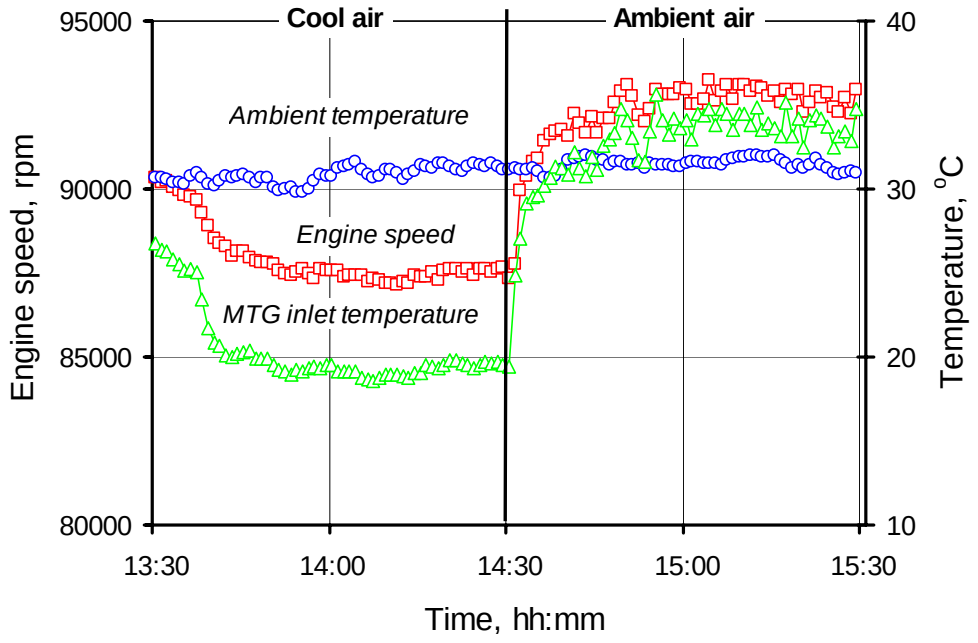

Figure 5. Constant MTG Power Output: Dynamic Change in MTG Engine Speed and Ambient and MTG Air Inlet Temperature with Time.

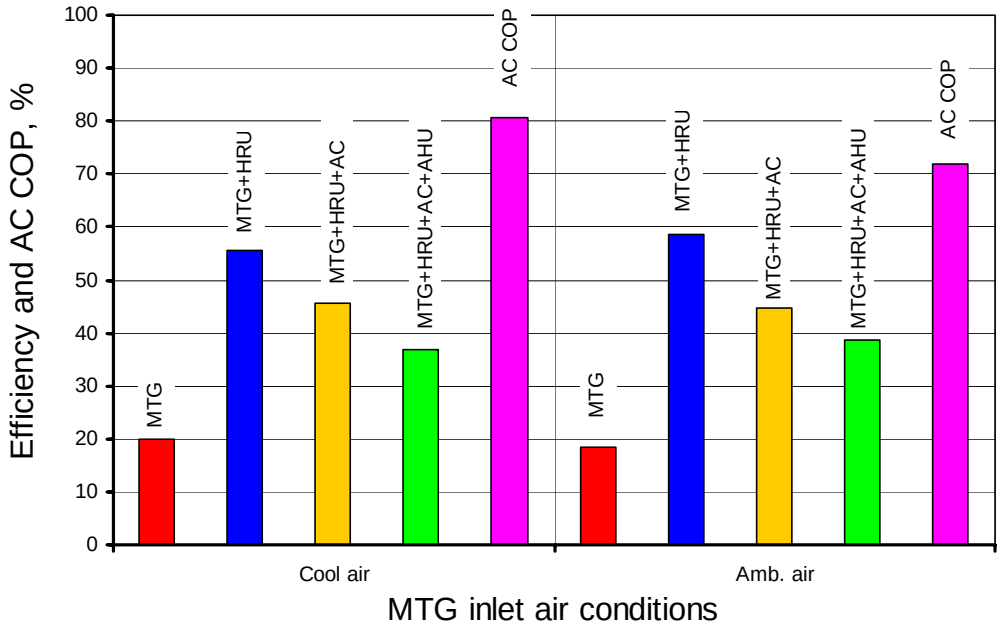

Figure 6. Constant MTG Power Output Tests: Efficiencies of the Different IES Arrangements and COP of the AC with and without Inlet Air Cooling (see Table 1).

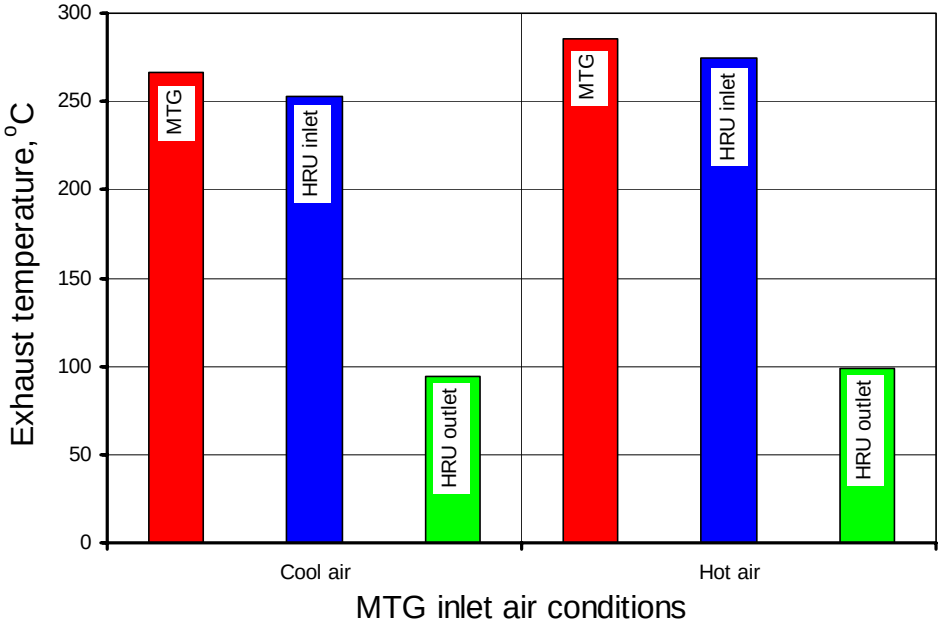

Figure 7. Constant MTG Power Output: MTG and HRU Exhaust Temperatures with and without Inlet Air Cooling (see Table 1).

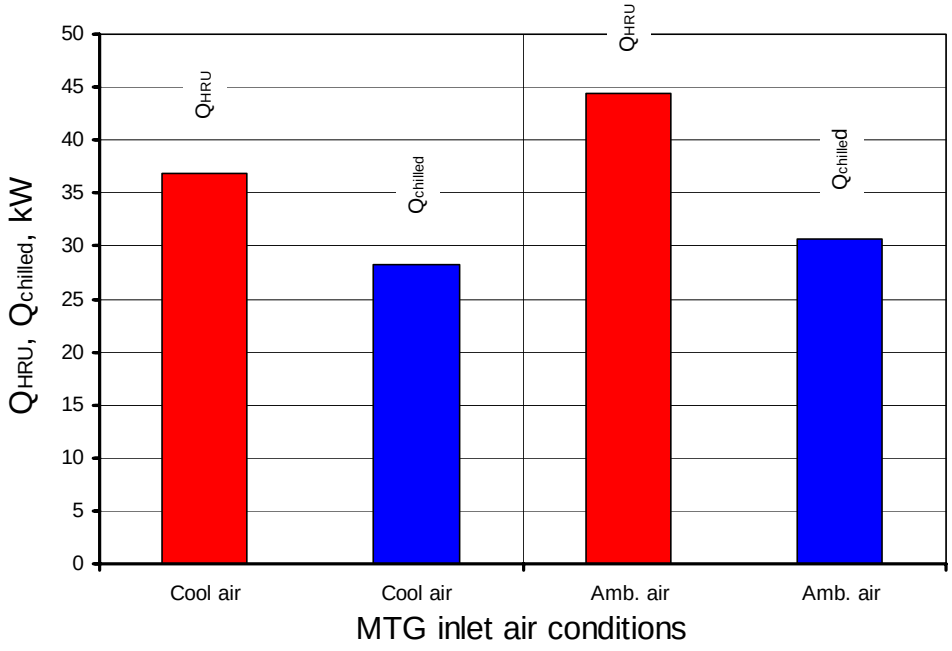

Figure 8. Constant MTG Power Output Tests: HRU and AC Capacities with and without Inlet Air Cooling (see Table 1).

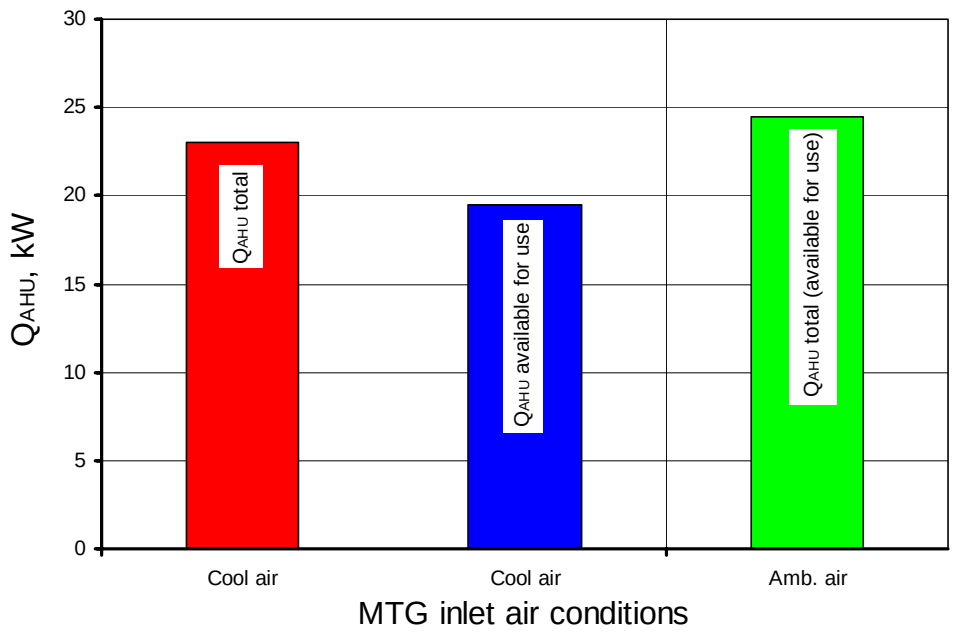

Figure 9. Constant MTG Power Output: AHU Air Cooling Capacity with and without Inlet Air Cooling (see Table 1).

Constant MTG Engine Speed (Maximum Power Output). The cooling of the MTG air inlet from 34.0°C (93.2°F) to 19.6°C (67.3°F) along with increasing the inlet relative humidity from 37 to 82.4% (Figure 10) resulted in an MTG power output increase of ~3.7 kW (Figure 11). It also resulted in an MTG efficiency increase from 18.6 to 20.2% (Figure 12) and in a drastic decrease in CO emissions from 60 to 17 ppmV (Figure 13). Regarding operation of the separate thermally-activated components and IES as a whole, it should be noted that introduction of cool air at the turbine inlet did not result in any significant change in system parameters. There was no significant change in heat recovery of the HRU (Figure 14); however, the MTG exhaust (or HRU inlet) gas temperature was lowered by ~8.4°C, or 15.2°F during the inlet air cooling operation (Figure 15). But this decrease was much smaller than constant electric power output case, and it was compensated by an increase in the MTG exhaust flow. The MTG electrical efficiency increased by 1.6% (from 21.8 to 25.5 kW). However, the overall IES efficiency did not change significantly (36.5 to 36.0%) given the same energy value for electric power and thermal output.

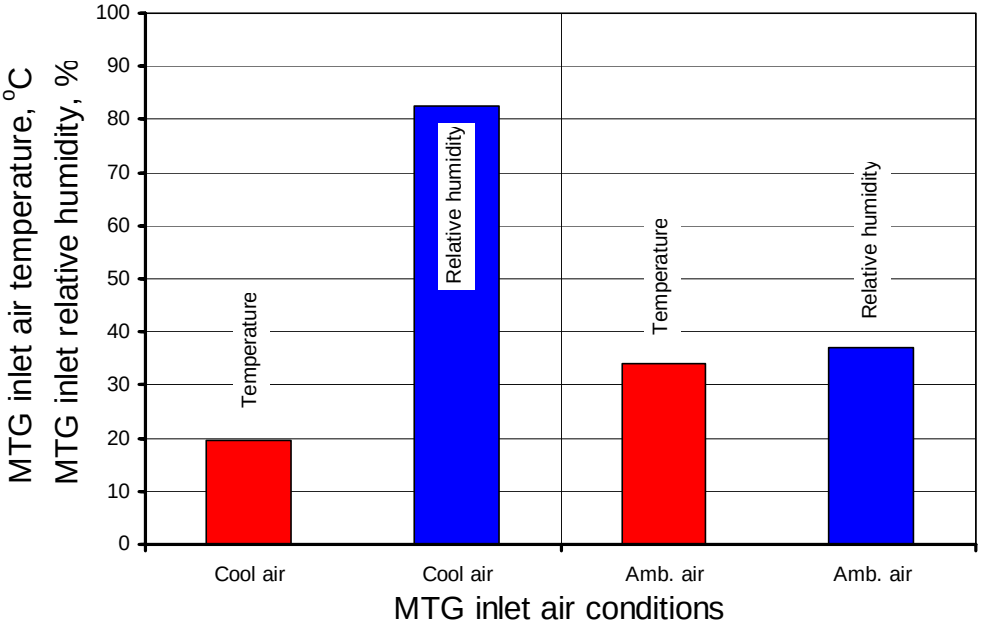

Figure 10. Constant MTG Engine Speed: MTG Inlet Air Temperature and Relative Humidity with and without Inlet Air Cooling (see Table 1).

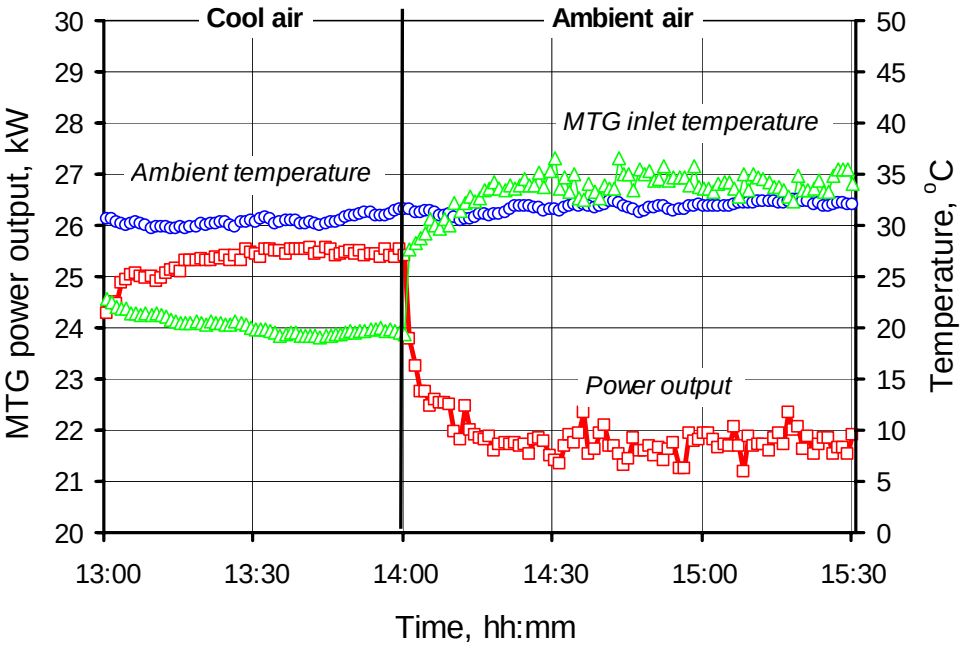

Figure 11. Constant MTG Engine Speed: Dynamic Change in the MTG Power Output and Ambient and MTG Air Inlet Temperature with Time.

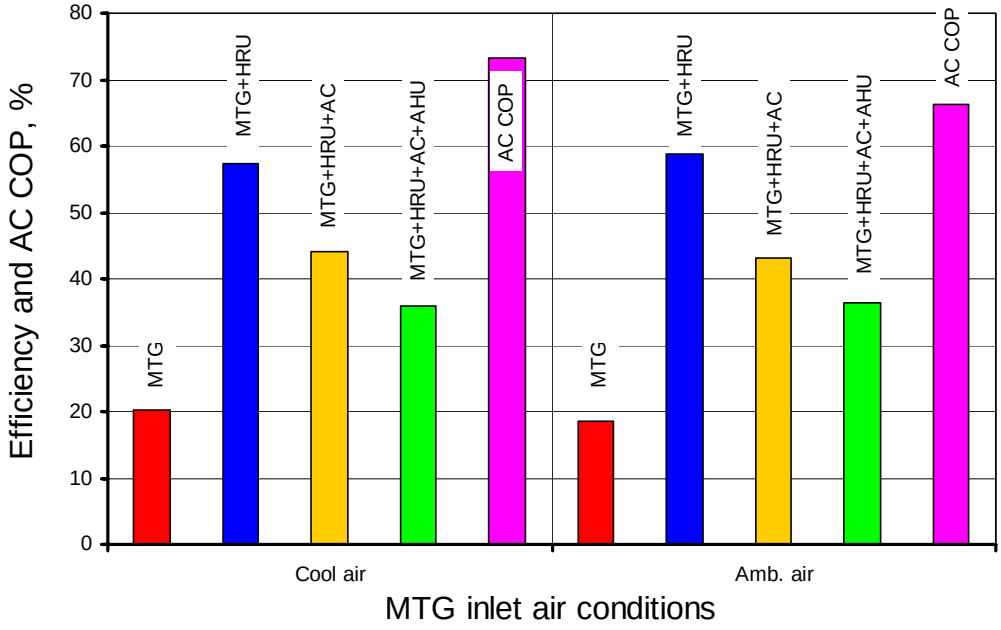

Figure 12. Constant MTG Engine Speed: Efficiencies of the Different IES Arrangements and AC COP with and without Inlet Air Cooling (see Table 1).

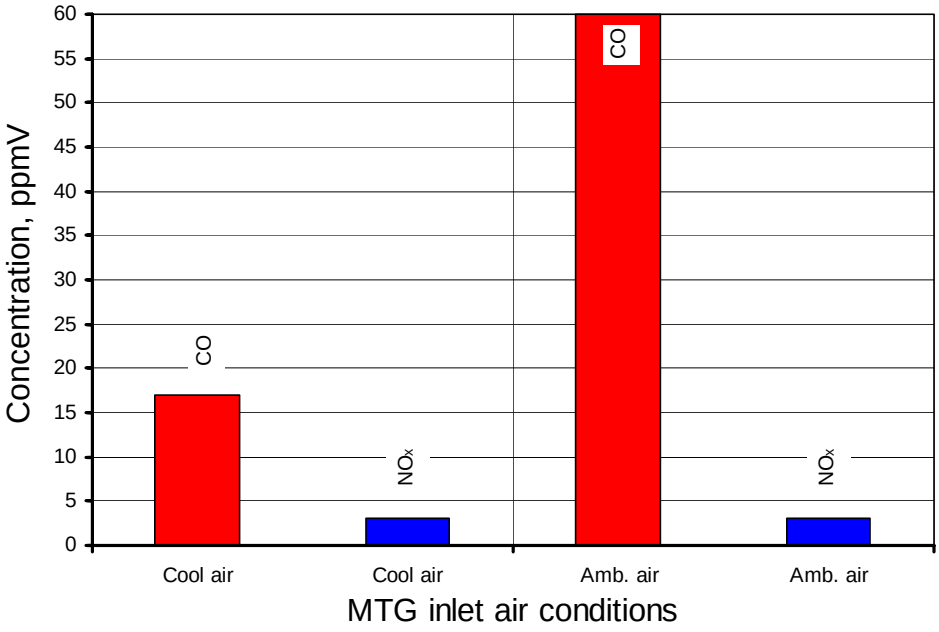

Figure 13. Constant MTG Engine Speed: CO and NO_x Emission Levels in MTG Exhaust Gas with and without Inlet Air Cooling (see Table 1).

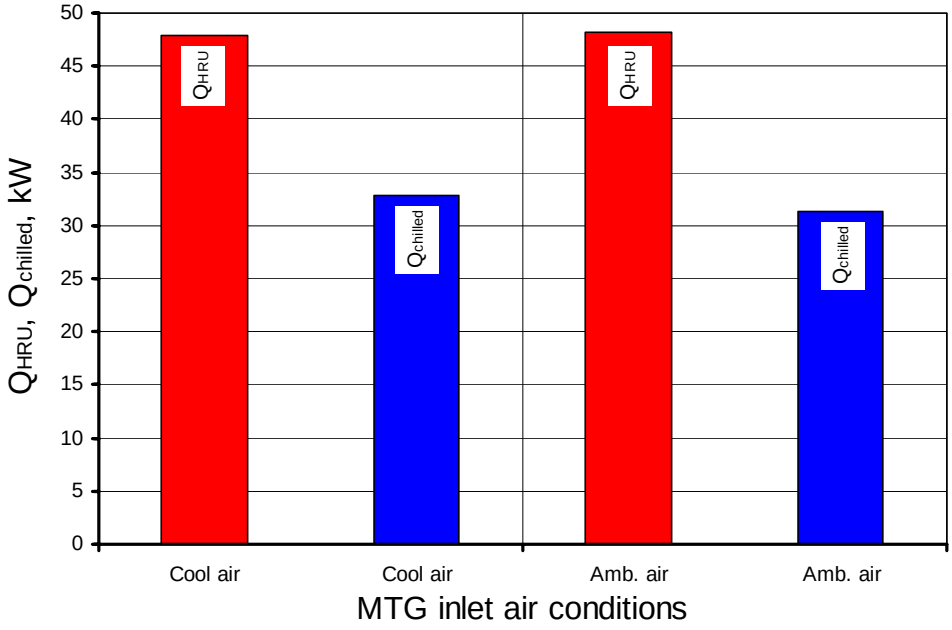

Figure 14. Constant MTG Engine Speed: HRU and AC Capacities with and without Inlet Air Cooling (see Table 1).

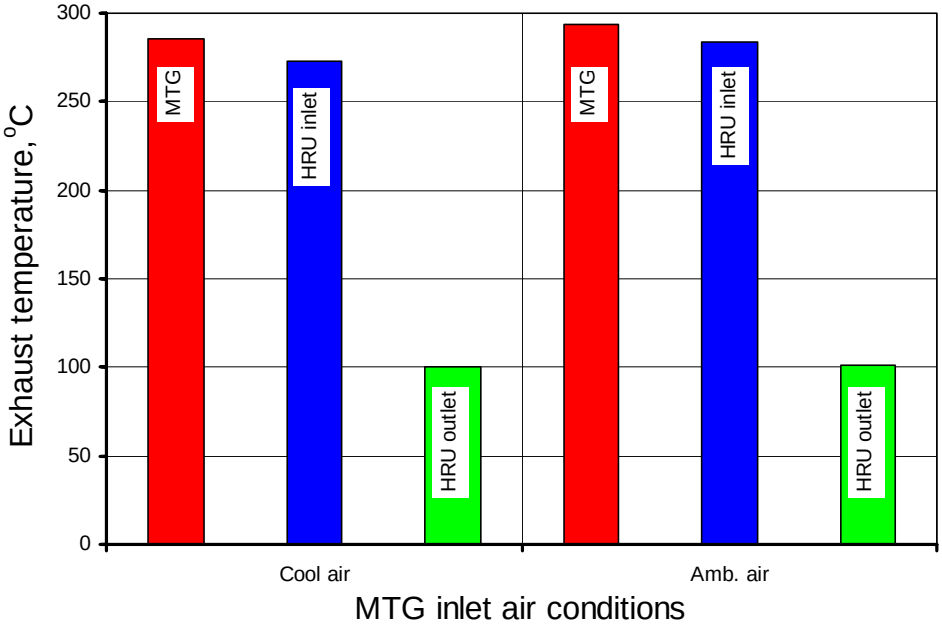

Figure 15. Constant MTG Engine Speed: MTG and HRU Exhaust Temperatures with and without Inlet Air Cooling (see Table 1).

MTG Inlet Air Humidification Tests

The first series of evaporative cooling tests (Table 2) was performed with the MTG held at a constant power output of 20 kW while operating without and with moisture injection at the MTG air inlet. A second series of tests (constant MTG engine speed) was conducted at maximum available MTG power output (~25 kW). In these tests the following evaporate cooling conditions were investigated: 0 and 0.25 kg/min (0.56 lb/min) of injected moisture flowrate. The inlet air to the MTG was pre-cooled upstream by the AC and AHU.

There was no major IES performance gains found in these tests during which there was a decrease in MTG air inlet temperature and an increase in inlet relative humidity during moisture injection. The MTG power output only varied slightly during the constant MTG engine speed test (increased 0.4 kW) as shown in Figure 16, while the MTG, MTG+HRU and MTG+HRU+AC efficiencies in both test series did not change significantly (Table 2, Figures 17 and 18).

Regarding the emissions, the only significant change was the decrease in CO (from 21 to 18 ppmV) during the constant engine speed test when the MTG power output increased .

The tests reveal that inlet air humidification does not improve MTG performance as well as the inlet air cooling. To obtain the same inlet temperature drop as was achieved with inlet air cooling, much higher moisture levels at the MTG inlet would be needed. However, such an increase in amount of moisture could be harmful to the operation of the MTG.

CONCLUSIONS

The series of tests at the IES Laboratory reveal that, although inlet cooling with and without moisture injection can result in performance improvement in some IES components (i.e., MTG efficiency and AC COP), there is no significant gain in overall IES efficiency. In fact with MTG inlet air cooling, the IES efficiency of the MTG+HRU+AC+AHU decreased slightly for both the constant MTG power output and constant MTG engine speed cases from that of ambient inlet air. The major reasons for the significant efficiency improvements are: (1) a decrease in heat available for recovery from the MTG due to its lower exhaust temperature with inlet cooling, and (2) a need to divert a portion of the cool air (parasitic) from the AHU to MTG inlet. In the case of inlet cooling with moisture injection (for humidification), much higher evaporative cooling is needed to produce any significant gain in IES performance. In order to achieve the same performance improvements as achieved by inlet cooling without moisture injection, a significant increase in the moisture levels entering the MTG would be required. However, these increased moisture levels could potentially be harmful to the operation of the MTG unit. These series of tests indicate that inlet air cooling is not recommended for the IES if the goal is to achieve efficiency gains (First-Law Efficiency) or reduce MTG exhaust emissions. However, it isn't completely evident that inlet air

cooling can be ruled out for larger MTG or for other types of DG. Future testing will need to be conducted in order to determine the effect of inlet cooling on performance characteristics of larger MTG-based IES or IES using other types of DG.

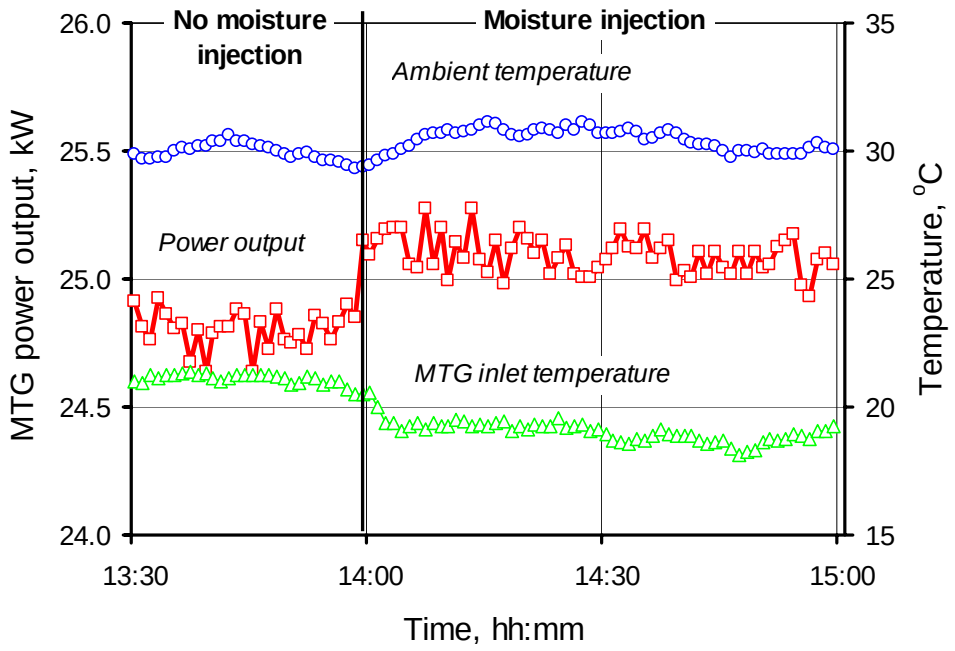

Figure 16. Constant MTG Engine Speed: Dynamic Change in the MTG Power Output, Ambient and MTG Air Inlet Temperature with Time.

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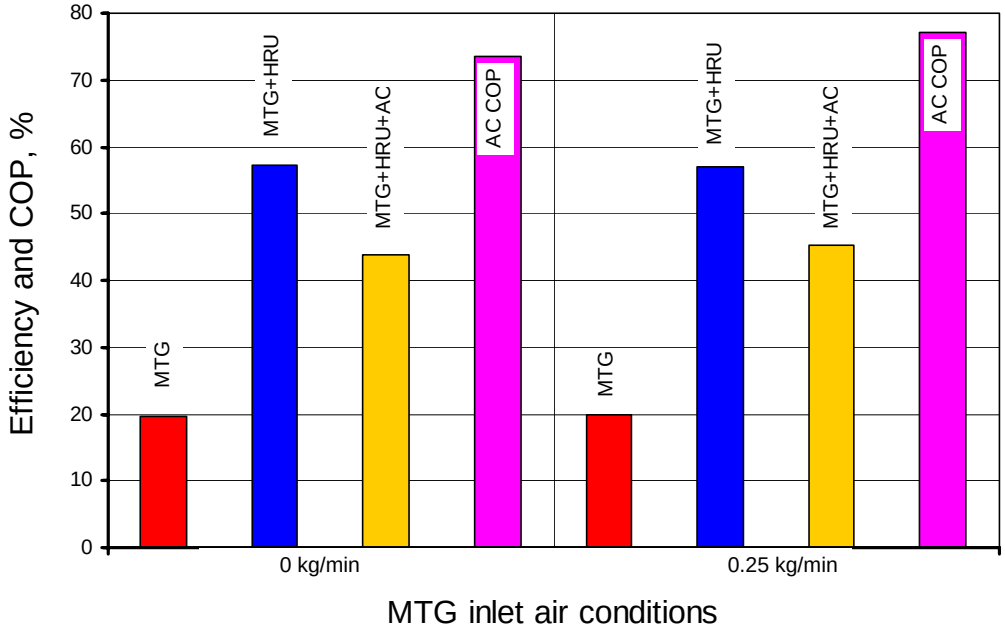

Figure 17. Constant MTG Engine Speed: Efficiencies of Different IES Arrangements and COP of AC at Different Inlet Moisture Levels (see Table 2).

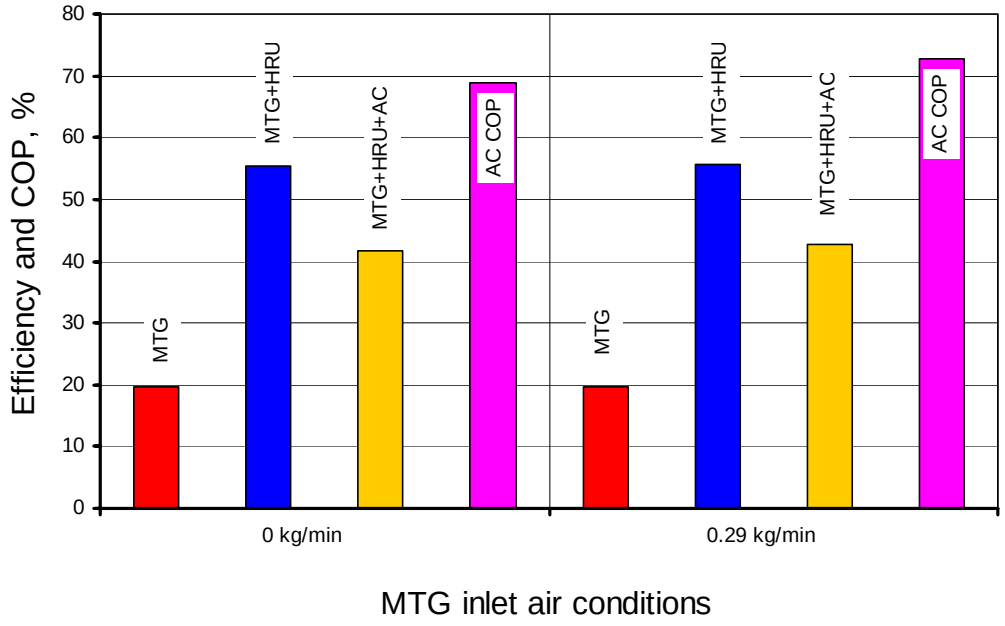

Figure 18. Constant MTG Power Output: Efficiencies of the Different IES Arrangements and COP of AC at Different Inlet Moisture Levels (see Table 2).

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