Experimental Thermodynamic Performance Analysis of a micro Humid Air Turbine

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Abstract:

Waste heat recovery has become more and more important for the profitability of small-scale Combined Heat and Power (CHP) plants like micro Gas Turbines (mGTs). Adding a saturation tower to the mGT unit is such a waste heat recovery route. The cycle includes the saturation tower after the compressor to humidify the compressed air. Simulations show that this cycle, known as the micro Humid Air Turbine (mHAT), increases mGT electric efficiency by 7%, improving the general economic performance. However the mHAT concept with saturation tower was never tested experimentally. To show the potential of the cycle, the Turbec T100 mGT of the University of Brussels was converted into a mHAT cycle by adding a spray saturation tower to the system. In this paper, we present the results of several water injection tests in the T100 mGT at part and nearly nominal load. The water injection experiments resulted in stable mGT operation at reduced rotational speed, reduced pressure ratio and increased electric efficiency. Experimental results showed a reduced fuel mass flow rate by 4.3% and a relative electric efficiency increase of 4.8% for the different experiments. In addition, the impact of the water on the other turbine parameters has been studied.

Keywords:

Micro Humid Air Turbine (mHAT), micro Gas Turbine (mGT), humidified Gas Turbine cycles, waste heat recovery.

1. Introduction

Micro Gas Turbines (mGTs) were considered very promising for small-scale Combined Heat and Power (CHP) production in the past [1]. They however never fully penetrated the CHP market. For instance, in the United States, only a limited fraction, 6.5% of the installed CHP capacity, uses mGT as primary mover, while 48.0% of the electricity produced by CHP units, is provided by Internal Combustion Engine (ICE) units [2]. Main reasons for the low interest in mGT units is their relative low electric efficiency (30% compared to 34-35% for ICE units) in combination with their heat-driven operation. The operation of the mGT as CHP unit is determined by the heat demand. In periods with low or no heat demand, the mGT is forced to shut down, since the operating cost is too high. Since the mGT specific capital cost is still high [3], any reduction in running hours has a negative effect on the global mGT performance [4].

In order to increase the flexibility of the mGT and shift its use towards various heat and power demand profiles, the waste heat in the exhaust gases can be used to generate auto-raised steam or hot liquid water, which is then re-injected in the cycle [5]. This so-called humidification of the mGT cycle will increase the electric performance, resulting in a higher profitability during periods with low or no heat demand.

Our research group found out that the optimal route for waste heat recovery in a mGT through water injection is the conversion of the mGT into a micro Humid Air Turbine (mHAT) [6]. We selected the mHAT cycle based on the high electric efficiency achievable, the relative low changes to the mGT CHP cycle — resulting in low additional capital cost — and the ability to operate with lower water quality. The conversion of the mGT into a mHAT still allows the production of heat, which makes the cycle the perfect candidate for flexible heat production [6]. According to our simulations, converting a mGT into a mHAT by adding a saturation tower between the compressor outlet and the recuperator inlet will increase the electric efficiency by 3.8% and 2.0% absolute or 13% and 7% relative when keeping respectively Turbine Inlet Temperature (TIT) or Turbine Outlet Temperature (TOT) constant [7].

The mHAT cycle has been studied in the past by means of simulations and experiments by several researchers [8-15]. Dodo et al. performed experiments on a modified 150 kW_e mGT. The effect of humidifying the working fluid was simulated by adding a Humid Air Turbine (HAT) and a Water Atomizing inlet air Cooling (WAC) line to the cycle. Experiments resulted in stable dry runs at 32% electric efficiency [8]. Additionally, Nakano et al. showed that the electric output could be increased by 6 and 11 kW_e when introducing respectively 4.5 g/s of water through the WAC line and 21 g/s through the HAT line. Corresponding efficiencies were increased by 1.0 and 2.0% absolute for WAC and HAT, resulting in a total efficiency increase by 3.0% absolute or 17% relative [9]. Parente et al. studied the thermodynamic [10] and economic performance [11] of the mHAT and the mHAT Plus cycle by means of simulations. The effect of air humidification on component level in the mHAT was studied by Zhang et al. [12]. More recently, Wei et al. investigated experimentally the off-design behaviour of a small-sized (25 kW_e) HAT cycle. The produced power output during a test at constant fuel flow rate and a test at constant TIT increased significantly by 3 and 9.5 kW_e due to the humidification [13]. Most recently, Nikpey et al. simulated the conversion of a Turbec T100 mGT into a HAT cycle. This conversion would result in an absolute electric efficiency increase of 1.7% [14], which is in correspondence to the results presented by the authors of this paper [7]. Finally, our research group has performed an economic analysis on the conversion of a mGT into a mHAT, showing that whenever investing in mGT technology is feasible, it is worth transforming the unit into a mHAT [15]. Despite the proven potential by means of simulations and preliminary experiments, the mHAT concept with saturation tower has never been experimentally tested. Our research group was the first to convert a mGT into a mHAT [16]. The first experiments on the mHAT test rig indicated its shortcomings but also the potential of water introduction. Stable mGT operation was obtained and electric efficiency remained stable. By increasing the amount of injected water, the electric efficiency can be increased [16].

In this paper, the results of experiments performed on a converted Turbec T100 mGT into a mHAT are presented. First, the experimental setup is presented. In a second section, the experimental procedure for humidified mGT tests is introduced. In a third section, the results of these tests on the global mGT performance as well as the component performance are presented. Finally, a conclusion is given together with future perspectives.

2. Experimental Setup

A Turbec T100 mGT has been modified to transform the original recuperated Brayton cycle into a mHAT (Fig. 1). After being compressed in the variable speed, radial compressor up to 4 bar (1), the hot compressed air is humidified in the saturation tower (2). In this saturation tower, hot water (82°C) is sprayed in the compressed air. The fully saturated compressed air is then preheated in the recuperator by the hot exhaust gasses from the turbine (3) and heated in the combustion chamber till ~890°C by burning natural gas (4). By expanding the hot compressed air over the turbine (5), the necessary power to drive the compressor is generated. The remaining shaft power is converted in electric power by the high speed generator (6). After preheating the saturated compressed air, the still hot exhaust gasses (186°C) are used to heat the water in the economizer (7). This hot water is routed towards the saturation tower, where it is atomized in the compressed air. In total 2.5 kg/s of water is sprayed in the saturation tower. To humidify the air, water will evaporate. To keep the amount of injected water constant, feedwater needs to be added to the water circuit (8).

As mentioned in the introduction, Aspen® plus simulations of the mHAT cycle predict a total efficiency increase of 3.8% under constant TIT condition and 2.0% under constant TOT condition at nominal electric output of the mGT (100 kW_e) and full humidification of the working fluid [7]. Since the Turbec T100 mGT operates under constant power output condition, rotational speed is varied by

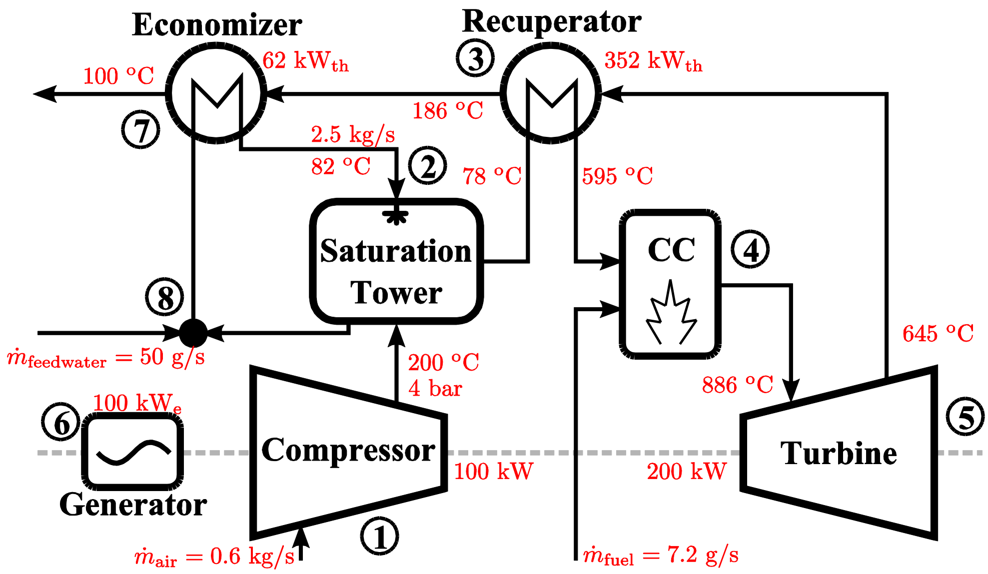
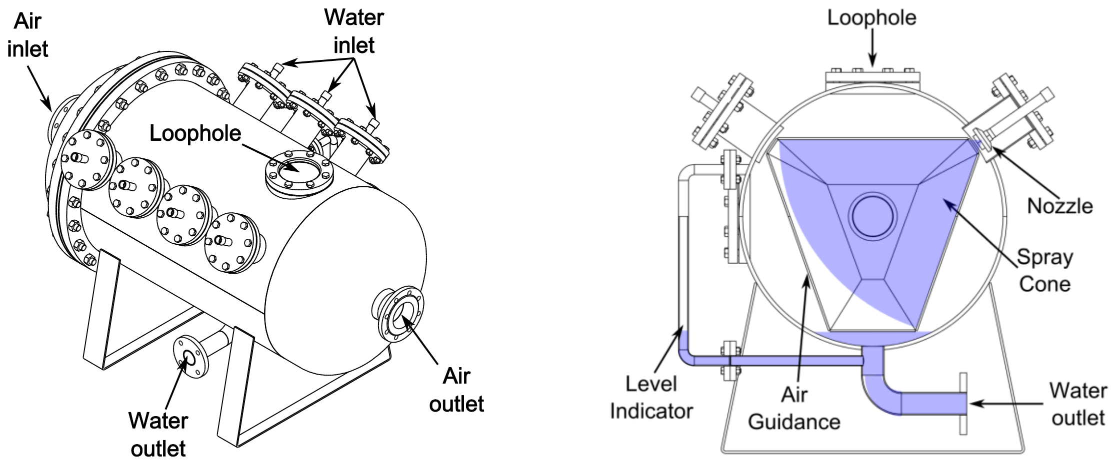


Fig. 1. The recuperated mGT cycle is turned into a mHAT by adding a spray saturation tower between the compressor outlet and recuperator inlet to saturate the compressed air to the cycle. The indicated thermodynamic properties were simulated using Aspen® plus.

the control system to keep the power output constant when the air is humidified. Simulations predict thus a constant power output under humidified conditions, while rotational speed and pressure ratio reduce. Additionally, due to the lower air mass flow rate through the system, the fuel flow rate is decreased, resulting in higher electric efficiency.

To convert a mGT into a mHAT, a saturation tower was added to the mGT cycle (Fig. 2). For the conversion of the Turbec T100, a specially designed spray saturation tower without packing material was added to the cycle (Fig. 2). A spray saturation tower was chosen over a classic tower with packing material to reduce the pressure drop and additional efficiency losses [17]. This spray saturation tower was developed based on two-phase flow simulations [18]. The spray tower is equipped with 7 nozzles to atomize the water in the compressed air (Fig. 2 (a)), cross-current to the air flow. By atomizing the water in the air stream, heat and mass transfer are enhanced, which speeds up the evaporation and



(a) (b)

Fig. 2. Designed and constructed spray saturation tower for the Turbec T100 mGT. The spray saturation tower is specially designed and constructed for the Turbec T100 mGT. The spray tower is equipped with seven 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).

humidification process. To force the air stream through the water spray, air guidance plates are placed in the saturation tower, while the surrounding vessel will hold the pressure (Fig. 2 (b)).

To measure the effect of the humidification of the compressed air on the performance, different measuring equipment were installed. Pressure, temperature and flow rate sensors have been installed to capture the performance of the mGT. Additional information concerning the used mGT, the Turbec T100 mGT, the additional modifications to integrate the saturation tower in the cycle and the used measuring equipment to capture the effect of water injection on the mGT performance can be found in [16].

A specific startup and shutdown procedure for the modified Turbec T100 had to be developed [16], since the control system of the mGT was not adapted. To avoid engine shutdown when initiating water injection, water injection was started prior to the start of the mGT (*wet startup*). Several attempts were made to initiate water injection while the mGT was running dry (*dry startup*). None of the experiments using the *dry startup* method was successful and no stable mGT operation could be obtained. All these tests resulted in flameouts due to the sudden water injection, resulting in compressor surge. In order to protect the machine, the results of the wet experiments presented in this paper are taking by using the *wet startup* procedure. Air needed to be bled during engine shutdown due to the additional volume added between compressor outlet and recuperator inlet (the saturation tower and piping network). Since the mGT control system was not adapted, this additional volume and pressure loss over the humidification unit where not taken into account by this control system. During engine shutdown, rotational speed is reduced rapidly. Due to the additional volume and pressure loss, the compressor will hit its surge limited, resulting in a compressor surge during shutdown. To prevent this compressor surge, a blow-off valve is opened during engine shutdown to increase surge margin and protect the compressor. Additional information concerning startup and shutdown procedure can be found in [16].

3. Experimental results

Previous humidification experiments performed on the test rig indicated that the mGT could be started successfully under humid conditions and resulted in stable operation [16]. The performance was however not improved due to several shortcomings. Additional experiments at nominal water injection (10 m³/h or 2.5 kg/s) and partial water injection were performed to study the effect of humidification on the mGT global and component performance. In addition, the results of the Aspen® plus simulations [7] would be validated using the experimental data.

In this section, first the results of water injection on the global mGT performance will be discussed. Afterwards, the effect of the injection on the compressor and recuperator, as well as the saturation tower performance will be discussed.

3.1. Global mHAT performance

The injection of water in the saturation tower has a positive effect on the T100 mGT performance (Fig. 3). Injecting the nominal amount of water (10 m³/h) in the saturation tower results in stable mGT operation at reduced rotational speed, constant power output and TOT (645°C) and increased electric efficiency. Tests were performed at 80, 85 and 90 kW_e power output. The spikes in the natural gas flow rate measurement, shown on Fig. 3, are a result of the unsteady operation of the natural gas compressor. Due to the high temperature in the T100 mGT operation room (above 35°C), the heat from the compressor could not be evacuated, possibly resulting in natural gas pressure drops, followed by a drop in flow rate, explaining the spikes. These changes influence the instantaneous calculated electric efficiency, but have no effect on the average calculated performance. The final average results of the experiments can be found in Table 1.

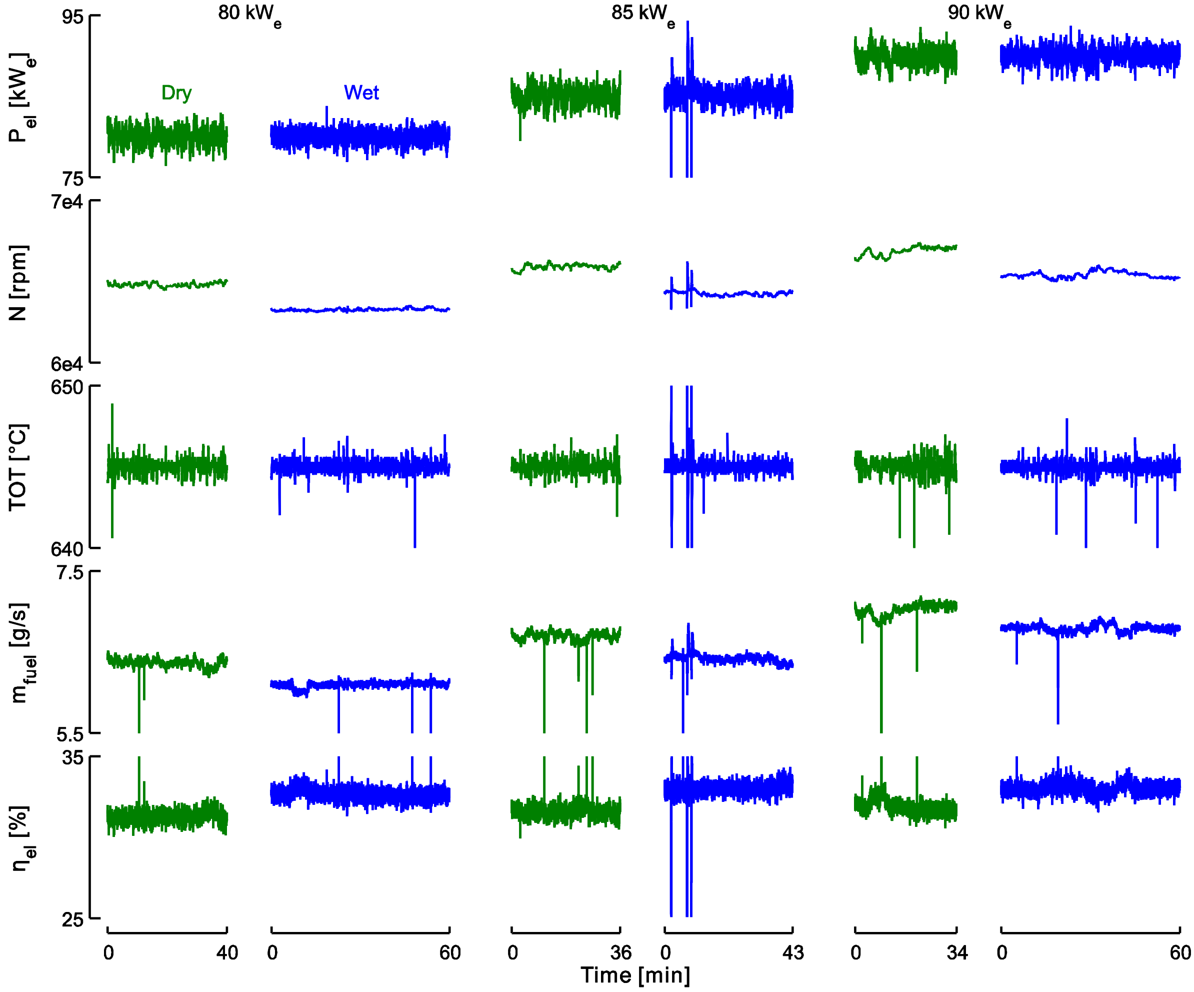


Fig. 3. Experiments with water injection at different power outputs all result in stable mGT operation at constant power production, reduced rotational speed and fuel flow rate and increased electric efficiency.

The electric efficiency increases for all experiments since the fuel mass flow rate reduces due to water injection, while the produced electric power remains constant (Table 1). For all cases, the produced electric power (P_{electric}) is equal to the requested output (P_{ref}) set by the mGT operator. The fuel flow rate $\dot{m}_{\text{fuel}}$ reduces since additional mass is added to the compressed air due to the evaporation of water in the saturation tower. This additional mass flow rate increases the available power on the turbine

Table 1: Results of stable water injection tests.

	Dry	**Wet**	**Dry**	**Wet**	**Dry**	**Wet**
P_{ref} (kW$_\text{e}$)	80.0	80.0	85.0	85.0	90.0	90.0
P_{electric} (kW$_\text{e}$)	80.0	80.0	85.0	85.0	90.1	90.2
T_{in} (°C)	20.8	16.7	21.1	17.6	20.6	18.1
$\dot{m}_{\text{water}}$ (m^3/h)	/	10.4	/	10.3	/	9.2
$\dot{m}_{\text{fuel}}$ (g/s)	6.4	6.1	6.7	6.4	7.0	6.8
η_{electric} (%)	30.3	31.7	30.5	32.0	30.8	31.8
$\Delta\eta_{\text{electric,corr}}$ (%)	/	1.0	/	1.1	/	0.8

shaft, while the power consumed by the compressor remains constant. As indicated in Table 1, the compressor inlet air temperature changed during the test due to the changing atmospheric conditions. Since the performance of the mGT depends on the inlet air temperature, the electric efficiency needed to be compensated for the temperature change. For this compensation previous dry reference efficiencies have been used [4]. Final average electric efficiency increases amounted 1.0±1.8%, 1.1±1.8% and 0.8±1.8% for respectively 80, 85 and 90 kW_e. These efficiency changes are below the predicted increases (1.7, 1.6 and 1.5% [7]). In addition, these changes are in the accuracy range of the efficiency measurements.

Even though the nominal amount of water was injected in the cycle (10 m^3/h), the electric efficiency increase was below the simulated values. This indicates that the compressed air is most likely not fully saturated, as will be shown later on. The saturation level could not be determined with the current set-up, since the compressor air mass flow rate and evaporated amount of water are not known [16]. A too low water injection temperature is a possible explanations for the lower humidity level. Due to control issues and heat losses in the water circuit, it was not possible to increase the water temperature till the necessary 82°C.

As mentioned in previous paragraph, due to technical reasons [16], the relative humidity or the exact amount of evaporated water could not be determined. Since the humidity level is not known, it is not possible to compensate the Aspen® plus simulations for the lower humidity level. However, by reverse engineering in Aspen® plus, trying to link the measured efficiency increase with a certain humidity level, the evaporated amount of water could be determined for the experiments from Table 1. Simulations indicated 19, 21 and 17 g/s of water was evaporated during the experiments, which is below the necessary amount of water for full saturation simulated in Aspen® plus (42, 44 and 46 g/s). General results however show that water injection has a positive effect on electric efficiency, even at low injection rates and water temperature. In addition, stable mGT operation was successfully achieved during all experiments at different power outputs, showing the robustness of the Turbec T100 mGT control system.

Additionally to the experiments performed at part load and full water injection (results shown in Table 1), the results of the preliminary experiments, at partial water injection, are compared to simulation results (Fig. 4). For all experiments, due to water introduction, electric efficiency increased, however the final absolute increase in electric efficiency was below the predictions from the simulations. There is a rather large scatter on the experimental results due to the different amount of injected water. Despite the huge uncertainty on the measurement results, it is clear that the difference is significant and has thus a physical reason. Since the injected water mass flow rate and/or the injection temperature were too low, facts that result in an incomplete saturation of the compressed air, the measured efficiency increase is below the predictions from simulations.

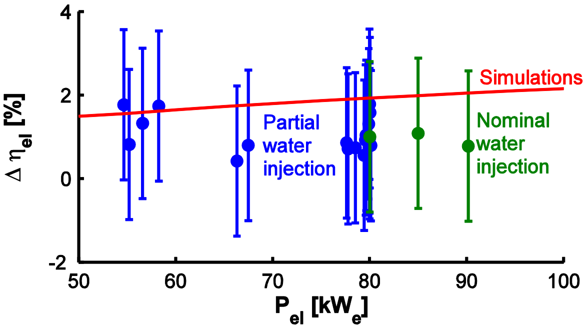


Fig. 4. The measured increase in electric efficiency is below the prediction from the Aspen® plus simulations due to an incomplete saturation of the compressed air.

3.2. mHAT component performance

The water injection has a positive effect on the global mGT performance. The performance of the main components of the mGT are now analysed in detail, in order to find an explanation for the lower global electric efficiency gain, compared to simulations. First, the performance of the saturation tower is analysed. Secondly, the shift in compressor operating point in studied and finally, the performance of the recuperator is discussed.

3.2.1 Saturation tower

The goal of the saturation tower is to humidify the compressed air leaving the compressor by spraying hot water in the air flow. According to simulation results, part of the heat necessary to evaporate the water is coming from the hot air, but an additional part is coming from the excess of water itself. This is indicated by the lower outgoing water temperature compared to the ingoing water temperature (Fig. 1). By doing so, additional heat is recovered in the mHAT cycle, which results in higher electric efficiency, compared to steam and water injection [6].

Experimental results however show that the outgoing water temperature is equal or even higher than the ingoing water temperature (Fig. 5). This indicates that all necessary heat from the water evaporation is provided by the compressed air, rather than from the hot water, explaining the lower

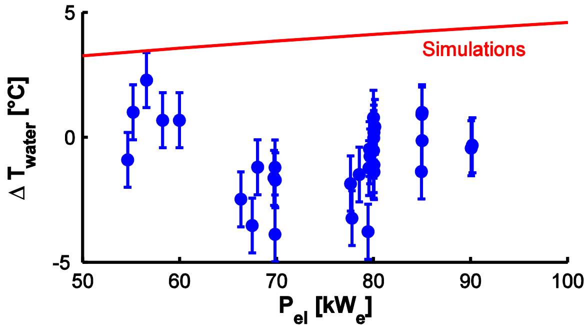


Fig. 5. The temperature drop over the saturation tower of injected water is limited due to an incomplete saturation.

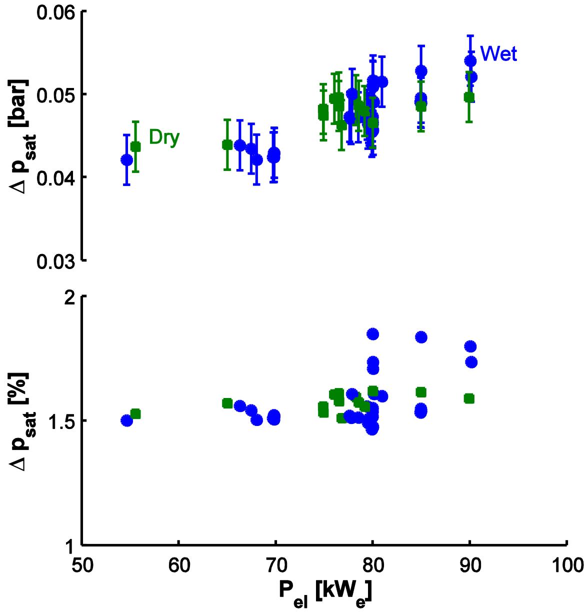


Fig. 6. The additional pressure drop in the saturation tower due to the water injection is very low.

electric efficiencies. To obtain the maximal efficiency increase, additional waste heat needs to be added to the cycle in the evaporation process. In these experiments, no additional heat is added to the cycle. The saturation tower acted as an aftercooler. Electric efficiency however still increases due to the change in working fluid composition and lower recuperator inlet air temperature (see paragraph 3.2.3).

The spray saturation tower was specially designed to reduce the head loss over the humidification unit. As mentioned before, the contact area between liquid and gas was enhanced by atomizing the liquid by sprays, rather than using packing material which would result in an additional pressure drop. Experiments indicate that the pressure drop induced by the water spray is very low (below the accuracy of the pressure sensors, Fig. 6), indicating that this pressure drop is in line with prediction from simulation results. The pressure drop over the entire humidification unit however was high (5%), which has a severe negative effect on the mGT performance. Main cause of the high pressure drop were the additional measuring equipment that were installed and the long tubes to connect compressor exhaust and recuperator inlet with the humidification unit (due to lack of space). In a future design of the humidification unit, this pipe length will be limited in order to reduce the loss in efficiency of the mGT.

3.2.2 Compressor

Water injection will result in a reduction of the surge margin of the compressor. Due to the additional mass added through the evaporation of the water in the saturation tower, more mass is going through the turbine. This results in a higher turbine power and thus more power available at the shaft for conversion into electric power by the generator. Since the Turbec T100 mGT operates under constant power output condition, the control system will slow down the compressor. By doing so the mass flow rate through the compressor is reduced, resulting in constant power output. By reducing the shaft speed and thus compressor mass flow rate, the operating point shifts towards the surge limit (Fig. 7). To protect the compressor against surge, air can be bled after the compressor outlet to increase surge margin. The air bleed will increase the mass flow rate through the compressor, keeping the compressor away from surge. Bleeding air however has a severe negative effect on the total performance.

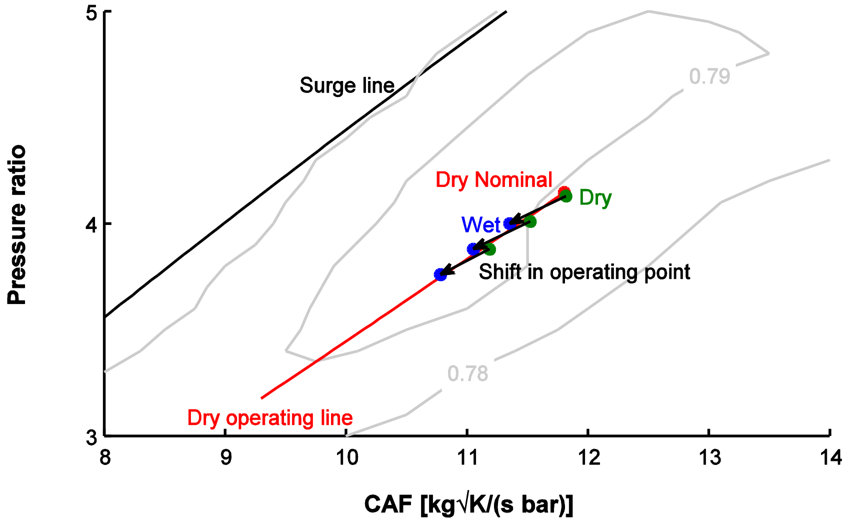


Fig. 7. Due to the water injection in the mGT cycle, the operating point shifts towards the surge limit of the compressor.

3.2.3 Recuperator

In the Turbec T100 mGT, a typical partial cross, partial counter flow heat exchanger [17] is used to preheat the compressed air before entering the combustion chamber. Under dry operating conditions, the temperature difference on the hot side of the recuperator is 50°C (difference between the Combustor Inlet Temperature (CIT) and TOT), which is the current standard for gas/gas heat exchangers. Lower temperature differences results in higher heat recuperator efficiencies, but will make the heat exchanger too expensive and big.

One of the advantages of adding water to the working fluid of the mGT cycle, is the increased heat recovery in the recuperator. Due to the lower cold inlet air temperature (Fig. 1) and the changed heat capacity of the working fluid (due to the addition of water), more heat can be exchanged. This is however limited by the contact area of the recuperator. Experimental results however show that the effect of the limited contact area is rather limited (Fig. 8). The temperature difference on the hot side of the recuperator is for all experiments approximately 50°C, which indicates that the recuperator has a favourable off-design behaviour. Additionally, the hot exhaust air entering the recuperator has a constant temperature of 645°C, set by the mGT controller. During water injection experiments, the control system was able to keep this temperature constant, which indicates that it is possible to run the commercial Turbec T100 mGT system without modifying the engine control system.

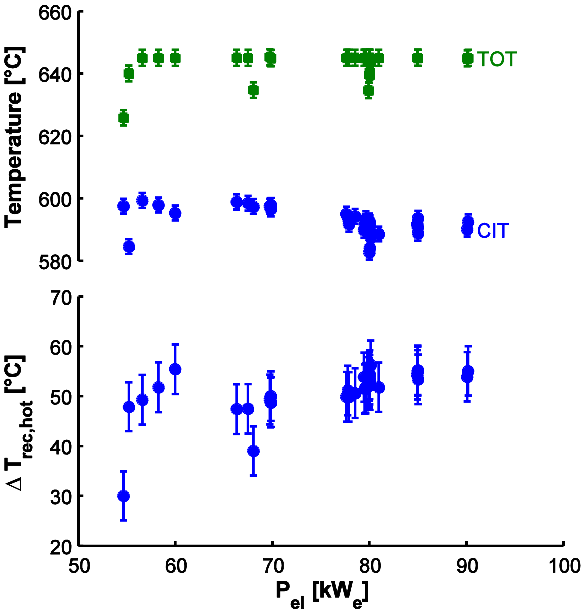


Fig. 8. The constant hot pinch temperature indicates that the Turbec T100 mGT has a favourable off-design behaviour for the mHAT application.

4. Conclusion

A Turbec T100 mGT has been converted into a mHAT by adding a saturation tower in between compressor outlet and turbine inlet. The main goal of this conversion was to demonstrate the beneficial effect of compressed air humidification on mGT performance.

Wet experiments at nominal water injection resulted in stable mGT operation at constant power output, reduced rotational speed, pressure ratio and fuel flow rate, resulting in an increased electric efficiency. During these wet tests, an absolute electric efficiency increase of 1.0±1.8%, 1.1±1.8% and 0.8±1.8% was measured at 80, 85 and 90 kW$_e$. The obtained electric efficiency is however below simulation results, which indicates that the compressed air leaving the saturation tower is not fully saturated. A too low water injection temperature is a possible explanation for the incomplete saturation.

Acknowledgments

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Nomenclature

Acronyms

CAF	Corrected Air Flow
CHP	Combined Heat and Power
CIT	Combustor Inlet Temperature
HAT	Humid Air Turbine
ICE	Internal Combustion Engine
mGT	micro Gas Turbine
mHAT	micro Humid Air Turbine
TIT	Turbine Inlet Temperature
TOT	Turbine Outlet Temperature
WAC	Water Atomizing inlet air Cooling

Greek symbols

Δ	difference
η	efficiency, %

Roman symbols

$\dot{m}$	mass flow rate, kg/s
N	rotational speed, rpm
P	electric power, kW
p	pressure, bar
T	temperature, °C

Subscripts and superscripts

el	electric
fuel	conditions of the fuel
hot	hot side
in	inlet conditions
rec	recuperator
ref	reference
sat	saturation tower
water	water

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