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LABORATORY R&D ON INTEGRATED ENERGY SYSTEMS (IES)

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ABSTRACT

The goal of the Integrated Energy Systems (IES) Program launched in 1999 by the U.S. Department of Energy (DOE) is to provide R&D and testing of distributed generation (DG) with thermally-activated (TA) technologies for waste heat recovery and improved overall efficiency. An example of an IES is the combination of onsite microturbine generation with heat recovery, HVAC, desiccant, and absorption chiller units. IES, in conjunction with other new energy efficient building technologies, will maximize the efficiency of energy use, reduce harmful emissions to the environment, improve power quality and reliability and provide flexibility for meeting electric power peak load demands as compared with large central power plants. The R&D performed at the Oak Ridge National Laboratory's (ORNL) IES Test Laboratory, a National User Facility, focuses on assessing the operational and emissions performance of current DG and TA technologies operated individually and in combination as an IES; developing and verifying mathematical models of the individual devices and IES; and developing test protocols and contributing to standards development for assessing current IES technologies.

The IES Test Laboratory is flexible in the configuration of DG (presently a 30-kW natural gas-fired microturbine generator) with various heat recovery units (presently an air-to-water heat recovery unit or HRU, direct- and indirect-fired desiccant dehumidification systems, and an indirect-fired single-effect absorption chiller). The exhaust gas from the microturbine generator (MTG) is used to drive the HRU and/or used directly in the direct-fired desiccant dehumidification unit. The hot air and hot water flows from the HRU can be controlled and directed via automated damper controls in order to test various IES configurations and operating modes.

The IES testing results produced so far show that the operating parameters and efficiencies of the overall system and individual devices depend on loading (electric and thermal), as well as on ambient weather conditions (temperature and humidity levels). Outdoor temperature is a major factor since the MTG is located outside and no attempt is currently being made to adjust its inlet air temperature, i.e., air cooling from the TA units. Under certain operating conditions and combinations of IES, the efficiency of the overall system can be as high as 55% (based on higher heating value of the natural gas and including all the parasitics).

INTRODUCTION

The problems caused by electric energy deregulation in the United States and other developed countries have created an important opportunity for distributed energy technologies (Popovic *et al.*, 2002; Fairchild *et al.*, 2001). In the report prepared in 2001 by the National Energy Policy Development Group, the concept of Combined Cooling, Heating and Power (CHP), now currently know as Integrated Energy Systems (IES), is identified as a strategy for addressing increased energy demands and peak power issues (NEP Report, 2001). Recent developments in distributed generation (DG) technologies have opened new opportunities for relatively small-scale IES that can be used in commercial buildings. DG in combination with thermally-activated (TA) technologies, which use waste heat directly for heating purposes or thermally-driven desiccant dehumidification and absorption cooling, provide important opportunities for IES to be a viable technology for buildings (Popovic *et al.*, 2002; Labinov *et al.*, 2002).

Microturbine generator (MTG) technology, as a prime mover, currently represents 250 kW or smaller sized units that have efficiencies of 25% or lower (including parasitic losses). In order to increase overall efficiency above

50%, the MTG has to be combined with waste heat recovery technology like thermally-activated desiccant systems and absorption technology (Popovic *et al*., 2002).

A DOE laboratory for testing IES was commissioned two years ago at ORNL and last summer the IES Test Laboratory was designated a "National User Facility". This designation provides industry with greater access and control of various IES testing at the laboratory as well as collaboration with government R&D efforts. The scope of the facility is to test DG in combination with TA technologies for optimum waste heat recovery and overall energy efficiency. The objectives of the laboratory include:

- collection of performance data on current DG and TA technologies both individually and operated as an integral part of an IES,
- development of models of the individual devices and verification of an IES model based on integrated operation,
- development of performance ratings for IES and the rating of current technologies by testing, and
- development of testing protocols and standards for assessing current IES technologies.

The goal of the IES program is to increase the overall energy efficiency of DG systems by integrating them with waste heat recovery and TA technologies. The TA systems use the DG's hot exhaust gas (by-product of power generation) to produce heating, cooling and/or to regenerate desiccant material used by dehumidification systems.

The IES Test Laboratory is a flexible configuration set-up of the DG unit with various heat recovery systems (Figure 1). The exhaust gas from the DG can either be used directly and/or routed to an air-to-water heat exchanger (also referred to as a heat recovery unit or HRU). The exhaust gas and water flows from the HRU can be varied and directed via automated damper controls to test various IES configurations and operating modes. The IES Test Laboratory is concluding the testing of a 30 kW MTG with a first generation HRU, direct and indirect-fired desiccant dehumidification systems and an indirect-fired 10-ton (120,000 Btu/h or 35-kW) single-effect absorption chiller. The MTG has been operated individually as well as integrated with various waste heat recovery configurations. Although, the current configuration at the IES Test Laboratory only includes MTG-based IES; it could be extended to encompass many other DG systems such as reciprocating engines and fuel cells.

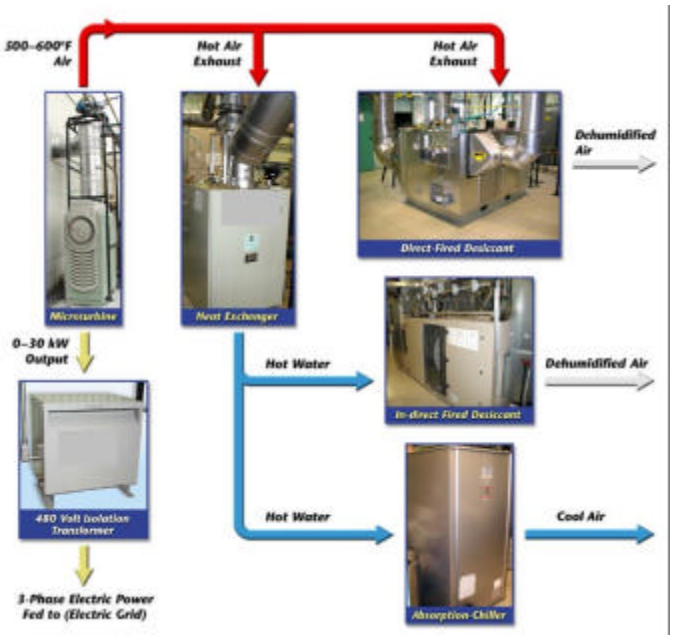

Figure 1 - IES Test Laboratory at Oak Ridge National Laboratory

1 TEST EQUIPMENT

The heat recovery components used with the MTG in this study consist of an air-to-water HRU, a direct-fired desiccant dehumidification system (DFDD), and a single-effect lithium bromide-water (LiBr-water) absorption chiller (AC). An air duct network from the MTG exhaust to the HRU and/or to the DFDD, a water loop from the HRU to the AC, and a mixing chamber leading to the air duct network (for mixing outside air with exhaust air) provide for flexible testing of various waste heat recovery conditions and loadings. The mixing chamber achieves two objectives: providing a greater volume of air and lowering of the temperature of the exhaust stream from the MTG.

The MTG, which is located on the outside of the IES Test Laboratory's building, is a three-phase 480 VAC/30 kW rated unit that can operate at 50 or 60 Hz and at ~unity power factor when connected to the electric power grid. The natural gas microturbine and the electric generator are on the same shaft. The MTG, which is designed to operate at a maximum speed of 96,000 rpm, produces high-frequency AC power that is rectified to DC and converted to 50 or 60-Hz AC power by the power conditioning electronics of the digital power controller (Rizy *et al.*, 2002).

In the IES mode, the MTG's exhaust gas which has a temperature of ~275°C (~527°F) is directed indoors to the heat recovery components. The MTG's exhaust passes through the HRU and leaves it at a temperature of ~124°C (~255°F). The exhaust gas from the HRU is used to regenerate the desiccant materials in the DFDD unit. The maximum rate of the water flow through the HRU is ~0.10 m^3/min (26 gpm) at a maximum temperature of 82.2°C (180°F). The temperature depends on several parameters like MTG load, ambient temperature, HRU water flowrate, *etc.* The hot water from HRU is directed to the generator of the AC.

2 TEST PROCEDURES

Previous tests at the IES Test Laboratory (Petrov *et al.*, 2003) have shown the effect of ambient temperature on IES performance. The current series of tests studied the effect of ambient temperature on cooling capacity (Q_{chw}) and coefficient of performance (COP) of the AC, and overall IES (MTG+HRU+AC) efficiency. The tests were performed at a constant MTG power output of 20 kW. This power setting was selected because it could be held constant over a wide range of ambient temperatures of 17.2 to 30.0°C (63 to 86°F). The hot water flow rate from the HRU and cooling water flow rate from the cooling tower (CT) were 0.15 m^3/min (39.8 gpm) and 0.28 m^3/min (74 gpm), respectively. The chilled water flow rate from the evaporator varied from 0.07 to 0.13 m^3/min (19 to 34 gpm).

In addition, the effect of combining the DFDD to the IES was also investigated. The tests were performed at the dry/wet bulb air inlet conditions of 29.4/24.3°C or 85/75.8°F and 35.0/23.9°C or 95/75°F (ARI, 1998) at constant ambient temperature. The other parameters, MTG power output, hot water, cooling water, and chilled water flow rates, were held constant. The exhaust gas from the MTG (flow rate of 11.33-14.16 m^3/min or 400-500 scfm) passed through the HRU and then entered the regeneration inlet plenum of the DFDD, where it mixed with the outside air to get a sufficient volume of -25.49 m^3/min (~900 scfm) for the regeneration air stream. The air flow rates of the DFDD were found to be within the range of 92.60 to 94.58 m^3/min 3,270 to 3,340 scfm (face velocity 318.4-325.3 m/min or 1,044.7-1,067.1 ft/min) for the process side and 25.63-25.77 m^3/min or 905-910 scfm (face velocity 88.1-88.6 m/min or 289.1-290.7 ft/min) for the regeneration side.

The AC cooling capacity (Q_{chw}) is defined as:

$$Q_{chw} = C_{Pw} \cdot r_w \cdot G_{chw} \cdot \left(t_{chw_in} - t_{chw_out}\right) \tag{1}$$

where $?_w$ is the density of water at the average temperature; G_{chw} is the volumetric flow rate of chilled water; C_{pw} is the water heat capacity at the average temperature; and t_{chw_in} and t_{chw_out} are the chilled water temperatures entering and leaving the AC.

The DFDD latent capacity (LC) is calculated using the following equation:

$$Q_{latent} = Q_{total} - Q_{sensible} \tag{2}$$

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

$$Q_{total} = r_{air} \cdot G_{process} \cdot \left(h_{process\ out} - h_{process\ in}\right) \tag{3}$$

$$Q_{sensible} = C_{P(air)} \cdot r_{air} \cdot G_{process} \cdot \left(t_{process\ out} - t_{process\ in}\right) \tag{4}$$

where $?_{air}$ 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; $C_{p(air)}$ is the air heat capacity; and $t_{process\ in}$ and $t_{process\ out}$ are the process inlet and outlet dry-bulb temperatures.

The test instrumentation and their measurement accuracies are given in Table 1.

Table 1: Instrumentation Used in IES Tests

Measurement	Instrumentation	Precision/Accuracy
Temperature	RTD	±0.1°C (±0.2°F) Range -200 to 850°C (-328 to 1,562°F)
Water flow	Flow meter	±1% Range 0 to 0.38 m^3/min (0 to 100 gpm)
Gas flow	Test meter	±0.2% Range 0 to 5.7 m^3/h (0 to 200 cf/h)
Dew-point temperature	Chilled mirror	±0.1°C (±0.2°F) Range -40 to 60°C (-40 to 140°F)
Power	Watt transducer	±0.5% of full scale Range 0 to 40 kW (0 to 136,577 Btu/h)

3 DISCUSSION

3.1 Effect of Ambient Temperature on Absorption Chiller (AC) Performance

The effect of ambient temperature on the temperature of exhaust gas entering and leaving the HRU (T_{eg}) and the AC cooling capacity (Q_{chw}) is shown in Figures 2 and 3. Q_{chw} increased with ambient temperature from approximately 19 kW (65,000 Btu/h) at 17.2°C (63°F) to over 26 kW (90,000 Btu/h) at 30°C (86°F). It should be noted that increased ambient temperature results in lower MTG efficiency and higher exhaust heat available for recovery (Figure 2). This in turn results in higher heat input to the AC unit. Since the AC is only operating at part load, higher heat input results in higher capacity and COP. This indicates that IES can follow the building cooling load. Figures 2 and 3 show the nearly linear dependence of T_{eg} and Q_{chw} with ambient temperature. In addition, the test results show increasing cooling capacity with increasing G_{chw}. Due to the design features of the first generation HRU (recently replaced with a second generation version), the maximum heating capacity produced was around 37.9 to 40.8 kW (130,000 to 140,000 Btu/h). This heat output was not enough to drive the AC at full rated load of 35 kW (120,000 Btu/h) of cooling. In order to achieve the full load, the AC needs a heat input of ~50 kW (172,000 Btu/h). It is anticipated that the second-generation HRU, which has double the surface area, will produce enough hot water to drive the AC at full load. This modification was made to the HRU by the manufacturer based in part by the backpressure testing at the IES Test Laboratory, which showed minimal effect on the performance of the MTG up to 0.02 atm (8”wc). The second-generation HRU unit is expected to improve its efficiency as well as the overall IES system efficiency.

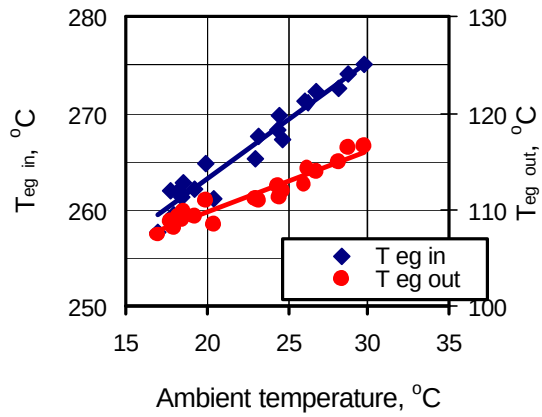

Figure 2 – Effect of Ambient Temperature on the Temperature of Exhaust Gas Entering ($T_{eg\ in}$) and Leaving ($T_{eg\ out}$) the Heat Recovery Unit

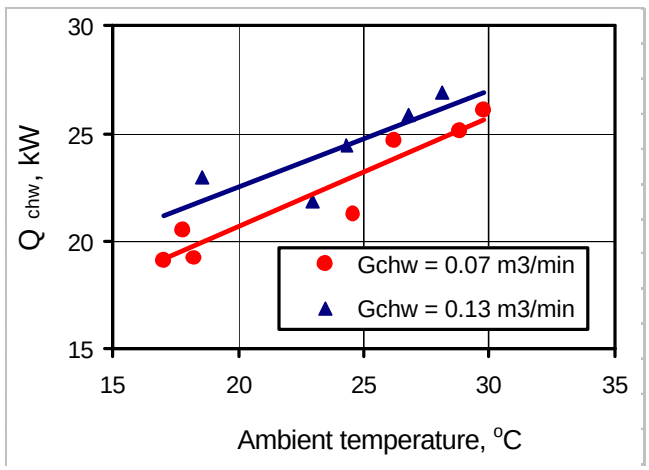

Figure 3 – Effect of Ambient Temperature on Cooling Capacity (Q_{chw}) of the Absorption Chiller (entering chilled water temperature is 17-30 °C (53-62 °F))

The effect of ambient temperature on IES efficiency for various IES configurations as well as the coefficient of performance (COP) of the AC are shown in Figures 4 and 5. The various IES modes include: MTG (producing electric power only), MTG+HRU (producing power and heating), MTG+HRU+AC (producing power and cooling). These parameters were calculated using the following equations:

MTG efficiency based on higher heating value (HHV) of natural gas was defined as:

$$E_{MTG} = (W_e/Q_{in\ HHV}) \cdot 100,\ \% \tag{5}$$

where W_e is the net electric power generated by the MTG and $Q_{in\ HHV}$ is the gas input (based on the HHV).

Efficiency of the IES system consisting of the MTG and HRU was defined as:

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

where Q_{HRU} is the heat recovered by the HRU and W_{HRU} is the electric power consumed by the HRU including the booster pump.

Efficiency of the overall IES system consisting of the MTG, HRU, and AC was defined as:

$$E_{MTG+HRU+AC} = (W_e + Q_{chw})/(Q_{in\ HHV} + W_{total}) \cdot 100, \% \quad (7)$$

where Q_{chw} as indicated above is the AC cooling capacity and W_{total} is the total electric power consumed by the HRU, AC, CT, and pumps.

COP of the AC was defined as:

$$COP = (Q_{chw}/Q_{HRU\ (AC)}) \cdot 100, \% \quad (8)$$

where $Q_{HRU\ (AC)}$ is the heat supplied by the HRU to the AC. It should be noted that this value may be 5-10% less than the heat recovered by the HRU due to heat losses in the water loop from the HRU to the AC.

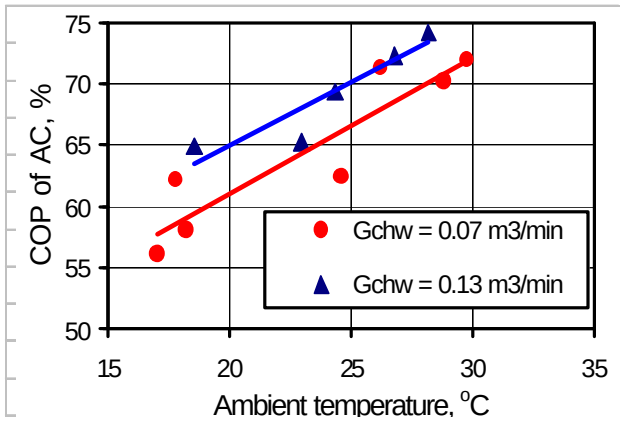

Figure 4 – Effect of Ambient Temperature on COP of Absorption Chiller (AC) (entering chilled water temperature is 17-30 °C (53-62 °F))

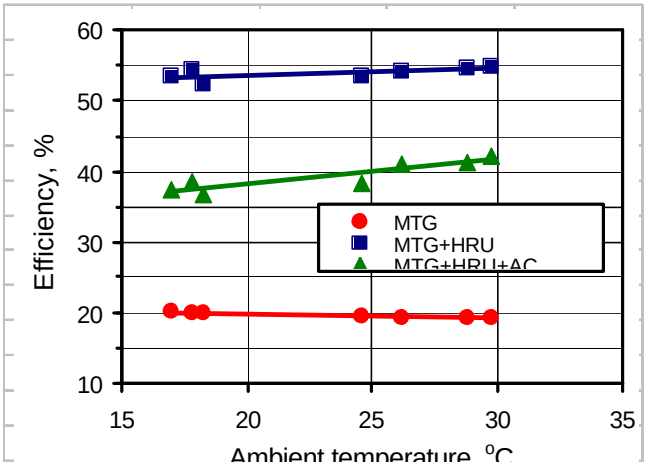

Figure 5 – Effect of Ambient Temperature on the Efficiency of Different IES Configurations

Results indicate that the COP of the AC increases with ambient temperature over the range of temperatures studied (Figure 4). The COP increased with ambient temperature from ~57 to 72% at the chilled water flow rate of 0.07 m^3/min (19 gpm). Increasing the chilled water flow rate from 0.07 to 0.13 m^3/min (19 to 34 gpm) resulted in a 3 to

4% increase in the COP. However, it should be noted that the COP was calculated based on the heat input from the HRU only without consideration of the increased parasitics to achieve this higher flow rate.

Figure 5 shows the ambient temperature-dependent comparison of operational IES efficiencies for different IES configurations. It is evident that the minimum efficiency (18-20%) is attributed to the electric power generation only, and the maximum is due to the combined production of electric power and heating (53-55%). Use of the heat generated by the HRU to drive the AC incidentally reduces the efficiency down to 37 to 42%. Therefore, the only way to increase the efficiency of the whole IES system is to maximize the use of the heat recovered by the HRU and to utilize the remaining heat of exhaust gas in other waste-heat driven equipments like the DFDD. This is discussed in section 3.2. Figure 5 shows that, in spite of a decrease in efficiency with ambient temperature of the MTG, the efficiencies of the IES as a whole increases with ambient temperature. This is especially noticeable for the MTG+HRU+AC efficiency (increases by 4.5 to 5%) and is due to the relatively sharp rate of the AC COP increase with ambient temperature (Figure 4).

The tests show that a change in the chilled water flow rate from 0.07 to 0.13 m^3/min (19 to 34 gpm) has practically no effect on the overall IES efficiency. Only a 0.5 to 0.8% average increase in the overall IES efficiency was observed. Taking into account that this difference in efficiency is within the overall experimental error of these measurements, and these two flow rates represent minimum and maximum permissible boundary conditions for the AC operation, it concluded that the overall IES efficiency over the ambient temperature range studied lies between 37 and 42%.

3.2 IES Performance with the Addition of the Direct-Fired Desiccant Dehumidifier (DFDD)

In these series of tests, two IES configurations were investigated: MTG+HRU+AC and MTG+HRU+AC+DFDD. In order to normalize the effect of ambient temperature on the comparison of performance characteristics of these two configurations, the tests were performed at the same ambient temperature. Table 2 lists the major test and performance parameters that were measured.

Table 2: Measured Performance Parameters of the IES with the Desiccant Dehumidifier.

Dry/wet bulb DFDD temperature, ^oC (^oF)	29.4/24.3 (85/75.8)	35.0/23.9 (95/75)
Ambient temperature, ^oC (^oF)	29.5 (85.1)	30.4 (86.7)
MTG net power, kW (Btu/h)	22.9 (78,457.7)	21.7 (74,456.1)
HRU heat capacity, kW (Btu/h)	40.9 (140,067.2)	41.3 (141,622.2)
AC cooling capacity, kW (Btu/h)	26.6 (91,054.0)	28.1 (96,271.1)
DFDD latent capacity, kW (Btu/h)	10.5 (36,107.4)	7.4 (25,388.1)
AC chilled water flow rate, m^3/min (gpm)	0.105 (27.7)	0.104 (27.6)
HRU hot water flow rate, m^3/min (gpm)	0.144 (38.0)	0.143 (37.9)

It is important to note that the activation of the DFDD regeneration fan (forced MTG exhaust gas through the HRU) did not change the quantity of heat recovered by the HRU as compared with the case without the DFDD: the difference was within 0.9 to 1.0%.

The efficiencies of the different IES configurations were calculated using Equations (5)-(7) above. With the addition of the DFDD, the overall IES efficiency was calculated as:

$$E_{MTG+HRU+AC+DFDD} = (W_e + Q_{chw} + Q_{latent})/(Q_{in\ HHV} + W_{total}) \cdot 100, \% \quad (9)$$

where W_{total} is the total electric power consumed by the HRU, AC, DFDD, CT, and pumps.

Figure 6 shows a comparison of the different IES efficiencies. The addition of the DFDD increased the overall IES efficiency by 5 to 7%. It should be noted that the IES efficiency with the DFDD depends not only on ambient temperature, but also on dry/wet bulb temperatures (dew-point, humidity ratio), with all other parameters constant. Previous tests (Petrov *et al.*, 2003) have shown that the latent capacity (LC) and latent COP (LCOP) of the DFDD depend on dew-point, or humidity ratio, of the incoming air: both LC and LCOP increase with these parameters. In this particular case the dew-point for the 29.4/24.3°C condition was 22.4°C (72.4°F), and 19.2°C (66.5°F) for the 35.0/23.9°C condition. As seen in Table 2, the LC of the DFDD for the 22.4°C dew-point condition was much higher than that for the 19.2°C dew-point inlet air.

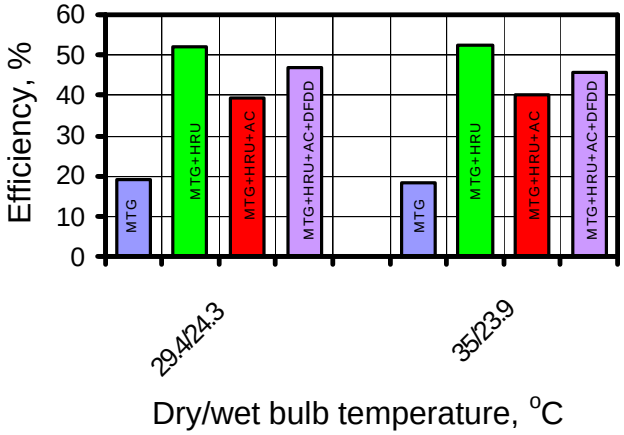

Figure 6 – Efficiencies of Different IES Configurations at Various Dry/Wet Bulb Conditions

CONCLUSIONS

Performance testing of several configurations of an MTG-based IES were conducted at the IES Test Laboratory. The final configuration consisted of a MTG, HRU, AC, and DFDD. The major objective of these tests was to determine the effect of ambient temperature on the different IES configurations. Test results show that in spite of the decrease in the MTG's efficiency with ambient temperature, the efficiencies of the IES configurations (MTG+HRU and MTG+HRU+AC) increased with ambient temperature. However, the addition of the AC to IES reduced the maximum overall efficiency from 55% (MTG+HRU) to 42% (MTG+HRU+AC). But some improvement in the overall efficiency (5-7%) could be achieved by the addition of the DFDD to the system although it is still slightly less than the MT+HRU configuration.

There are several ways to increase the overall efficiency of the MTG-based IES: (1) maximize the use of the heat recovered in the HRU; (2) minimize heat losses from the HRU by reducing the length of the hot water loop and the exhaust ducting system; (3) use part of the cool air produced by the AC to provide inlet air cooling to the MTG; and (4) use a larger MTG to better match the regeneration air flow rate of the DFDD. These will be subjects for future tests.

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RESUME

Le but du programme Système d'Energie Intégré (IES), lancé dans les années 1999 par le Département de L'énergie (DOE) aux Etats-Unis, est de fournir la recherche et développement (R&D) et de tester la génération distribuée (DG) avec les technologies d'activation thermique (TA) pour la récupération des pertes de chaleur et l'amélioration du rendement global. Un exemple d'IES est la combinaison sur place de microturbine de génération avec le rétablissement de chaleur, ventilateur et air conditionné, dessiccateur, et les unités d'absorption de chiller. IES, conjointement avec d'autres nouvelles technologies de construction, a pour but d'améliorer la qualité, la fiabilité et l'efficacité énergétique, réduire les émissions nuisibles à l'environnement, et de pourvoir les demandes des pics de surcharges électriques comparé au grande centrale électrique. Les études de recherches et développements, menées au Laboratoire National d'Oak Ridge (ORNL) et à IES (Laboratoire de Test), sont focalisées i) sur l'évaluation des performances opérationnelles et d'émissions de la génération distribuée actuelle et les technologies d'activation thermique, opérés individuellement et en association avec les IES; ii) le développement et la vérification des modèles mathématiques des appareils individuels et des IES; et iii) le développement des protocoles de tests et contribuer au développement de normes pour évaluer les technologies actuelles des IES.

Le laboratoire test des IES est flexible dans la configuration de génération distribuée (en ce moment à 30-kW pour le générateur microturbine au gaz naturel) avec les diverses unités de récupération de chaleur (en ce moment une unité de récupération de chaleur air-eau ou HRU, système central direct et indirect de dessiccation-dehumidification, et un système central à effet unique d'absorption chiller). Le gaz d'échappement du générateur de microturbine (MTG) est utilisé pour conduire le HRU et/ou utilisé directement dans l'unité de centrale de dehumidification dessiccation. L'air et l'eau chaude du HRU peuvent être variés et dirigés vers les contrôleurs d'amortisseur automatisés afin de tester les diverses configurations des IES et les modes opératoires.

Les résultats d'essai des IES produits jusqu'à ce jour montrent que les paramètres opératoires et l'efficacité du système général et des dispositifs individuels dépendent de la surcharge (électrique et thermique), de même que des conditions climatiques (la température extérieurs et les niveaux d'humidité). La température extérieure est un facteur majeur du fait que le MTG est localisé à l'extérieur et actuellement aucune tentative n'a été faite pour ajuster la température d'arrivée d'air, c.-à-d., refroidissement de l'air depuis les unités de TA. Sous certaines conditions opératoires, en association avec les IES, l'efficacité du système général peut atteindre 55% (basé sur une valeur de chauffage plus élevée que gaz naturel y compris tout les parasites).