Cogeneration Performance Testing

University Turbine System Research (UTSR)
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Introduction

FlexEnergy's new generation microturbine, GT333S, is designed to primarily target two major market industries: Oil and Gas (O&G) and Combined Heat and Power (CHP) [1]. For O&G application, GT333S outputs 333kW power at 33% efficiency on an ISO day (59°F or 15°C, sea level, 60% relative humidity) based on the lower heating value (LHV) fuel [1]. Once integrated with hot water cogeneration system, GT333S has also shown major advantage in heat recovery rate at onsite power generation [1]. The main objective during the fellowship was to conduct several performance tests on GT333S, especially on a unit with CHP installation.

The United States and many European governments encourage various CHP incentives; it is challenging for FlexEnergy to meet or exceed such requirements. For example, California's Self-Generation Incentive Program (SGIP), EU Cogen Directive, and Public Utility Regulatory Policies Act (PURPA) require efficiency of 60% (HHV), 75% (LHV), and 42.5% (LHV), respectively.

During the fellowship period, following performance testing of GT333S cogeneration were accomplished:

1. Performance update with high ambient temperatures
2. Effect of shutting off the water during the open damper system on water temperature

The two assignments were performed on a newly-designed 12-row cogeneration heat exchanger installed at FlexEnergy facility in Portsmouth, NH. This large cogeneration system is capable of passing high water flow rates at 225 gallons per minute, having higher efficiency than those of previous generation system.

In addition to the cogeneration heat exchanger work, two other thermodynamic cycle studies were performed on possible innovations to the recuperated gas turbine cycle. Due to the proprietary nature of these studies, they will not be presented herein. Moreover, extensive work was performed on improving the modeling of the recuperator heat exchanger, including testing. These results are also proprietary.

1. Performance Update

From June 8 to July 19 of 2016, 60 cogeneration performance data were collected at FlexEnergy's Test Facility Station 6 (running time from 2537hrs to 2710hrs). Each day, two or three cogen performance points were taken. The ambient temperature (T1) varies from 76.5°F to 108.1°F, typical summer days in New Hampshire.

The performance update is based on predictions for the 12-row copper heat exchanger (HX) model from the HX manufacturer. To evaluate each performance points, the FlexEnergy thermodynamic cycle prediction tool was run at each of the test conditions. The model of the hot water HX was calibrated to match the manufacturer's specification. This permitted the measured heat recovery ($Q_{,\text{ measured}}$) to be compared with the expected heat recovery ($Q_{,\text{expected}}$). As shown in Figure 1, actual heat recovery was within 2% of the required heat recovery %.

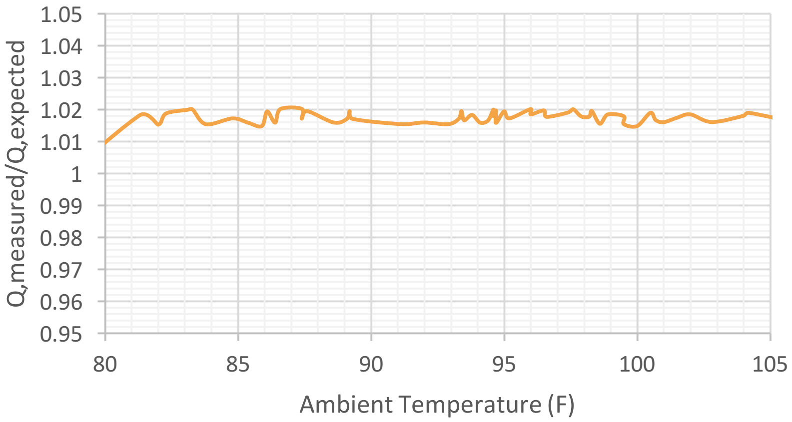

Figure 1. Normalized heat recovery as a function of ambient temperature

For this performance update, EU Cogen Directive efficiency was focused since it is the hardest requirement of 75% LHV. To calculate the EU Cogen Directive overall efficiency, following equation is used:

$$\eta_{\mathrm{EU}} = \frac{(\text{Electrical Power} + \text{Heat Recovery})}{\text{Fuel Energy}}$$

Note that all the efficiencies described in the study are based on LHV, not HHV. In Table 1, ambient temperatures were broken into three categories. It is evident that the electrical efficiency decreased by 1% for every 10°F rise. Efficiency for EU Cogen was dropped as well, but very slightly compared to the electrical one, passing the qualification.

Table 1. Summary of efficiencies, categorized by 10°F ambient temperatures.

Ambient Temperature, T_1	**T Range$_1$**	**T Range$_1$ + 10°F**	**T Range$_1$ + 20°F**
$\eta_{LHV,\ average,\ measured}$	30.6%	29.7%	28.9%
η_{EU}	83.4%	83.1%	82.9%

The reason for such electrical efficiency drop is that work on the compressor gets large for hot summer days and leads to the less power generation. Work of turbine is mostly consumed by the compressor, about 60%, and rest of work is for electrical generation. Work on the compressor is defined as:

$$W_{comp} = m \cdot C_p \cdot (T_3 - T_2)$$

where $(T_3 - T_2)$ represents the temperature difference across the compressor. Assuming an isentropic compressor, the ratio of temperatures is determined as following:

$$\frac{T_3}{T_2} = \left(\frac{P_3}{P_2}\right)^{\frac{\gamma-1}{\gamma}}$$

Because the pressure ratio across the compressor is reasonably constant (at constant speed turbine), an increase in ambient temperature raises T_2 and T_3. Since the temperatures are in Rankine, the temperature difference becomes larger. Hence, turbine work is consumed more on hot days so there's less work left for power generation.

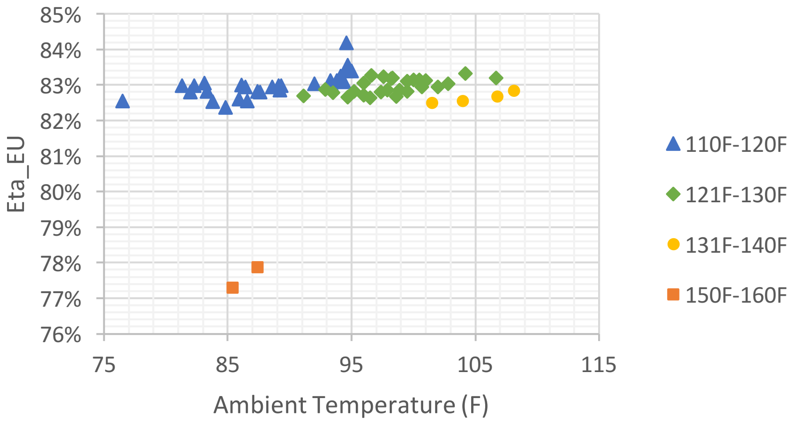

Figure 2. EU Directive Cogen efficiency as a function of $T_{ambient}$ and categorized by $T_{water,\ in}$

In Figure 2, EU Directive efficiencies is categorized in four ranges of water inlet temperature. The incentive efficiency is fairly consistent for increasing ambient temperature, however, it slightly drops for rising water inlet temperature. Efficiency significantly drops for even higher water temperature.

However, the data shows that the water inlet temperature does not affect the electrical efficiency. As shown in Figure 3, efficiency decreases with ambient temperature, not with water inlet temperature. Notice that even for the high water inlet temperature, points follow the trend.

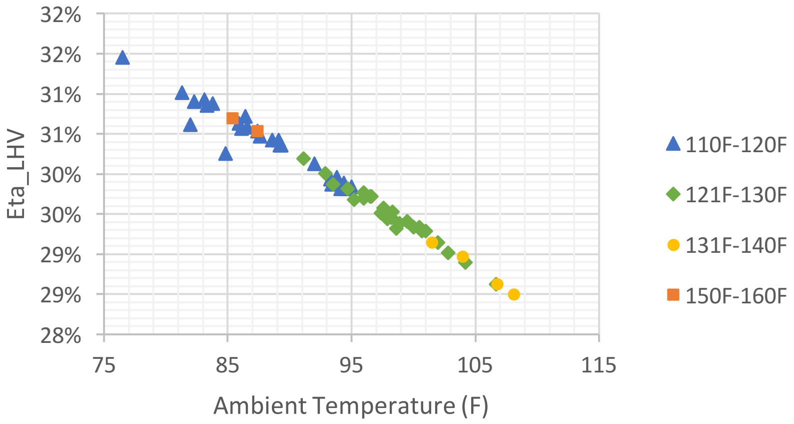

Figure 3. LHV efficiency as a function of $T_{ambient}$ and categorized by $T_{water, in}$

2. Shut off water during the open damper system

The purpose of this test is to observe the water temperature variances when the water source was cutoff during the 12-row cogen HX was running in open damper system. When the damper system is open, air bypasses the cogen HX; the damper system is closed as the air passes through the HX.

Test Setup

Once the water flows into the test station, the GT333S was started. As the station generates on-grid power, the damper was closed by setting the water temperature at 185°F. Waiting about 40 minutes to an hour until the machine stabilizes, the damper system is set back to open position and when it fully opened, the cogen water was cutoff immediately. The process was monitored until the water temperature rose up to 190°F. At this point, the gas turbine was shutdown to avoid the potential generation of steam. The test was repeated two times in different manners. First day, the water was cutoff for an hour and half; Second day, the water was cutoff until the temperature reached at 190°F.

Results

TE 401 = Temperature of water into the heat exchanger [°F]
TE 402 = Temperature of water out of the heat exchanger [°F]

Test 1

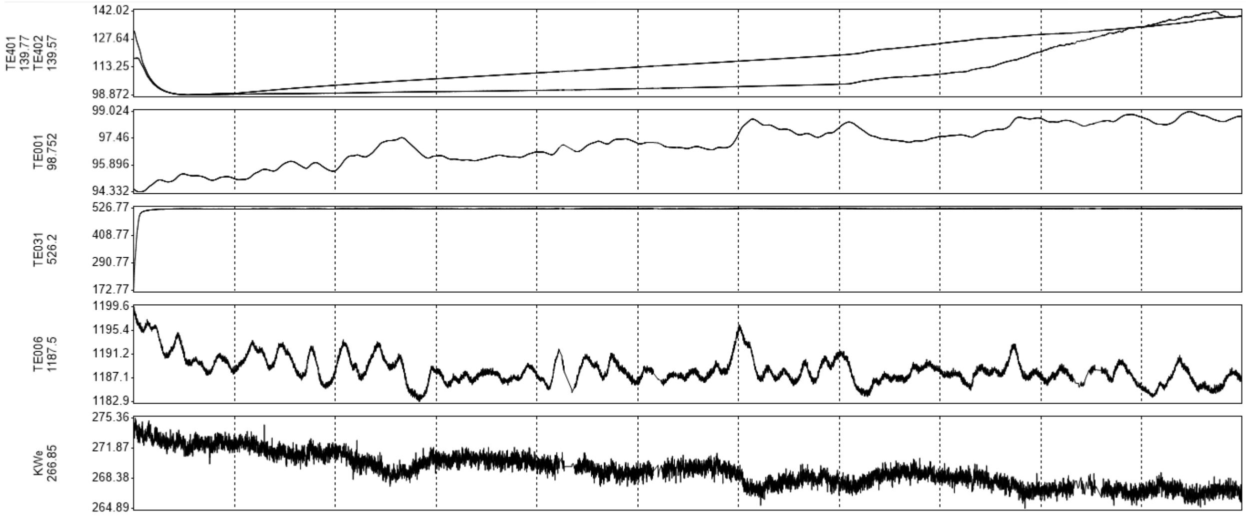

Figure 4. Trend data recorded as a function of time 07/12/2016

In Figure 4, the first plot represents TE 401 and TE 402 as a function of time. Second plot describes the ambient temperature (TE 001), whereas the third plot describes the air temperature at exhaust duct, downstream of the cogen heat exchanger (TE 031). Next plot represents the recuperator inlet temperature (TE 006). Lastly, the plot shows the real power generation (kWe). Test 1 was conducted about an hour and half. After the water was shutoff, the water temperature gradually increased, as observed in Figure 4. Past 70 minutes, the water inlet temperature (TE 401) rose sharply and after 85 minutes, the temperature exceeds TE 402, the outlet temperature. However, few minutes later, TE 401 drops and follows TE 402.

Test 2

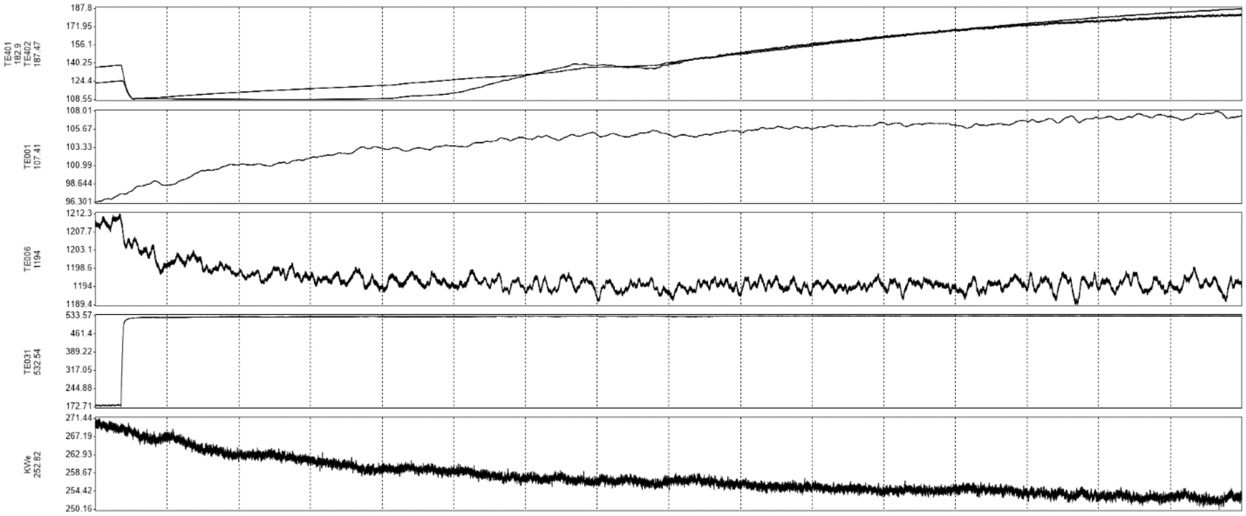

Figure 5. Trend data recorded as a function of time 07/13/2016

Test 2 lasted about four hours. It is clear that for one and a half hour, TE 401 and TE 402 follows the trend which observed in Test 1, as shown in Figure 5. Then, TE 401 and TE 402 merged together and gradually increased another 1.5 hours until the temperature reached 172°F. In last 30 minutes, TE 402 was slightly higher than TE 401 but within 6°F. The test was stopped shortly after TE 402 reached above 190°F.

Discussions

The energy added to water can be determined as following:

$$Q = m \cdot Cp \cdot dT = \rho V \cdot Cp \cdot dT$$

where Cp is specific heat of water, ρ is water density, and V is the volume. Properties of water are defined based on average temperature at 148°F. The approximate volume of the cogen HX water tube was referenced from the manufacturer's specification sheet and FlexEnergy 12-row cogen drawing, as described in Table 2. Calculated volume is 484.1in^3, which is equivalent of 0.28ft^3. As a result, the energy added to water is 171.3Btu with 10°F rise between TE401 and TE402.

Table 2. Tube sizing specification

Tube Outer Diameter [in]	0.625
Tube Wall Thickness [in]	0.049
Heat Exchanger Height [in]	41.5
Quantity of tubes used	168

From the slope of water temperature, the energy added to water can be calculated. The water temperature varied from 108°F to 188°F. By adding a trend line, as shown in Figure 6, the slope was approximately determined as 21.83°F/hr.

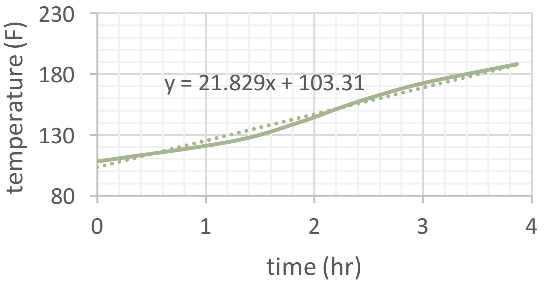

Figure 6. Temperature rise as a function of time

In order to solve for amount of water flow for 10°F rise between TE401 and TE402, following equations were considered:

$$\dot{Q} = m \cdot Cp \cdot \frac{dT}{dt} = \dot{m} \cdot Cp \cdot dT$$

$$\dot{V} = \frac{\dot{m}}{\rho}$$

where $\dot{Q}$ is the energy rate, $\dot{m}$ is mass flow rate, and $\dot{V}$ is volumetric flow rate in gpm. By equating the energy rate ($\dot{Q}$), the amount of water flow for this case was determined to be 0.076gpm.

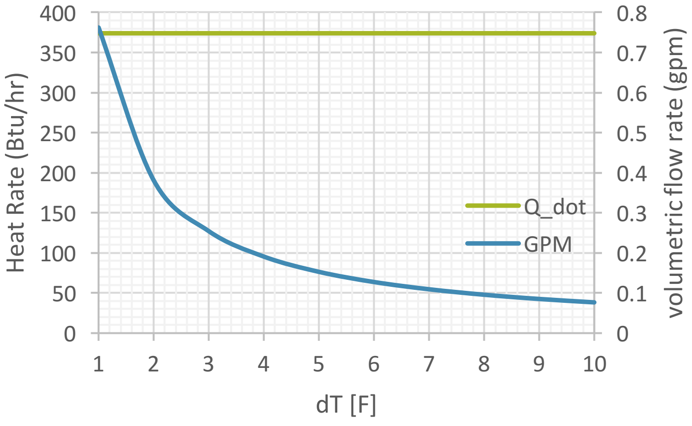

Figure 7. Heat (Q) and volumetric flow rate as a function of dT

As the temperature difference decrease, required water flow rate increases, as evidenced in Figure 7. The heat rate added to water versus temperature difference is illustrated in Figure 7. The equations were modeled by Engineering Equation Solver (EES). Table 3 summarizes the overall results.

Table 3. Summary of the cogen test for 10°F rise between TE401 and TE402

Tube Volume [ft^3]	0.28
Heat added [Btu]	171.3
Rate of Heat added [Btu/hr]	374
Volumetric Flow rate [gpm]	0.076

Conclusions

In conclusion, tests confirm that it is not recommended to operate the GT333 without at least some amount of water flow and heat rejection from the cogeneration hot water system. The evaluation results indicate that the need for 0.076gpm of water flow. Due to the safety concern, it is recommended to have at least 5gpm of water flow for a 10°F rise between inlet and outlet temperatures.

Acknowledgements

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References

[1] Armstrong J., et al. "Development and Testing of a 333 Kilowatt Industrial Gas Turbine" Proceedings of ASME Turbo Expo, June 14-16, 2016, Seoul, South Korea