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# STEADY-STATE EXPERIMENTAL CHARACTERIZATION OF A FLEXIBLE HUMIDIFIED MICRO GAS TURBINE

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## ABSTRACT

With the increasing share of renewable energy in the total electricity production, the need for flexibility in electrical power production has increased. In some cases, flexibility has even become more important than high efficiency as a primary technology selection criterion. Micro Gas Turbines (mGTs) offer high flexibility for decentralised electricity production due to their limited power output (up to 500 $kW_e$) and operation at variable shaft speed. However, the electrical efficiency of mGTs is rather low (30%). Therefore, mGTs are mainly used in Combined Heat and Power (CHP) applications in which case their total efficiency rises to 80%. In addition, like most CHP plants, mGT operation is mainly heat driven, which has a severe negative effect on the mGT's flexibility.

Humidifying the mGT–converting it into a micro Humid Air Turbine (mHAT)–offers a solution. The waste heat in the exhaust gases is recovered in the mHAT by evaporating auto-raised hot water behind the mGT compressor, resulting in an increased electrical efficiency and a more flexible mGT operation. The mHAT concept combines the high flexibility of the mGT with higher electrical efficiency.

In this paper, we present a complete overview of the results of experiments performed on our humidified Turbec T100 mGT over the last three years. As a proof of concept, the mGT at the Vrije Universiteit Brussel 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 at part and nominal load conditions. Stable runs both at constant power and constant rotational speed mode were achieved during water injection experiments. The latest results show a 4.2 percentage point electrical efficiency increase at constant rotational speed.

## NOMENCLATURE

| | |
|---|---|
| CHP | Combined Heat and Power |
| CIT | Combustor Inlet Temperature |
| ICE | Internal Combustion Engine |
| IEA | International Energy Agency |
| GT | Gas Turbine |
| mGT | micro Gas Turbine |
| mHAT | micro Humid Air turbine |
| VUB | Vrije Universiteit Brussel |
| TOT | Turbine Outlet Temperature |
| TIT | Turbine Inlet Temperature |

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## INTRODUCTION

The International Energy Agency (IEA) (2014) has recently announced that by 2100 our entire economy should be $CO_2$ neutral to limit the effects of climate change. To meet the requirements for limiting global warming, the installed capacity of renewable energy production is increasing rapidly. For the EU, in 2014, renewable electricity generation accounted for 28% of total gross electricity generation (Eurostat, 2016). Due to the high volatility and uncertainty on the predictions of renewable power production from wind and solar energy, there is a strong need for flexibility in the classical electrical power production (EURELECTRIC, 2011).

Micro Gas Turbine (mGTs) operating at variable rotational speed offer this flexibility for decentralized power production due to their limited power output (limited to 500 $kW_e$) (Akorede et al., 2010). Especially when used in Combined Heat and Power (CHP) applications, the mGT displays a very high efficiency of 80%. Additionally, mGTs offer several advantages over their main competitors, Internal Combustion Engines (ICEs): reduced maintenance and engineering costs, a small amount of moving parts, lower noise and vibration level, multi-fuel capabilities and opportunities for lower emissions and cleaner exhaust. However, the major drawback of mGTs is their relative low electrical efficiency (30%, compared to 40% for ICE units with the same power output (Pilavachi, 2002)). This results in a heat-driven use of the mGT. In periods with low or no heat demand, part of the heat should be discarded to keep the mGT operating at high electrical load. Compared to ICEs, the lower electrical efficiency of mGTs makes them less attractive in such a case and economic constraints could even lead to complete shutdown. The specific capital cost of mGTs is still high (Galanti & Massardo, 2011). Due to this high capital cost, any shutdown has a severe negative effect on the economic performance of the mGT (Delattin et al., 2008).

A way to enhance the overall economic performance of an mGT CHP unit is to improve the electrical efficiency of the mGT during periods with low heat demand. Increasing the electrical efficiency will make the mGT more competitive against the ICE. A possible route to improve the electrical efficiency of the mGT is introducing water (vapour/liquid) in the cycle (Jonsson & Yan, 2005). In periods with a low or no heat demand, the lost thermal power can be recovered by injecting auto-raised steam/heated water inside the mGT cycle.

The optimal route for waste heat recovery in an mGT through water injection was found to be the conversion of the mGT into a micro Humid Air Turbine (mHAT) (De Paepe et al., 2014b). The mHAT cycle was selected based on the high electrical efficiency achievable and relative low number of required adaptations to the mGT CHP cycle. These factors result in a low additional capital cost and the ability to operate with a lower water quality. The conversion of an mGT into an mHAT still allows the production of heat, which makes the cycle the perfect candidate for flexible heat production from an mGT. Such a conversion is economically feasible in scenarios with high electricity and low gas prices (Montero Carrero et al., 2016a; Montero Carrero et al., 2016c).

The beneficial effect of converting an mGT into an mHAT has already been studied by several authors (Dodo et al., 2004; Nakano et al., 2007; Nikpey et al., 2014; Parente et al., 2003; Wei & Zang, 2013; Zhang & Xiao, 2006); however, none of the above mentioned papers actually studied an mGT directly connected to a saturation tower. At the Vrije Universiteit Brussel (VUB), we were the first to convert a commercial mGT into an mHAT by coupling it with a saturation tower.

In this paper, we present a complete overview of the results of experiments performed on our humidified Turbec T100 mGT over the last three years. As a proof of concept, the mGT at Vrije Universiteit Brussel 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 mGT performance at part and nominal load conditions.

First, we will introduce the mHAT cycle followed by a presentation of the simulation results. In the subsequent section, the results of experiments, both performed at constant power output and constant rotation speed, will be discussed.

## CYCLE DESCRIPTION

The Turbec T100, which is a classical recuperated Brayton cycle is converted into an mHAT by introducing a saturation tower in between compressor outlet and recuperator inlet (Figure 1). The air entering the cycle is compressed in the variable speed radial compressor (1). In the saturation tower (2), the hot compressed air is humidified by spraying heated water. In this saturation tower, the thermal energy stored in the water is transferred to the air by water evaporation (which can be seen by the temperature decrease of the water over the saturation tower). The outgoing, saturated air is preheated by the hot exhaust gasses in the recuperator (3) and heated further in the combustion chamber by burning natural gas (4). By expanding the hot gasses over the turbine (5), the necessary power to drive the compressor is delivered to the shaft. The remaining shaft power is converted into electrical power in the high speed generator (6). After leaving the recuperator, the remaining heat of the hot exhaust gasses is recovered in the economizer (7) by heating up again water, which is sent back to the saturation tower. To keep the circulating water mass flow rate constant, feedwater is added to the cycle before the economizer (8).

The Turbec T100 installed in the lab of the VUB can be operated both at constant power and constant rotational speed mode. In constant power mode, the rotational speed of compressor and turbine is controlled, to keep the generated power constant. However, the rotational speed is limited to 70000 rpm at nominal power output (100 $kW_e$) and lower at part load. In constant rotational speed mode,

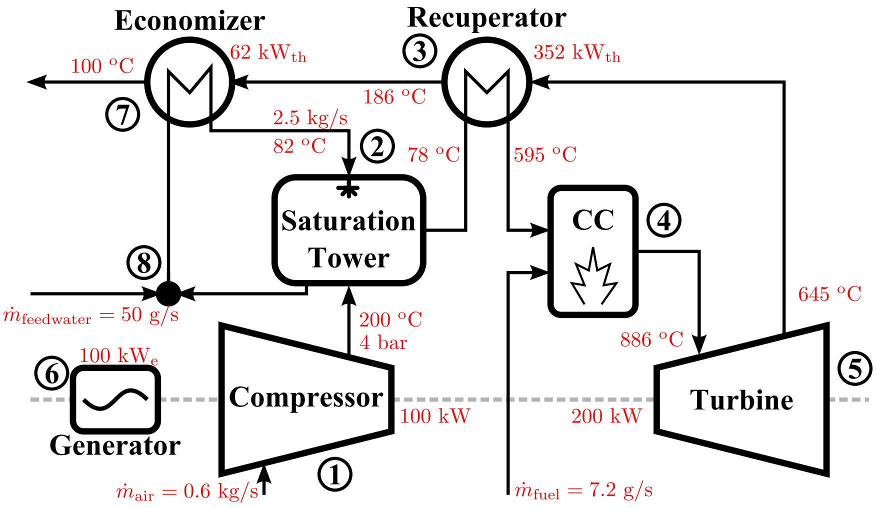
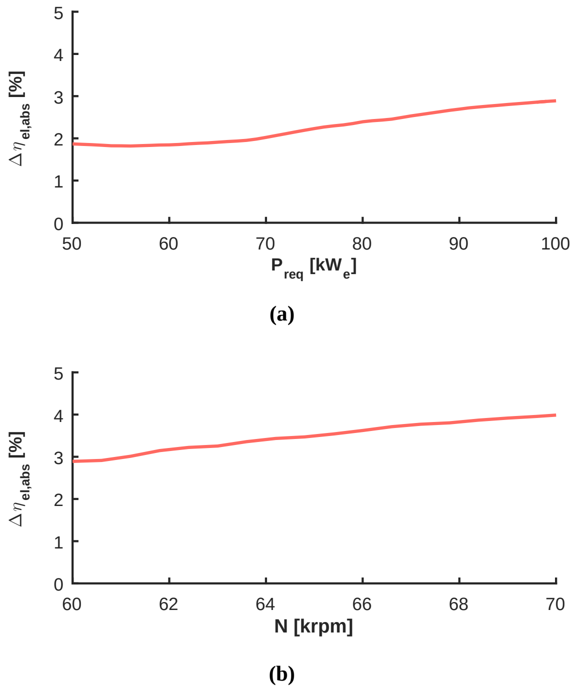


**Figure 1: The recuperated mGT cycle is turned into an mHAT by adding a spray saturation tower between the compressor outlet and recuperator inlet to saturate the compressed air to the cycle. The indicated thermodynamic properties were simulated using Aspen® plus (De Paepe et al., 2014b).**

the rotational speed is set at a specific value, resulting in a different power output. The maximum allowed power output was limited to 105 $kW_e$ to protect the power electronics and particularly the power booster of the Turbec T100. In order to ensure maximal electrical efficiency, the fuel flow rate to the combustion chamber is controlled to keep the Turbine Outlet Temperature (TOT) constant at 645°C.

By introducing water in the cycle, part of the air flow rate through the turbine is replaced by water vapour. Due to the choking of the turbine, the air mass flow rate through the compressor will drop, resulting in more mass going through the turbine than the compressor. At constant rotational speed, this mass imbalance results in a higher remaining net power on the shaft, leading to an increase in produced electrical power. Additionally, the composition of the combustor inlet air changes, leading to a higher heat capacity. On the one hand, due to this higher heat capacity, more fuel will be required to heat the humid air in the combustion chamber to keep the TOT constant. On the other hand, the higher heat capacity affects the turbine and the recuperator. In the turbine, a lower Turbine Inlet Temperature is required, which has a positive effect on the fuel consumption. In the recuperator, heat exchange is improved, thus more heat is recovered. When considering all of these three counteracting effects, the fuel flow rate will still increase, however this increase is limited compared to the gain in produced electrical power, resulting in a net electrical efficiency increase.

At constant power output, the control system will interfere by reducing the rotational speed to keep the power output constant and equal to the value set by the operator. Due to the rotational speed reduction, the total mass flow rate through the combustion chamber will decrease, resulting in a lower fuel mass flow rate compared to the dry operation at the same requested power output. The lower fuel flow rate in combination with the constant power output, will also result in an electrical efficiency increase. The effect of introducing water in the mGT cycle in constant power and constant rotational speed modes is presented in Figure 2. The results were generated using Aspen Plus models of the dry mGT and mHAT cycle (De Paepe et al., 2014b).



(a)

(b)

**Figure 2: By introducing water to the mGT cycle, the efficiency increases, both in constant power (a) and constant rotational speed (b) mode. The absolute increase is however higher in constant rotational speed mode.**

## EXPERIMENTAL SETUP

The Turbec T100 mGT of the VUB has been converted into an mHAT by installing a saturation tower in between the compressor outlet and the recuperator inlet. This saturator, a spray tower without packing material, was specifically designed for the T100 (De Paepe et al., 2014a). By spraying water, the contact surface between the liquid and gaseous phase increases, enhancing and speeding up the heat and mass transfer process. Since no packing material is used, the pressure drop over the saturation tower could theoretically be reduced by 66% (De Paepe et al., 2014a). However, due to a lack of space, the saturation tower needed to be placed alongside the mGT (rather than on top) further to the compressor outlet and recuperator inlet (Figure 3). The additional piping required network introduces an average pressure loss of 10% (De Paepe et al., 2014c). This pressure loss will shift the compressor operation towards the surge limit. To avoid this, during water injection experiments, air was bled (De Paepe et al., 2014c).

To measure the performance of the mHAT cycle, the T100 mGT has been equipped with temperature, pressure and flow rate sensors. Additionally, we developed a specific ‘wet start-up’ procedure consisting in starting water injection prior to starting the mGT. Beginning with water injection while the mGT is in use (the so called ‘dry start-up’ method) resulted in flame-out in the combustion chamber due to the sudden change in combustor inlet temperature. More details about the experimental setup, the surge margin control and the specific mHAT start-up and shutdown procedures are further described by De Paepe et al. (2014c).

## EXPERIMENTAL RESULTS

In this section, we present an overview of the main results of different water injection experimental campaigns. In a first subsection, the overall performance of the T100 mGT with water injection in constant power output mode is discussed. Next, the performance in constant rotational speed mode is presented and discussed. In a final subsection, the performance of some key parts of the mGT, the compressor, recuperator and saturation tower, in humidified conditions, is analysed.

### Constant power mode

A test at 60 kW$_e$ power demand and with air bleed clearly shows the effect of water injection on the electrical efficiency of the mHAT cycle (Figure 4). With increasing injected water flow rate in the saturation tower, the electrical efficiency will also rise. Although the T100 mGT was operating in this test in constant power mode, it can be observed how the generated power increases with escalating water flow rate. Due to the air bleed and additional air pressure drop over the piping network and the saturation tower, the compressor needs to go to higher rotational speed to reach the requested power output. For each power output, a maximum allowed rotational speed is given (in the case of 60 kW$_e$ and the given inlet temperature, around 63000 rpm). Once this speed is reached, the mGT keeps operating at constant maximum rotational speed, rather than at constant power production mode. Measurements of the rotational speed indicate that in dry mode and at low water injection flow rates, the rotational speed remains constant (Figure 4). The evaporation of water in the saturation tower increases the turbine mass flow rate, which in this case raises the electrical power output until the requested power is reached. Once this power output is attained, the control system starts reducing this rotational speed to keep the power output constant (as indicated in Figure 4).


(a) (b)

**Figure 3: Pictures of the integration of the saturation tower in the mGT cycle in between the compressor outlet and recuperator inlet (a) and of the saturation tower with circulation pump, valves and sensors (b).**

Water injection at part and full nominal load of 100 kW$_e$ in constant power mode resulted in stable mHAT operation at reduced rotational speed, pressure ratio and increased electrical efficiency. Figure 5 presents an example of such a test, performed at part load (70, 80 and 90 kW$_e$) and nominal load of 100 kW$_e$, with air bleed to protect the mGT. Water injection has similar effects on mGT performance at all different requested power outputs: electrical operation at requested power output, reduced rotational speed and increased electrical efficiency.

The average results of the best test in constant power mode can be found in Table 1. For all experiments, the electrical efficiency increases with water injection. In all cases, the produced electrical power in dry mode is below the operator controlled requested power output, as a result of the air bleed in combination with the limitation of the control system. On the other hand, in wet mode the requested power output could be reached. The fuel flow rate increases due to the additional water in the working fluid. General results show that water injection has a positive effect on electrical efficiency in constant power output mode, even at low injection rates and low 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. Since the inlet air temperature of the compressor changed during the test, the dry electrical

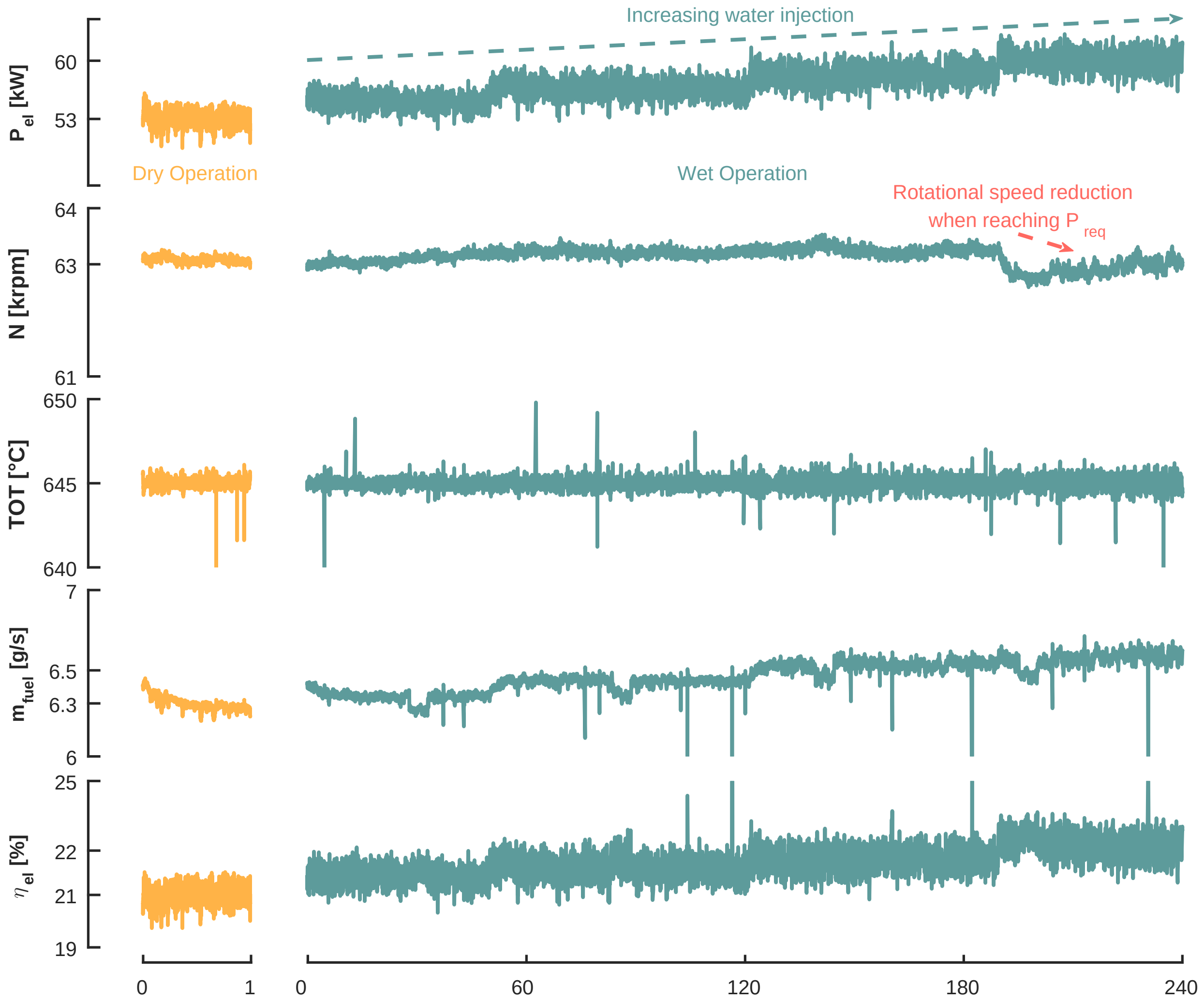


**Figure 4: Increasing the injected water mass flow rate at part load (60 kW$_e$) results in higher power production and electrical efficiency.**

efficiency needs to be compensated. Values of the dry reference efficiencies were corrected using data from previous experiments (Delattin et al., 2008). Final average absolute electrical efficiency increases amounted to 0.9±1.8%, 2.0±1.8 and 3.3±1.8% (temperature compensated) respectively. These values differ from the simulations results (2.4%, 2.7% and 2.9% respectively (Figure 2.(a)), which can be explained by the incorrect dry

**Table 1: Results of stable water injection tests at constant power output mode.**

| | *Dry* | *Wet* | *Dry* | *Wet* | *Dry* | *Wet* |
|---|---|---|---|---|---|---|
| $P_{ref}$ (kW$_e$) | 80.0 | 80.0 | 90.0 | 90.0 | 100.0 | 100.0 |
| $P_{electric}$ (kW$_e$) | 73.3 | 80.0 | 78.6 | 90.0 | 79.1 | 100.0 |
| $N$ (rpm) | 68013 | 63513 | 70028 | 65557 | 70027 | 67958 |
| $N$ (% of nominal) | 97.2 | 90.7 | 100.0 | 93.7 | 100.0 | 97.1 |
| $T_{in}$ (°C) | 21.5 | 18.9 | 21.6 | 19.5 | 20.8 | 20.5 |
| $\dot{m}_{fuel}$ (g/s) | 7.5 | 7.8 | 8.1 | 8.4 | 8.1 | 9.0 |
| $\eta_{electric}$ (%) | 23.0 | 24.2 | 22.9 | 25.1 | 22.9 | 26.0 |
| $\Delta\eta_{electric,corr}$ (%)[1] | / | 0.9 | / | 2.0 | / | 3.3 |

[1] As dry baseline reference, the modified mGT with additional pressure loss and air bleed was used, rather than the unmodified dry mGT. This allows having a clear and representative assessment of the impact of humidification on the mGT cycle performance, excluding losses induced by the non-optimized integration of the saturation tower.

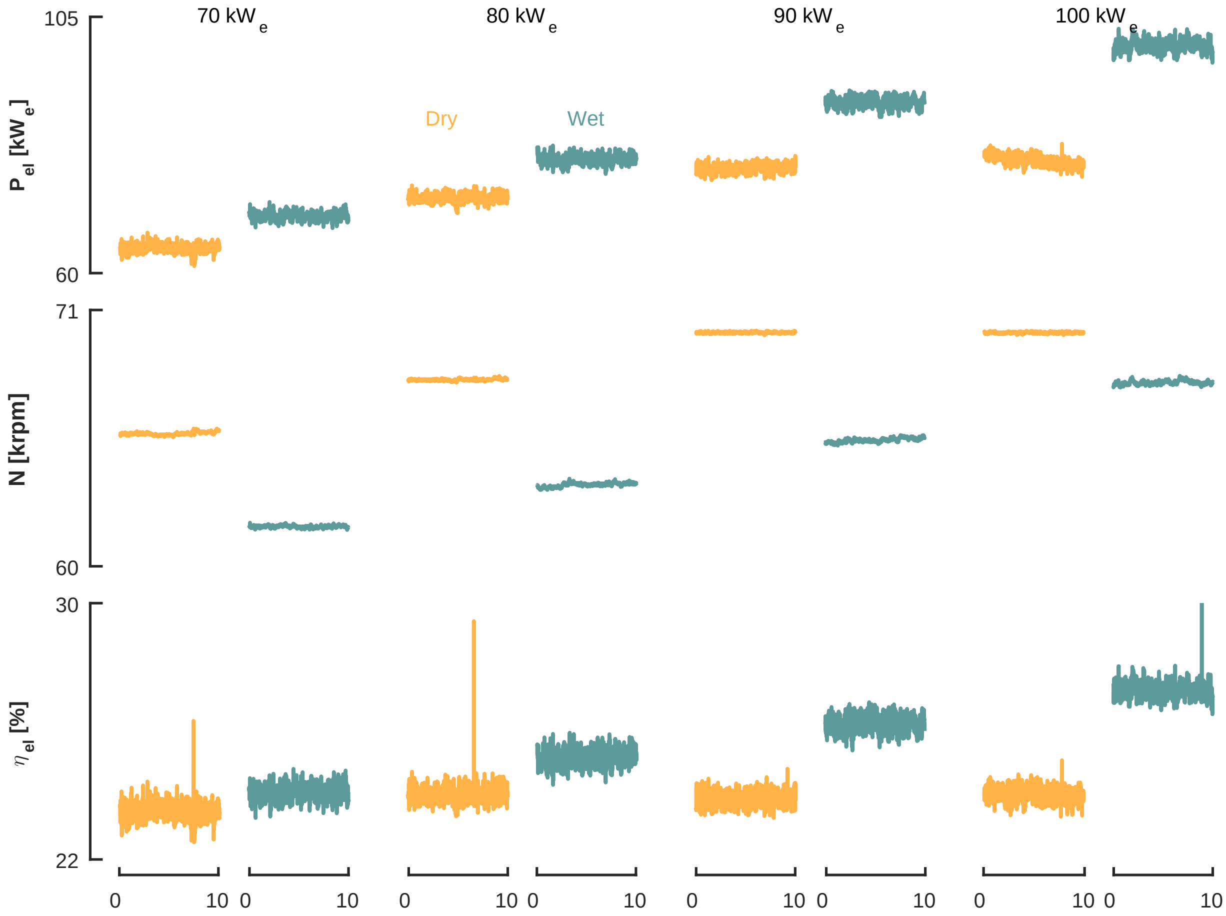


**Figure 5: Experiments with water injection in constant power output mode at different output levels all result in stable mGT operation at constant power production, reduced rotational speed and increased electrical efficiency.**

reference. The experimental reference is not representable, since the requested power output could not be reached (see further).

As previously mentioned, the controller imposes a maximum rotational speed for each requested power output—the maximum at nominal conditions being 70000 rpm. Due to the air bleed and the pressure loss induced by the humidification unit, when operating in dry conditions the T100 hits the corresponding maximum rotational speed before reaching the requested electrical power. Therefore, dry and wet operating points cannot be compared—they have different values for both power output and rotational speed. Thus, the efficiency increase obtained with water injection cannot be properly assessed in this operation mode. In order to address this problem, we modified the controller so that the T100 mHAT could run at fixing the rotational speed.

## Constant rotational speed mode

We carried out several test campaigns in constant rotational speed mode, both with and without water injection. During these tests, the rotational speed varied from 63700 rpm till 69020 rpm (i.e. from 91.0% till 98.6% of the nominal value) in steps of 1% (700 rpm). We chose not to reach the design rotational speed (70000 rpm) because simulations in Aspen Plus revealed that the expected power output with water injection at this speed (~115 kW$_e$) could be harmful for the power electronics. Given that at 69020 rpm the produced power was 103 kW$_e$, which already exceeded the nominal value of the T100, we decided to stop increasing the speed at this point.

Figure 6 shows the results for a test campaign in constant rotational speed mode. It can be observed how the electrical power output for wet and dry operation varies while the rotational speed for both cases is kept constant at a specific point. Therefore, in this operation mode it is possible to have a common ground for both 'dry' and 'wet' operation, thus allowing for a quantitative evaluation of the efficiency increase obtained with water injection.

The best obtained results at constant rotational speed are shown in Table 2. To ensure that the average results well represent each point, the mHAT ran for at least 30 min at each set rotational speed. During the time of the tests, which were carried out through an entire day, the ambient

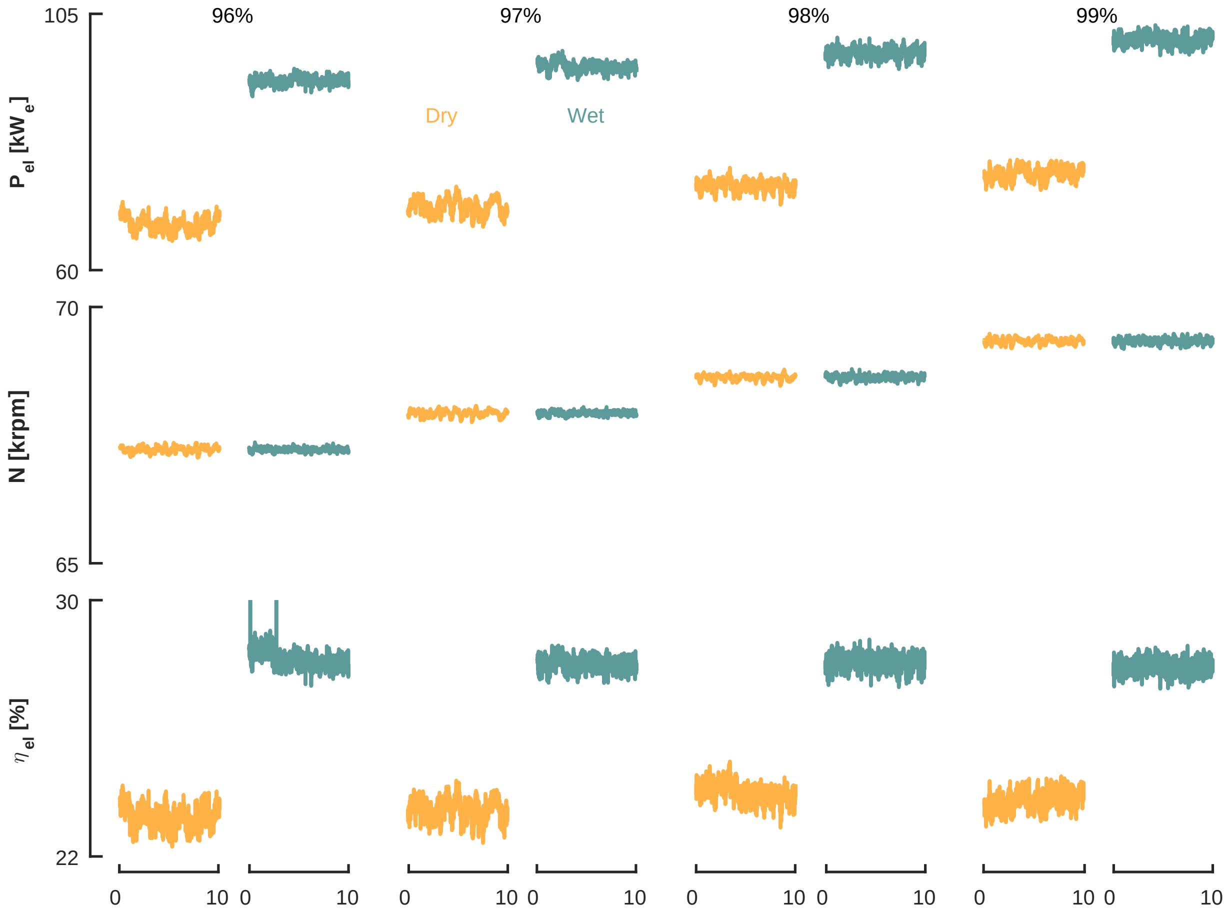


**Figure 6: Experiments with water injection in constant rotational speed mode at different speeds all result in stable mGT operation at constant rotational speed and increased electrical power output and efficiency.**

temperature changed. In order to correctly assess the efficiency increase with wet operation, we have corrected the dry efficiency values to the same ambient temperature as the wet cases based on simulation results.

The effect of water injection is similar for all the points: if the rotational speed is fixed, the electrical power output increases by more than 30% with water injection. In addition, the heat capacity of the air entering the combustion chamber is greater. Therefore, to maintain TOT constant at 645°C the fuel flow rate is higher. Overall, the obtained increase in electrical power output overcomes the higher fuel consumption, leading to electrical efficiency increases ranging from 3.6±0.5% to 4±0.5% for the tests shown in Table 2.

**Table 2: Results of stable water injection tests at constant rotational speed mode.**

| | *Dry* | *Wet* | *Dry* | *Wet* | *Dry* | *Wet* |
|---|---|---|---|---|---|---|
| $N$ (rpm) | 63720 | 63720 | 66520 | 66520 | 68990 | 68990 |
| $N$ (% of nominal) | 91.0 | 91.0 | 95.0 | 95.0 | 98.6 | 98.6 |
| $P_{electric}$ ($kW_e$) | 54.5 | 72.1 | 66.8 | 86.9 | 76.5 | 102.7 |
| $T_{in}$ (°C) | 25.1 | 22.6 | 23.2 | 23.4 | 25.1 | 22.7 |
| $\dot{m}_{fuel}$ (g/s) | 6.0 | 6.7 | 7.0 | 7.8 | 8.0 | 8.9 |
| $\eta_{electric}$ (%) | 22.2 | 26.1 | 23.5 | 27.2 | 23.7 | 28.1 |
| $\Delta\eta_{electric,corr}$ (%)[1] | / | 3.5 | / | 3.7 | / | 4.0 |

[1] As dry baseline reference, the modified mGT with additional pressure loss and air bleed was used, rather than the unmodified dry mGT. This allows having a clear and representative assessment of the impact of humidification on the mGT cycle performance, excluding losses induced by the non-optimized integration of the saturation tower.

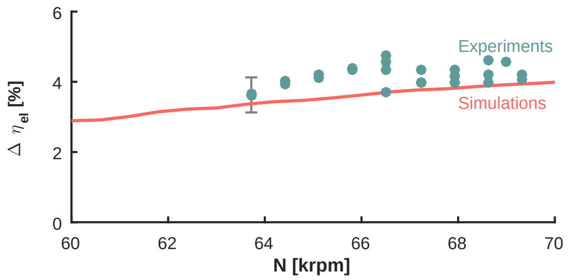


**Figure 7: The measured increase in electrical efficiency in constant rotational speed mode is above the prediction from the Aspen® simulations, because the air bleeding favours the efficiency increase.**

The efficiency increase obtained with water injection with respect to dry operation data—the later corrected to match the ambient temperature of the wet tests—for all the optimised wet experiment (the ones displayed in Table 2 plus some preliminary tests) is shown in Figure 7. Because of the constraints of the facility it was not possible to implement flow measurement techniques; therefore, we cannot determine how much air is actually bled during the tests. It is important to bear in mind that air bleeding leads to higher electrical efficiency increases when comparing dry and wet operating points; this is why in Figure 7, the experimental results appear to be better than simulations. Nonetheless, it is obvious that water injection does lead to an electrical efficiency increase. In constant rotational speed mode, the T100 mHAT at VUB allows assessing this increase, which ranges between 3.6±0.5% and 4.2±0.5%.

Similar to the results from Table 1 and Table 2, the modified mGT with additional pressure loss and air bleed was used as dry baseline reference for Figure 7. Comparing the experimental results with the unmodified dry mGT performance — which would be more appropriate in an economic analysis — would underestimate the performance of the mHAT. The experimental performance of the mHAT is penalised by pressure losses resulting from the non-optimal integration of the saturation tower, caused by site-specific limitations, sensor installations and the air bleed loss, which was necessary to protect the compressor against surge. In a final industrial version of the mHAT, the integration of the saturation tower will be optimized, limiting the pressure losses to 0.5%, limiting the loss in efficiency to 0.15 percentage point, compared to the dry standard mGT (Lagerstrom & Xie, 2002). The final expected efficiency increase of this optimized mHAT at constant rotation speed will be in the same range as the obtained experimental results (i.e. 3.6 to 4.2±0.5%.).

## mHAT components performance

Besides the compressor and the turbine, the recuperator and the saturation tower are two important components that determine the efficiency of the Turbec T100 mGT converted to mHAT. In this subsection, the performance of both the saturation tower and the recuperator will be discussed. To this end, results of the experiments presented in Figure 7 have been used.

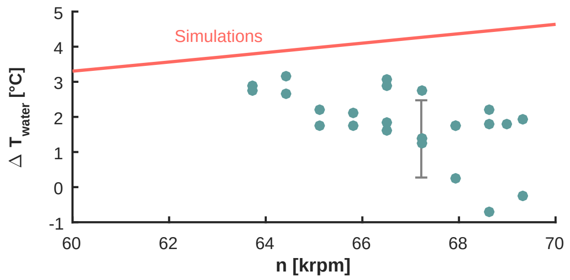


**Figure 8: The temperature drop over the saturation tower of injected water is in line with the predictions from simulations.**

The goal of the saturation tower is to humidify the 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 water itself. This is indicated by the lower outgoing water temperature compared to the ingoing water temperature (Figure 2). As a consequence, additional heat is recovered in the mHAT cycle, which results in higher electrical efficiency, compared to steam and water injection (De Paepe et al., 2014b).

Experimental results show that the temperature of the outgoing water temperature is in most cases lower than the ingoing water temperature (Figure 8), as was predicted in the simulations. This indicates that part of the necessary heat for the water to evaporate is indeed not only provided by the sensible heat of the compressed air, but also taken from the hot water, explaining the high electrical efficiency increases reported in Figure 7.

The spray saturation tower was especially designed to reduce the head loss over the humidification unit. 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 difference in pressure drop between the in- and outlet duct of the saturation tower, taking into account the droplet separator, during dry and wet operation is very low (below the accuracy of the pressure sensors, Figure 9). This indicates that the pressure drop induced by the water spray is in line with the prediction from simulation results (De Paepe et al., 2014a). However, the pressure drop over the entire humidification unit was high (8% in dry mode and 6% in wet mode, Figure 9), which has a severe negative effect on the mGT performance. The main causes of the high pressure drop were the additional measuring equipment that was installed and the long tubes to connect compressor exhaust and recuperator inlet with the humidification unit (given that, because of the lack of space, the saturator had to be placed further away than initially planned). 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. During water injection

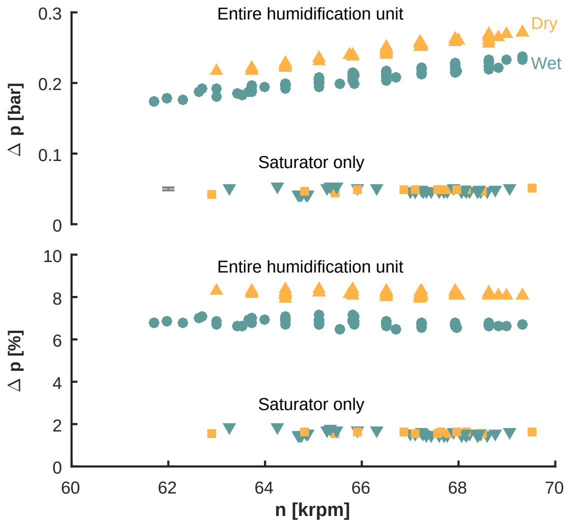


**Figure 9: The additional pressure drop in the saturation tower due to the water injection is very low.**

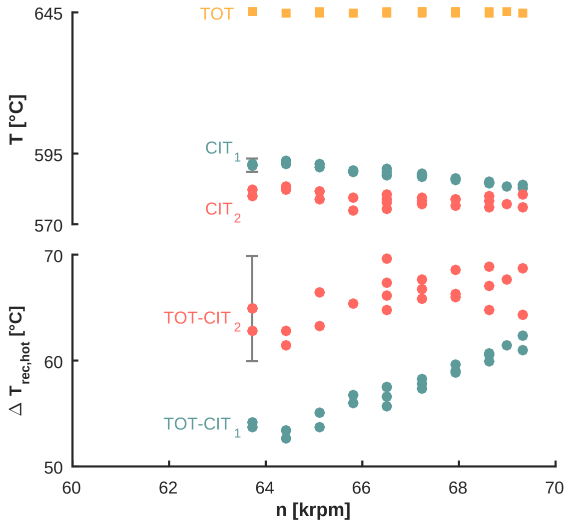


**Figure 10: The constant hot pinch temperature indicates that the Turbec T100 mGT has a favourable off-design behaviour for the mHAT application.**

experiments, the total gas mass flow rate through the saturator drops, together with the gas density (as a result of the lower temperature). The lower pressure drop during water injection (Figure 9) is thus a result of the lower air volumetric flow rate.

In the Turbec T100 mGT, a typical partial cross, partial counter flow heat exchanger (Lagerstrom & Xie, 2002) 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 give rise to higher heat recuperator efficiencies, but will make the heat exchanger too expensive and big.

As mentioned in the cycle description, 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 and the altered heat capacity of the working fluid (because of the addition of water), more heat can be exchanged. This is however limited by the contact area of the recuperator. Nevertheless, experimental results show that the effect of the fixed contact area is rather limited (Figure 10). The temperature difference on the hot side of the recuperator is close to this 50°C (slightly higher) for the majority of the experiments, which indicates that the recuperator has a favourable off-design behaviour. The temperature of the outgoing cold stream is measured at 2 different positions: at the top of the recuperator (CIT$_1$) and at the bottom (CIT$_2$). The small difference (10°C) between CIT$_1$ and CIT$_2$ is mostly due to their position (a similar recuperator imbalance was recorded in dry operation mode). During preliminary water injection experiments, bigger differences have been observed, as a result of liquid water entering the recuperator on the cold inlet. By optimizing the injection pressure in the saturation tower, the imbalance in the recuperator was successfully reduced (Montero Carrero et al., 2016b).

As a final remark, the constant TOT (645°C) measured during the water injection experiments indicates that the control system is capable of keeping this temperature constant. It is thus possible to run the commercial Turbec T100 mGT system without modifying the engine control system.

## CONCLUSION

In the present paper we presented an overview of the experiments with water injection in nominal conditions carried out at the unique T100 mHAT facility present at the VUB. This mHAT unit is equipped with a dedicated spray saturation tower which offers the potential to reduce pressure losses compared to traditional units designed with packing material.

We conducted two experimental campaigns; one keeping the original settings of the T100 mGT, i.e. with the control system modifying the rotational speed so as to obtain a constant electrical power output equal to the requested value by the operator. For a second campaign, we modified the controller so that the mHAT could run at fixed rotational speed instead of at constant electrical power output. During both campaigns, we aimed at optimizing the water injection pressure and temperature to ensure that the required water evaporated in the saturation tower.

Wet experiments at nominal water injection resulted in stable mHAT operation at both constant power output and constant rotational speed. In constant power output mode, water injection resulted in a reduced rotational speed, pressure ratio and fuel consumption. A full characterisation of the mHAT performance at constant power output was not possible, since due to the limitations of the control system, no representable dry reference could be captured. Therefore, we focused on the experiments at constant rotational speed. In this mode, the power output with water injection increases by more than 30% with respect to dry operation. Fuel consumption also rises due to lower CIT values, increased mass flow rates in the combustion chamber and increased heat capacity of the air and steam mixture. Overall, experimental results demonstrate the patent benefits of water injection on mGT performance: the electrical efficiency in wet operation at constant rotational speed increases by up to 4.2% absolute compared to the modified dry mGT with air bleed. By optimizing the integration of the saturation tower in the mHAT cycle will result in similar efficiency increases compared to the dry standard mGT cycle.

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## REFERENCES

Akorede, M. F., Hizam, H., & Pouresmaeil, E. (2010). Distributed energy resources and benefits to the environment. *Renewable and Sustainable Energy Reviews, 14*(2), 724-734.

De Paepe, W., Contino, F., Delattin, F., Bram, S., & De Ruyck, J. (2014a). New concept of spray saturation tower for micro Humid Air Turbine applications. *Applied Energy, 130*, 723-737.

De Paepe, W., Contino, F., Delattin, F., Bram, S., & De Ruyck, J. (2014b). Optimal waste heat recovery in micro gas turbine cycles through liquid water injection. *Applied Thermal Engineering, 70*(1), 846-856.

De Paepe, W., Montero Carrero, M., Bram, S., & Contino, F. (2014c). T100 micro Gas Turbine converted to full Humid Air Operation: Test rig evaluation. *Conference Proceedings (ASME paper GT2014-26123),* V03AT07A020 , 011 pages.

Delattin, F., Bram, S., Knoops, S., & De Ruyck, J. (2008). Effects of steam injection on microturbine efficiency and performance. *Energy, 33*(2), 241-247.

Dodo, S., Nakano, S., Inoue, T., Ichinose, M., Yagi, M., Tsubouchi, K., Yamaguchi, K., & Hayasaka, Y. (2004). Development of an Advanced Microturbine System Using Humid Air Turbine Cycle. *ASME Conference Proceedings (ASME Paper GT2004-54337),* 167-174.

EURELECTRIC. (2011). Renewables Action Plan (RESAP): Flexible Generation: Backing up renewables.

Eurostat. (2016). Energy from renewable sources (Vol. http://ec.europa.eu/eurostat/statistics-explained/index.php/Energy_from_renewable_sources#Electricity_generation_from_renewable_sources (Accessed 5/4/2016)).

Galanti, L., & Massardo, A. F. (2011). Micro gas turbine thermodynamic and economic analysis up to 500kWe size. *Applied Energy, 88*(12), 4795-4802.

International Energy Agency (IEA). (2014). Tracking Clean Energy Progress 2014.

Jonsson, M., & Yan, J. (2005). Humidified gas turbines – a review of proposed and implemented cycles. *Energy, 30*(7), 1013-1078.

Lagerstrom, G., & Xie, M. (2002). High Performance and Cost Effective Recuperator for Micro-Gas Turbines. *ASME Conference Proceedings (ASME Paper GT2002-30402)*, 1003-1007.

Montero Carrero, M., De Paepe, W., Bram, S., Musin, F., Parente, A., & Contino, F. (2016a). Humidified micro gas turbines for domestic users: an economic and primary energy savings analysis. *Energy, doi:10.1016/j.energy.2016.04.024*.

Montero Carrero, M., De Paepe, W., Magnusson, J., Parente, A., Bram, S., & Contino, F. (2016b). Experimental characterisation of a humidified T100 micro gas turbine. *ASME Conference Proceedings (ASME paper GT2016-57265)*, 11 pages.

Montero Carrero, M., De Paepe, W., Parente, A., & Contino, F. (2016c). T100 mGT converted into mHAT for domestic applications: Economic analysis based on hourly demand. *Applied Energy, 164*, 1019–1027.

Nakano, S., Kishibe, T., Araki, H., Yagi, M., Tsubouchi, K., Ichinose, M., Hayasaka, Y., Sasaki, M., Inoue, T., & Yamaguchi, K. (2007). Development of a 150kW microturbine system which applies the humid air turbine cycle. *ASME Conference Proceedings (ASME paper GT2007-28192)*, 1041-1048.

Nikpey, H., Majoumerd, M. M., Assadi, M., & Breuhaus, P. (2014). Thermodynamic analysis of innovative micro gas turbine cycles. *ASME Conference Proceedings (ASME paper GT2014-26917),* V03AT07A029 (009 pages)

Parente, J., Traverso, A., & Massardo, A. F. (2003). Micro Humid Air Cycle: Part A – Thermodynamic and Technical Aspects. *ASME Conference Proceedings (ASME Paper GT2003-38326), 2003*, 221-229.

Pilavachi, P. A. (2002). Mini- and micro-gas turbines for combined heat and power. *Applied Thermal Engineering, 22*(18), 2003 - 2014.

Wei, C., & Zang, S. (2013). Experimental investigation on the off-design performance of a small-sized humid air turbine cycle. *Applied Thermal Engineering, 51*(1–2), 166-176.

Zhang, S., & Xiao, Y. (2006). Steady-State Off-Design Thermodynamic Performance Analysis of a Humid Air Turbine Based on a Micro Turbine. *ASME Conference Proceedings (ASME Paper GT2006-90335)*, 287-296.