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Experimental Characterization of a T100 micro Gas Turbine converted to Full Humid Air Operation.

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Abstract

Micro Gas Turbines (mGTs) were considered very promising for small-scale Combined Heat and Power (CHP) production. They however never fully penetrated the CHP market, resulting in a limited market share. Due to their low electric efficiency (30% versus 80% CHP efficiency), the operation of the mGT is strongly heat-driven. In applications with a non-continuous yearly heat demand, like domestic heating systems, the mGT would be shut down for long periods, resulting in a reduced amount of yearly running hours. These limited running hours make the mGT as small-scale CHP less profitable compared to other technologies, like reciprocating engines. Converting the mGT into a micro Humid Air Turbine (mHAT) offers a solution. The waste heat in the exhausted gases is recovered in the mHAT by evaporating auto-raised hot water behind the mGT compressor, resulting in a higher electric efficiency and a more flexible mGT operation. In this paper, we present the results of experiments on a modified Turbec T100 mGT. As a proof of concept, the mGT has been equipped with a spray saturation tower to humidify the compressed air. The goal of these experiments was to evaluate the beneficial effect of compressed air humidification on the mGT performance. Two stable runs at constant pressure ratio and rotation speed were recorded during water injection. Final electric efficiency results show a relative electric efficiency increase of 1.2% and 2.4%. These changes are however in the range of the accuracy of the measurements. Further experiments are therefore necessary to fully characterise the behaviour of the mHAT at part and nominal load. Fine-tuning of the water injection control strategy is also identified as a key parameter to reduce the auxiliary power losses.

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Nomenclature

CHP	Combined Heat and Power
HAT	Humid Air Turbine
mGT	micro Gas Turbine
mHAT	micro Humid Air Turbine
TIT	Turbine Inlet Temperature
TOT	Turbine Outlet Temperature

1. Introduction

Micro Gas Turbines (mGTs) have several advantages compared to internal combustion engines for small-scale Combined Heat and Power (CHP) production: low vibration level, cleaner exhaust and lower maintenance cost [1]. Their low electric efficiency (30%) makes that the mGT operation as CHP is mainly heat driven. In application with a non-continuous heat demand, like domestic applications, this results in a forced shutdown and a lower amount of running hours. A low amount of running hours has a negative effect on mGT economics [2]. Converting the mGT into a mHAT, by installing a saturation tower to humidify the compressed air, offers a solutions. According to Jonsson and Yan, the Humid Air Turbine (HAT) has the highest efficiency of all humidified gas turbines [3]. Turning a mGT into a mHAT can increase the electric efficiency by 6% relatively [4], while reducing the specific capital cost by 10% [5]. The HAT cycle, as proposed by Rao [6], has been constructed and tested experimentally during the EvGT project at Lund University [7]. However, experiments with a recuperated mHAT with saturation tower have never been reported.

In this paper, we present our first experiments on a Turbec T100 mGT converted to mHAT. The T100 mGT was equipped with a spray saturation tower, designed according to two-phase flow simulations [8]. The goal of these experiments was to show the beneficial effect of water injection in a mGT on its performance.

In the following sections, we will first discuss the mHAT test rig and the designed saturation tower. Then, the experimental results are discussed. The start-up procedure is evaluated together with the mGT performance. Out of these results, recommendations for future tests are formulated.

2. mHAT test rig

The basis of the mHAT test rig is a Turbec T100 mGT. The T100 is a typical recuperated Brayton cycle. The T100 produces up to 100 kW_e electric power and 166 kW_{th} thermal power by producing hot water at a temperature of 70°C. At nominal operating conditions, the electric efficiency is equal to 30%, resulting in a global CHP-efficiency of 80% [9]. To convert the T100 mGT in a mHAT, a spray saturation tower (Figure 1, (2)) is added to the cycle, to humidify the compressed air coming from the compressor (1) by injecting an excess of water in the saturation tower. The saturated air is preheated in the recuperator (3) by using the remaining heat in the exhaust gasses. Natural gas is burned in the combustion chamber (4) to reach maximal Turbine Inlet Temperature (TIT) of 950°C in order to keep the electric efficiency high. The hot gasses expand in the turbine (5), delivering the necessary power to drive the compressor. The remaining turbine power is converted into electric energy by the generator. The T100 control system keeps the power

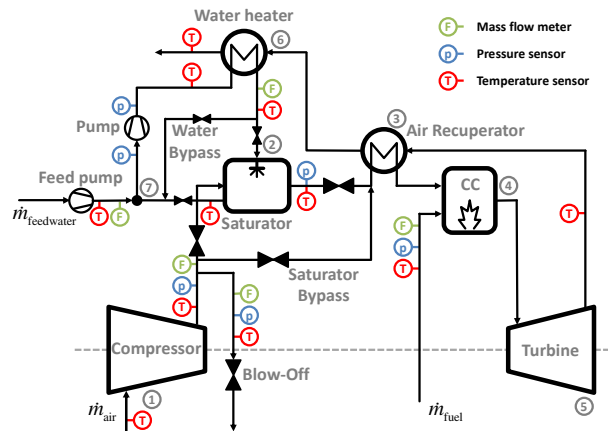


Figure 1: The recuperated mGT cycle is turned into a mHAT by adding a spray saturation tower between the compressor outlet and recuperator inlet to fully humidify the compressed air.

production constant at given set point, determined by the operator, by changing the rotation speed of the compressor and turbine.

Since an excess of water is injected in the saturation tower, only a small amount will evaporate (2%) [8]. The excess water is rerouted back to the water heater, where the remaining heat from the flue gases is transferred to the water (6). Finally, feed water is added to the system (7) to keep the flow of circulating water constant at 2.5 kg/s [4]. As indicated on Figure 1, several sensors were added to the system to measure the effect of the water injection on the mGT performance.

The novel component in the mGT cycle, the spray saturation tower (Figure 1, (2)), was designed using the results of a two-phase flow analysis [8]. In a classic saturation tower, the heat and mass transfer between the compressed air and the water is enhanced by using packing material [10]. In this application, the contact area has been enhanced by atomizing the water through nozzles. Our simulations had indicated that it is possible to develop a spray saturation tower of equal size and pressure drop as a typical packed saturation

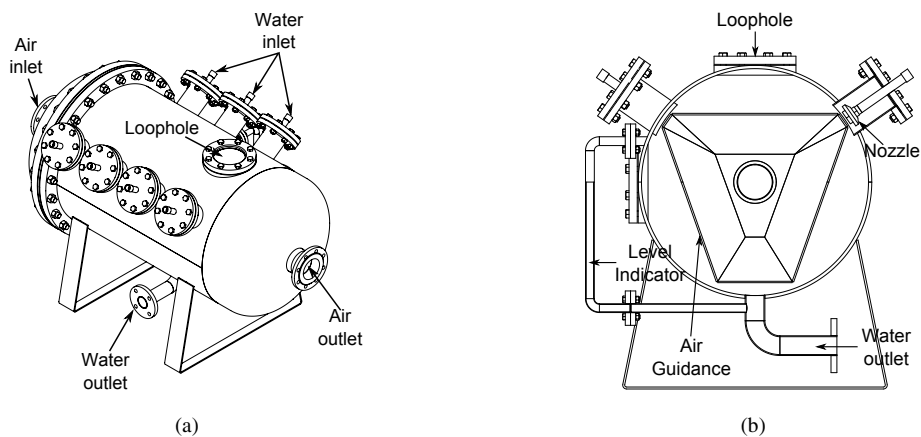


Figure 2: The spray saturation tower is especially designed and constructed for the Turbec T100 mGT. The spray tower is equipped with 7 nozzles to atomize the water to increase the contact surface between water and compressed air (a). Air guidance plates are installed to force the air through the water spray (b).

tower [8]. The constructed saturation tower consists of a pressure vessel that holds the air pressure (Figure 2). The water is injected by 7 nozzles, spaced in a staggered position, this to keep the tower length limited and to prevent droplet coalescence (Figure 2 (a)). The nozzles are fed by two collectors to keep the injection pressure and thus the flow rate constant. The air is forced through the water spray cone by three air guidance plates (Figure 2 (b)).

A blow-off and bleed valve is added to the mHAT test rig (Figure 1). Due to limited space, the saturation tower was placed relatively far from the compressor outlet and recuperator inlet. Therefore a long piping network needed to be installed to connect the saturation tower to the mGT. This piping network dissipates a large pressure drop (4.33%). This pressure drops shifts the compressor operating point towards the surge limit. To prevent surge during the tests, part of the compressor air is bled.

3. Experimental results

Two successful water injection experiments have been performed. For each test, the same procedure for start-up has been applied. Prior to the wet test, 2 dry runs – one with and one without air bleed - of 1 hour have been performed to heat up the mHAT test rig. The dry test runs also serve as reference case. Bleeding air results in a 4.4% absolute electric efficiency loss (Table 1). After the dry test runs, water injection was initiated. Initial tests had indicated that direct transition of dry run to water injection is not possible. The sudden injection of water in the systems changes the operating conditions of the mGT drastically. The existing control system is not capable of handling these changes, resulting in a mGT operation failure. Therefore, water injection was started before the mGT was started (Figure 3). During this initial test (Test 1), only a low amount of water was injected, by bypassing most of the water over the saturation tower (Figure 1). Once the water injection had been initiated, the mGT was started. The mGT completed its start-up procedure without any problems or delay compared to the dry start-up and stable mGT operation was recorded after 660 s. The mGT run was terminated after 3 hours (Figure 3). A second wet run, using the same procedure, has been performed to check the repeatability of the wet start-up procedure and the measurement results. The second test (Test 2) was successfully terminated after 1.5 hours.

Results of the two water injection tests show that the effect of the water injection is rather limited on the mGT performance (Table 1). Both Turbine Outlet Temperature (TOT), compressor outlet pressure (p_{comp}) and rotation speed (n) slightly change. The produced power (P_{gen}) is however increased, while the natural gas flow rate (\dot{m}_{fuel}) remained constant, resulting in a small electric efficiency (η_{el}) increase (1.2% and 2.4% relatively). These changes are however of the same order of magnitude as the measurement error (2%). The absolute efficiency increase of 0.3% and 0.6% in Test 1 and 2 (Table 1) are rather low compared

Table 1: Results of stable water injection tests indicate the effect of the water injection on the mGT performance is limited due to the limited amount of injected water.

	Dry		Wet	
	No bleed	Bleed	Test 1	Test 2
P_{gen} (kW _e)	60.1	53.1	54.0	55.0
n (rpm)	61210	62645	62793	62689
\dot{m}_{fuel} (kg/s)	7.6	7.9	7.9	8.0
η_{el} (%)	28.7	24.3	24.6	24.9
TOT (°C)	639.3	640.2	643.1	641.0
p_{comp} (bar)	3.58	3.64	3.64	3.65

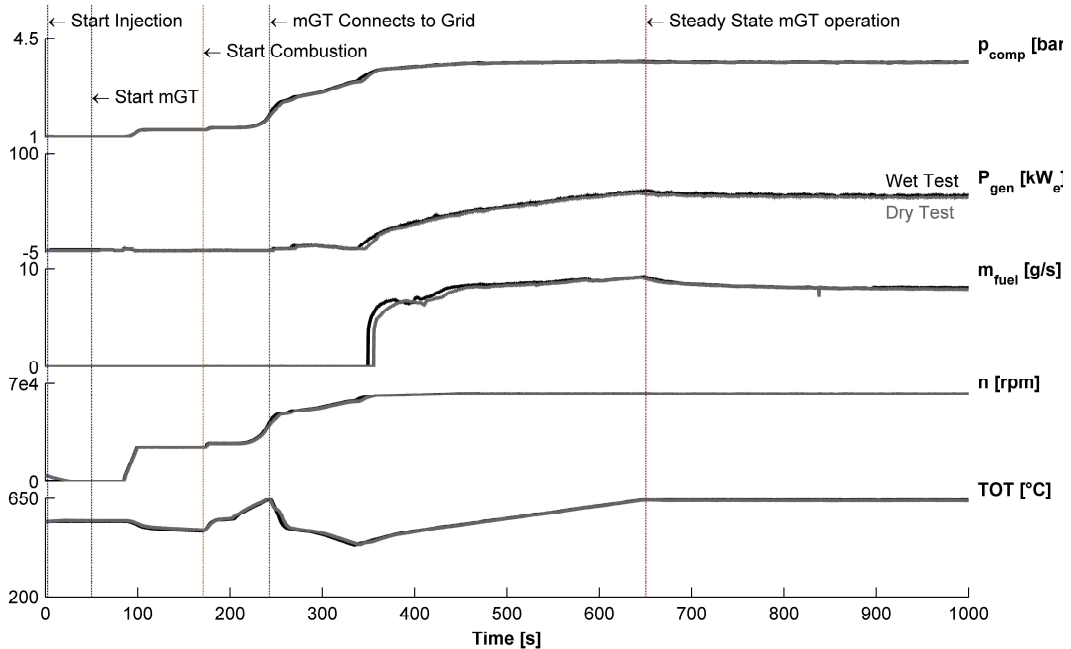


Figure 3: Time series of some key parameters during start-up for a dry and wet test run. Compressed air was bled to prevent the compressor going into surge. Both start-ups were finished after 660 s, when the mGT reached steady state operating conditions. The injection of water has no effect on the start-up time.

to the reported absolute efficiency increase of 3% by Nakano et al. when running a 150 kW_e mGT with HAT line at 60% of the nominal load [11]. The lower efficiency increase can be explained by the limited amount of injected water.

During these first tests, the amount of injected water was limited, since it was uncertain whether the mGT control system was able to operate the mGT with an additional amount of water going to the turbine. The successful tests have shown that no modifications are strictly necessary for the control system even though the start-up procedure has been adapted. In future tests, the injected amount of water will be increased. This will have a more significant effect on the mGT performance.

4. Conclusion

In this paper, we presented our first water-injection experiments on our mHAT test rig. These experiments were performed to evaluate the test rig design and to show the effect of water injection on the mGT performance.

- A wet start-up procedure was developed and successfully tested. The mGT finished its start-up procedure successfully, resulting in two stable wet operations of 3 h and 1.5 h at constant rotation speed, TOT and pressure ratio. The existing Turbec T100 mGT control system was capable of controlling the mHAT test rig.
- Electric efficiency was increased by 1.2% and 2.4% relatively. These changes are however in the range of the accuracy of the measurements. The limited efficiency changes can be explained by the limited

amount of injected water. The performance of the mGT can be enhanced by increasing the amount of injected water.

- Further experiments are necessary to fully characterize the performance of the test rig at nominal and part load operating conditions. The first successful tests however already showed the potential of the test rig.

Acknowledgements

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