Proceedings of ASME Turbo Expo 2018
Turbomachinery Technical Conference and Exposition
GT2018
June 11-15, 2018, Oslo, Norway

GT2018-75979

MODEL BASED DIAGNOSTICS OF AE-T100 MICRO HUMID AIR TURBINE CYCLE

Mariam Mahmood*[1,2], Alessio Martini[1], Aristide F.Massardo[1], Ward De Paepe[3]**

[1]Department of Mechanical Engineering (DIME),University of Genova, Italy
[2] National University of Sciences and Technology (NUST), Pakistan
[3] Thermal Engineering and Combustion Unit, University of Mons (UMONS), Belgium
*Email: mariam.mahmood@edu.unige.it
**Previous affiliation: Vrije Universiteit Brussel (VUB), Belgium

ABSTRACT

Micro gas turbines (mGT) are emerging power sources for distributed generation facilities with promising features like environment friendliness, high fuel flexibility, cost effectiveness and efficient cogeneration of heat and power (CHP). However, curtailed heat demand during summers reduces the plant operating hours per year and negatively affects the overall economic feasibility of a CHP project. The micro Humid Air Turbine (mHAT) cycle is one of the novel cycles to increase the electrical efficiency of the gas turbine by utilizing the exhaust gas heat in periods of low heat demand, thus avoiding the system shutdown. However, the water injection system can introduce additional pressure losses in the mGT cycle, which may lead to compressor surge and it may also affect the recuperator performance in the long run due to corrosion. Hence, numerical simulation and diagnostic tools are essential for cycle optimization of mHAT and prediction of performance degradation.

This work is focused on the real time application of the AE-T100 model for the mHAT system located at the Vrije Universiteit Brussel (VUB), which is based on the T100 mGT equipped with a spray saturation tower. The AE-T100 model is a steady-state simulation tool for mGT cycles, which has been developed within a collaboration between the University of Genova (Unige) and Ansaldo Energia, and has been successfully applied at the Ansaldo Enegia test rig (AE-T100) for the diagnostic purpose. For this study, the basic AE-T100 model has been modified to simulate the humidified cycle according to the VUB plant configuration. The modified AE-T100 model has been validated against the experimental data obtained from the mHAT unit at nominal and part load.

Once the model was validated using real operating conditions, it has been used for monitoring the recuperator performance over large number of tests in dry mode, conducted over the past five years, as well as initial tests in wet mode, from the VUB-mHAT system. This work has proved the modeling capability of the AE-T100 tool to simulate the mHAT cycle with reasonable accuracy and first diagnostic application of the AE-T100 tool, in dry mode. However, the lack of data available at present in wet mode does not allow to provide a complete and robust diagnostics of this novel cycle under wet operation.

Hence, this preliminary analysis will provide basis for more detail diagnostics of the mHAT cycle using AE-T100 tool, over a longer time period under wet operation, in future.

NOMENCLATURE

Abbreviations

AE-T100	Ansaldo Energia - T100
CHP	Combined generation of Heat and Power
DG	Distributed Generation
DSA	Dynamic System Analyser
EFmGT	Externally Fired micro Gas Turbine
ISO	International Standards Organization
LHV	Lower Heating Value
mGT	micro Gas Turbine
mHAT	micro Humid Air Turbine
RMSE	Root Mean Square Error
TIT	Turbine Inlet Temperature
TOT	Turbine Outlet Temperature

Alphanumeric Variables

$e_{rel,i}$	Relative percent error of i^{th} parameter
Rec_{eff}	Recuperator effectiveness
$Rec_{des,eff}$	Recuperator design effectiveness
$x_{field,i}$	Field value of i^{th} parameter
$x_{tuned,i}$	Tuned model value of i^{th} parameter

INTRODUCTION

In past few decades, the global energy market has been influenced by fluctuating oil prices, dwindling supply of conventional fuels and concerns about greenhouse gas emissions. Hence, electricity markets are adopting clean and efficient energy production systems to cope with the stringent fuel supply, deregulated energy markets and also to mitigate the environmental deterioration caused by fossil fuel consumption [1]. In this scenario, small-scale Distributed Generation (DG) systems are expected to play a vital role in present and future power infrastructure. In addition to the economic feasibility offered by DG systems, combined generation of heat and power (CHP) with small decentralized CHP units (in the range of 30 kW_e - 200 kW_e, for multiple-household applications, schools, hotels, hospitals, etc) is an emerging technology. Such CHP systems have the potential of realizing considerable energy savings in comparison with traditional separate production systems, with net efficiency up to 80% [2-4]. However, the feasibility of a CHP unit is strongly linked to the continuous heat production: when there is no or low heat demand during summers (particularly for residential cases), the exhaust heat from the co-generation facility has to be rejected. Hence, the net efficiency of the CHP production systems drops down to the electrical efficiency [5].

The Micro Gas Turbines (mGTs) are attractive power generation source in DG systems, with their promising features like high rate of exhaust heat recovery in CHP mode, compact size, high fuel flexibility, cleaner exhausts and low maintenance and operational cost. However, mGTs still have lower electrical efficiencies than similarly sized reciprocating engine generators (with 85% effective recuperator the efficiency can be as high as 30 to 33%) [6]. Hence, curtailed heat demand will lead to the mGT running at part load or even to a shutdown of the unit due to lower electric efficiency and not competitive with electricity from the grid. Thus, a finite number of running hours per year negatively affects the overall feasibility of a CHP project and results in lower investment payback [7].

Several alternative routes have been researched to improve the mGT performance and enhance the heat recovery like compressed air humidification [8-10] and water or steam injection [11-13]. These wet mGT cycles introduce flexibility in the operation of CHP plants, as they are able to achieve variable power-to-heat ratio and the engine can still operate at full electric load while covering the lower heat demand [14]. The micro Humid Air Turbine (mHAT) cycle is one of these novel cycles to increase the electrical efficiency of the mGT: exhaust gas is utilized to heat up water and then inject it back into the cycle to humidify the compressed air. Thus, air humidification improves the overall cycle performance by efficient utilization of waste heat and avoids system shutdown during hotter periods with reduced heat demand [15-17].

Starting form model development, several experimental campaigns have been carried out for thermodynamic performance analysis and optimizing the waste heat recovery through steam injection in a typical recuperated mGT cycle [18, 19], as well as to study the impact of steam rich mass flow rate on mGT behavior in the hybrid systems [20]. These experiments have proved the beneficial impact of steam injection on mGT performance i.e higher electrical efficiency at reduced shaft speed. This experimental work has also demonstrated the capability of the T100 to handle compressed air humidification.

Considerable research activities have also been carried out in the field of experimental characterization [21], and numerical modeling of the mHAT cycle. Montero Carrero *et.al* [22] have modeled the dynamic behavior of a Turbec T100 machine, which has been modified into mHAT cycle, with the help of the TRANSEO tool: a simulation tool which has been developed by Thermochemical Power Group (TPG) at the University of Genova, for real time and transient analysis of complex energy systems [23]. This study is aimed at modeling the dynamic behavior of such a complex system in order to protect the components during transient operation and simulating the cycle performance in case of load fluctuations.

In addition to the overall system analysis of the mHAT cycle, component modeling and thermodynamic assessment of the humidifier has also been in focus. Parente *et.al* [24] have performed a thermodynamic analysis and a preliminary cost evaluation for a packed bed humidifier with two different approaches: the full integration of the mass-energy balance and mass transfer equations (called SAT model), and an atmospheric cooling tower-based model (called CT model). Two simulation cases are discussed: a test case, with experimental results from the pilot-plant of the University of Lund, and a case study of the saturators for the optimized HAT cycles of a plant with a 50 MW power output.

Pedemonte *et.al* [25, 26] have performed an experimental analysis of a pressurized humidification tower with structured packing for HAT cycle. This experimental campaign was carried out over 162 working points, covering a relatively wide range of possible operating conditions. In the subsequent study, the authors have correlated all the data points collected previously, based on two different approaches: polynomial correlation and second using a set of new non-dimensional groups, and compared these correlations to represent the data. These correlations are useful for describing the off-design behavior of the pressurized saturation tower. The overall thermodynamic analysis showed the relation of the saturator's performance (in terms of air outlet humidity and temperature) with inlet water temperature, the inlet water over inlet dry air mass flow ratio and the inlet air temperature.

Air humidification has proven to be a very efficient way to re-introduce the thermal power in the mGT cycle and by doing so, allowing for waste heat recovery. De Paepe *et al.* [27, 28] have presented the test rig evaluation and thermodynamic performance analysis based on the initial tests conducted on T100 mHAT system. Experimental characterization of the mHAT at full load has demonstrated the patent benefits of water injection on mGT performance: power output of mHAT increases by more than 30% with respect to the dry operation, and electrical efficiency increases by up to 4.2% absolute points [29].

However, water injection can introduce additional pressure losses in the mGT cycle due to the humidification unit and added piping, which may lead to compressor surge as surge margin is reduced [15,16]. Air humidification may also affect the recuperator performance in the long run due to corrosion, especially on the hot side. Given that this component is the most expensive of the cycle amounting up to 30% of the total capital cost [30]—the lifetime of the recuperator determines the lifetime of the mGT. Water injection significantly reduces the lifetime of the recuperator [31].

Hence, the correct assessment of the lifetime reduction during wet operation as a result of the faster degradation of the recuperator is essential for the economic feasibility of this novel cycle. The existing economical analyses showing the potential of humidified cycles like the STIG and mHAT use the classical lifetime of mGTs and consider constant cycle performance. The validity of these models depends on the correct estimation of the performance degradation and the unit lifetime. Since the humidification of mGT cycles is a rather novel concept and limited full operational test rigs and experimental data is available, hence, numerical simulation and diagnostic tools are essential for cycle optimization of the mHAT and prediction of performance degradation to allow for the correct economical assessment.

The present work intends to contribute towards this analysis. The work starts with modeling the mHAT system located at Vrije Universiteit Brussel (VUB), through the application of the AE-T100 model. The AE-T100 model has been developed within collaboration between the TPG at the University of Genova (Unige) and Ansaldo Energia. The AE-T100 model is a steady state simulation tool for mGT in off-design conditions and it also possesses the diagnostic capability of mGT cycles. Model development, basic structure, tuning, first phase of validation through the Ansaldo Energia test rig (AE-T100) and diagnostic applications of the model have been presented in the previous studies [32, 33].

In this study, the basic AE-T100 model has been modified to simulate the humidified cycle according to the VUB plant layout. The modified AE-T100 model has been validated against experimental data obtained from the mHAT unit, and recuperator performance has been analyzed at nominal and part load, under wet and dry operation. Since the mHAT cycle under study is a novel cycle , unique of its kind, which is still under development, and there is not yet enough experimental data available of wet operation to do full diagnostics. Hence, the AE-T100 tool is applied to analyze the recuperator performance degradation in the VUB- mHAT system over the past five years, based on several sets of experimental data. The recuperator actual design effectiveness, determined based on the new set of design conditions, is compared with the initial value provided by the supplier. This comparison determines the recuperator performance degradation since the start of experimental activities on the mHAT system, in dry mode.

Hence, this performance analysis has provided the basis for a complete and robust diagnostics of this novel cycle. In the future, this AE-T100 diagnostics tool will be extended to and validated under wet conditions, when further experimental data will be available.

THE PLANT LAYOUT

The VUB-mHAT test rig consists out of a Turbec T100 mGT (version 2), which is a typical mGT based on the recuperated Brayton cycle, and a spray saturation tower for cycle humidification (schemical layout shown in Figure1). In the T100, air being compressed in the radial compressor (1) is preheated in the recuperator (3) using the hot exhaust gasses coming from the turbine, before the temperature is increased up to the maximal Turbine Inlet Temperature (TIT) of 950°C in the combustion chamber (4) where it combusts with natural gas. By expanding over the turbine (5), the necessary power to drive the compressor is delivered and the remaining mechanical power on the shaft is converted into electrical power in the high-speed generator. The remaining heat in the exhaust gasses is converted into thermal power for heating purpose in the Economizer (6).

The T100 is equipped with a control system, keeping both the electrical power output and the Turbine Outlet Temperature (TOT) constant. The electrical power output is kept constant by varying the rotational speed of the compressor, allowing to operate at high efficiency at part load. To maintain the efficiency of the mGT, TIT should be kept high. Due to the technical limitations concerning the measurement of TIT, the TOT measurement is used by the control system to adjust the fuel flow rate. The control system will aim at keeping TOT at 645°C.

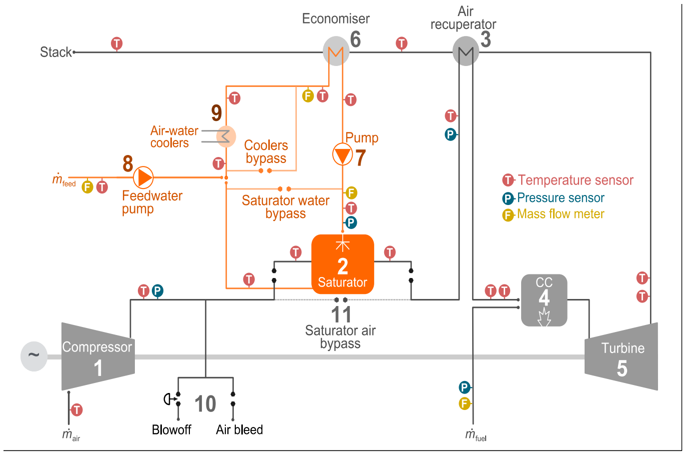

Figure 1. The schematic layout of the VUB-mHAT along with all the sensors installed in the facility. In grey, the elements corresponding to a typical recuperated mGT. In orange, the components that have been added to transform the unit into an mHAT (reproduced from [29]).

By introducing a saturator in between the compressor outlet and the recuperator inlet ((2) in Figure 1), the compressed air can be humidified by injecting hot water coming from the economizer, which will partially evaporate. Hence, waste heat is recovered in the cycle in the form of water vapor in the working fluid. For the VUB-mHAT test rig, a specific saturator, using a water spray instead of packing material to enlarge the contact area between water and air, and to enhance heat and mass transfer, has been developed and installed [34]. Figure 2 shows the saturation tower designed for the mHAT cycle and mGT integerated with humidification unit. In the system, a bypass for the compressed air was installed over the saturation tower, to allow dry operation of the mGT without having to pass through this saturator and by doing so, limiting the pressure losses (11). Next to the saturator, the test rig has been equipped with several sensors (as shown in Figure.1) to measure temperature, pressure and flow rates, enabling the assessment of the impact of cycle humidification on the mGT performance (a full description of the installed sensors can be found in [29]).

Figure 2. Saturator for VUB-mHAT system (left), T100 test rig modified to connect with humidification unit (right).

The test results used for this study have been obtained from the VUB-mHAT test rig previously, following the same test procedure as presented in reference [27], and full impact of the humidifcation on the cycle has been assessed in references [28] and [29]. This test procedure includes an initial dry run of the mGT to preheat the installation prior to water injection, followed by a wet run. Water injection is initiated before the mGT is started, since direct injection during a dry run leads to sudden flameout of the mGT due to the sudden change in combustor inlet air temperature. At the end of each water injection test, a dry reference was captured, by performing a dry run.

For the humidified tests with the VUB-mHAT test rig, the original mGT control system was slightly adapted. As described by Montero Carrero et.al [29], due to the rather high pressure losses induced by the saturator and the connecting piping, the requested power output could not be obtained during the dry reference run, which does not allow for a correct comparison of the mHAT performance with dry mGT operation. Therefore, both dry and wet experiments have been performed at constant rotational speed at the VUB-mHAT test rig.

Extensive experimental work has been carried out in dry mode, during past five years (from 2012 to 2017), at the speed ranging from nominal rotational speed of 70,000 rpm (100%) to part load (down to 86%). Figure 3 shows the speed range during all the dry tests: each point corresponds to a test. However, these tests are not uniformly distributed over the period of five years: maximum number of tests have been conducted during 2012, with very few tests conducted during 2017.

Since the VUB-mHAT system is still under development, hence few number of tests have been performed in the wet mode during the year 2015. Similar to the dry tests, wet tests are also not consistent over the period of one month: maximum number of test have been conduced during second half of Septemebr 2015. During the wet tests, the rotational speed was varied between nominal rotational speed (70,000 rpm) and partial rotational speed (down to 89% of the nominal speed, Figure 4).

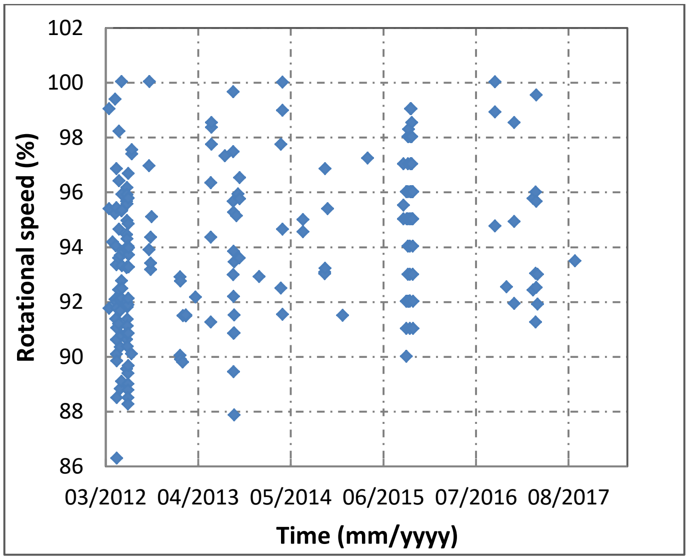

Figure 3.Tests conducted at VUB-mHAT test rig in dry mode.

The second control loop in the controller, being TOT control, was not changed during the wet experiments. Test results showed that without changing the control system, a constant TOT of 645°C could be obtained during wet runs at constant rotational speed, highlighting the stability of the control system [29]. Finally, to protect the compressor against surge during emergency shutdown, during all wet experiments, a small fraction of the compressor air flow rate was bled ((10) on Figure 1).

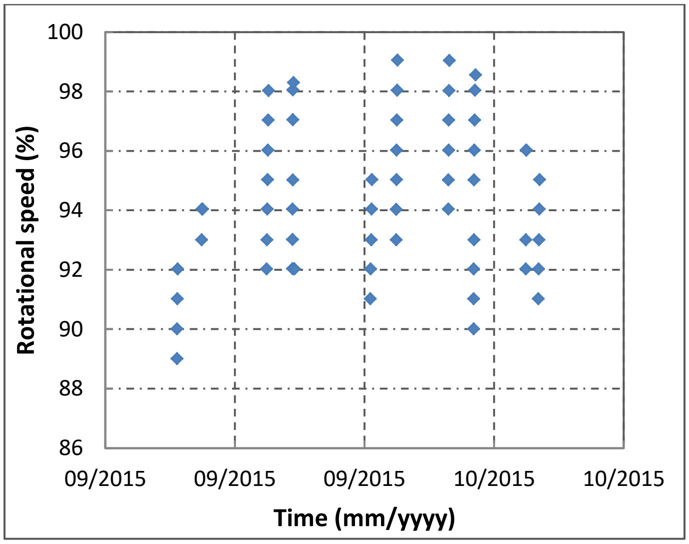

Figure 4.Tests conducted at VUB-mHAT test rig in wet mode.

MODELING THE VUB-mHAT CYCLE

The AE-T100 model is a steady state simulation tool for mGTs in off-design conditions. It is developed from the original BT-100 model available at Ansaldo Energia, and validated against a reference model Dynamic System Analyser (DSA), which has been originally developed by VOLVO. Thermodynamic equations for each component are solved in the MATLAB environment, based on the design conditions and inputs provided by the user through graphical user interface (GUI). Overall mathematical approach involves the iterative process based on the Newton-Raphson method inside the MATLAB code, to determine the mGT parameters. Model development and basic layout of the AE-T100 has been explained in [32].

Modifications To The Basic AE-T100 Model

In order to simulate the VUB-mHAT cycle, the basic AE-T100 model has been modified accordingly (red components in Figure 5). Considering the simple approach, this modification does not involve any saturator model, but it simply involves the addition of an additional Mixer (M) in the basic model and consequent changes in the thermodynamic parameters of the cycle. Thus, the saturation tower is modeled with the help of the Mixer, where a water stream at 80°C, heated by the exhaust gases, is mixed with compressed air. As a result, the outlet air of the saturator is fully humidified, having higher enthalpy, higher mass flow rate and higher specific heat capacity, which is then fed to the Recuperator (Rec). Afterwards, the mHAT cycle is modeled with the same approach as in the previous configuration of AE-T100 model. However, more detail on the mathematical approach and thermodynamic equations cannot be mentioned explicitly due to proprietary. Figure 5 shows the modified AE-T100 model layout for theVUB-mHAT cycle.

Legend	
S	Splitter
D	Duct
M	Mixer
ED	Exhaust Diffuser
HE	Heat Exchanger
G	Generator
CC	Combustion chamber
C	Compressor
Rec	Recuperator
T	Turbine
S	Stack
FWP	Feed Water Pump
S.T	Saturation Tower

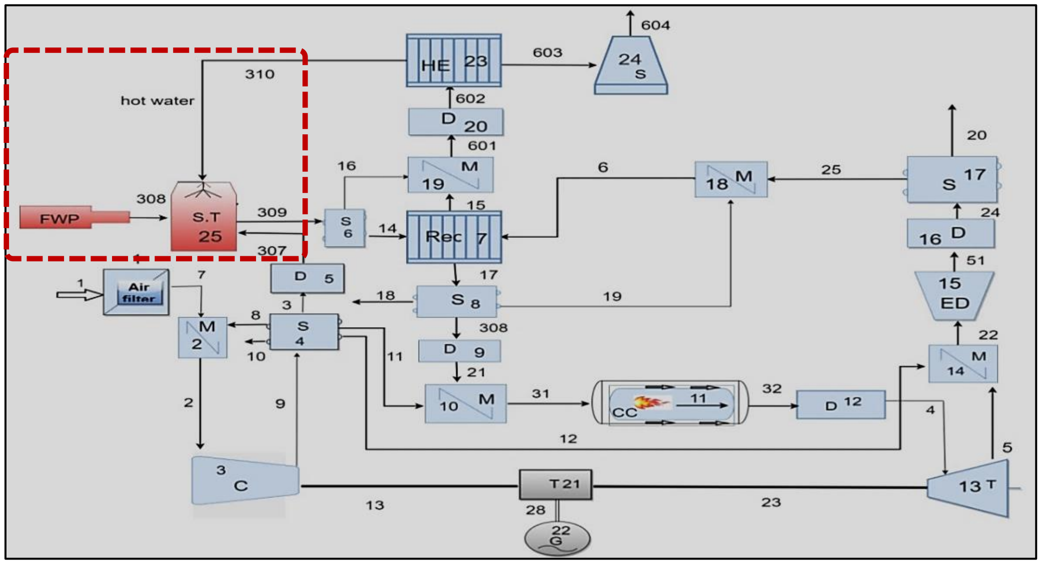

Figure 5. Modified AE-T100 model for VUB-mHAT cycle: legend on the left shows the component symbols. The components of the original dry model are presented in blue, while the newly integrated components to allow for the simulation of cycle humidification are presented in red.

Model Tuning Concept

The numerical modeling assumes ideal performance of the whole system, referring to the initial or non-degraded mGT. Due to experimental activities over time, machine performance degrades, and so the design conditions also change. After a certain time period, the machine performs on a different set of design conditions than initial ones. In order to model the real machine functioning, the AE-T100 model requires proper tuning of the design parameters at the specific operating conditions, to get the corresponding off-design conditions. Therefore, model tuning is the first step for real time application of the AE-T100 model.

For this study, the AE-T100 model is tuned according to the operating conditions of the VUB-mHAT system, for which experimental data have been acquired under stable operating conditions of the machine (detail of experimental data have been mentioned in the previous section). In order to estimate the design conditions, the reverse problem technique is applied i.e estimation of design conditions based on the field results, using the DSA tool. This DSA tool, which has been developed by VOLVO, provides the design conditions according to the operating point of the real machine, which is different from the ISO conditions.

The process starts with the AE-T100 model application to simulate the actual machine performance, and then model results are compared with the field data. The relative percentage error of the model values with respect to the experimental ones for each parameter is calculated according to Eq.1, and then average value of all the errors i.e Root Mean Square Error (RMSE) is calculated according to Eq.2. Then the RMSE is checked against a desired tolerance; if the RMSE value meets the defined criterion, it indicates the correct set of design conditions.

$$e_{rel,i} = \frac{(x_{field,i} - x_{tuned,i})}{x_{field,i}} \times 100 \qquad (1)$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N} (e_{rel,i})^2}{N}} \qquad (2)$$

where N represents total number of parameters

In case where the RMSE value exceeds the defined limit, the DSA tool is applied with a different fuel and leakages. This tuning provides a new set of design conditions. Afterwards, the AE-T100 model is applied again with the design conditions obtained from the DSA tool, and compare the results with field data, and checked RMSE. This iterative process is continued until the defined criterion of RMSE is satisfied. This tuning practice provides the correct design conditions for the AE-T100 model, so that the whole model is able to simulate the actual machine performance in the off-design conditions, with the minimum percentage error of all thermodynamic parameters.

Figure 6 represents the process flow for the tuning of the design conditions of the AE-T100 model. Unlike manual tuning, this tuning algorithm has been implemented by an automatic routine in the model, so that we are able to tune the model with less computational effort. This automatic routine is based on a loop in the code, applying the tuning algorithm as discussed in the previous paragraph.

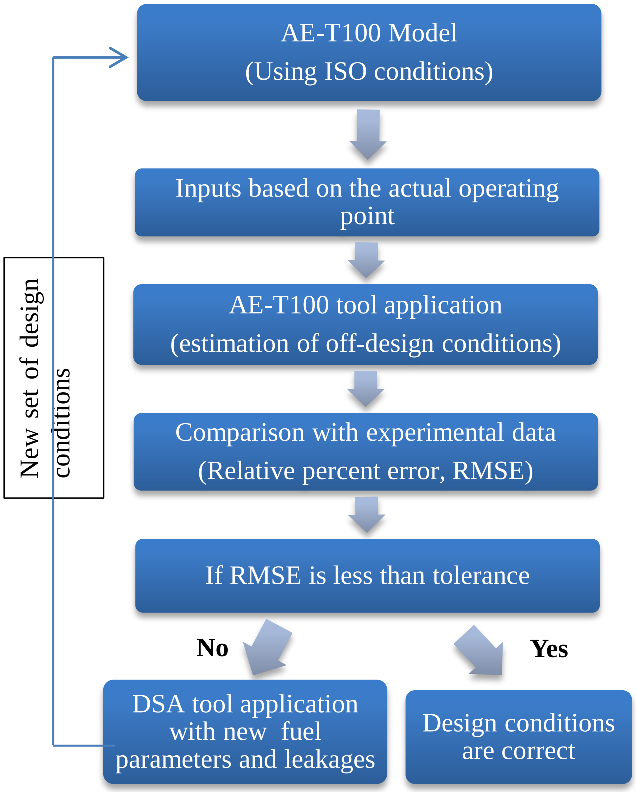

Figure 6. Process flow for AE-T100 model tuning

Model Validation in Real Operating Conditions

The new set of design conditions for test at nominal load in dry and wet mode have been estimated by the tuning routine explained in previous section (Figure 6). Table 1 presents the results of the comparison among tuned model and experimental values at full load condition, in dry operation of the mHAT rig.

Table 1.Comparison of tuned model values with experimental values at full load in dry mode

Parameter	x_{field}	x_{tuned}	e_{rel} (%)
Compressor outlet temperature (^{o}C)	219.75	224.45	-2.13
Compressor outlet pressure (barg)	3.37	3.43	-1.80

Recuperator inlet air pressure	3.26	3.20	1.87
Recuperator air outlet temperature (^oC)	598.45	602.55	-0.68
Turbine inlet temperature (^oC)	949.36	935.71	1.43
Net electrical power (kW)	91.57	94.11	-2.77
Fuel flow rate (g/s)	8.54	8.53	0.10
		RMSE	1.75

In addition to the dry tests, the AE-T100 model has also been applied in real operating conditions of the VUB-mHAT cycle in the wet mode. For this purpose, the AE-T100 model has been tuned and validated against the field data in wet mode, following the same tuning routine as in the case of dry mode. Table 2 presents the results of the comparison among tuned model and experimental values at full load condition, in wet operation of the mHAT rig.

Table 2. Comparison of tuned model values with experimental values at full load in wet mode

Parameter	x_{field}	x_{tuned}	e_{rel} **(%)**
Compressor outlet temperature (^oC)	213.67	217.62	-1.84
Compressor outlet pressure (barg)	3.50	3.44	1.51
Recuperator inlet air pressure	3.26	3.21	1.51
Recuperator air outlet temperature (^oC)	582.64	588	-0.91
Turbine inlet temperature (^oC)	945.9	936.14	1.03
Net electrical power (kW)	96.96	96.15	0.83
Fuel flow rate (g/s)	8.96	8.95	0.11
		RMSE	1.22

Since, for both dry and wet conditions, RMSE is less than the tolerance level (which was set at 5% considering the certain number of unknown parameters in the actual mHAT cycle, e.i. compressor air mass flow rate and bleed flow rate), this proves that the AE-T100 model is tuned to simulate the actual performance of the mHAT test rig, with reasonable accuracy at full load conditions.

RESULTS AND DISCUSSION

As mentioned before, despite the potential benefits of the mHAT cycle in terms of higher electrical efficiency and power output, water injection has also some negative effects on the mGT cycle: additional pressure losses in the cycle due to the humidification unit and performance degradation of the recuperator. Since air humidification also increases the water vapor content of air entering the recuperator, which may cause corrosion in the recuperator. Thus, the recuperator effectiveness can degrade over the time of experiments. Hence, current analysis is focused only on the recuperator performance in the mHAT cycle, in both dry and wet operation.

The new design conditions which have been estimated by tuning at full load are used:

- To estimate the off-design performance of the recuperator over the experimental data provided by VUB-mHAT facility in both dry and wet mode, most of which are conducted at part load operating conditions.
- To estimate the new recuperator design effectiveness in order to analyze its degradation through the comparison with the initial design value provided by the supplier.

The off-design recuperator performance at variable loads is shown in Figure 7, in both wet and dry mode. All the values of recuperator effectiveness have been reported in non-dimensional form with respect to the standard value from the supplier, since actual values cannot be mentioned due to proprietary.

When looking at the recuperator effectiveness, it is clear to see that the performance of the component increases when shifting from full load to part load, for the dry, as well as the wet case (Figure 7). This increase is evident, since at part load, the air flow rate passing through the compressor is lower and thus less air enters the recuperator cold side. At the same time, the air flow rate on the hot side is also reduced, however the contact area for heat exchanger remains constant, finally resulting in higher effectiveness when going from full to part load operation.

When comparing the increasing trend in recuperator effectiveness in dry and wet operation when shifting to part load, we can see a quasi linear trend for the increasing effectiveness. However the increase in effectiveness towards part load operation is slightly higher in the dry case, compared to the wet case. At the same time, the net heat exchange in the wet case is significantly higher due to the lower cold side inlet air temperature (hot side inlet air temperature remains constant at 645°C due to the TOT control), the reduced mass flow rate and increased specific heat capacity of the working fluid due to the humidification process. So although the net heat exchange is higher in the wet case, the lower effectiveness at part load indicates that there is potential to recover even more heat by redesigning the recuperator, focusing on wet operation performance.

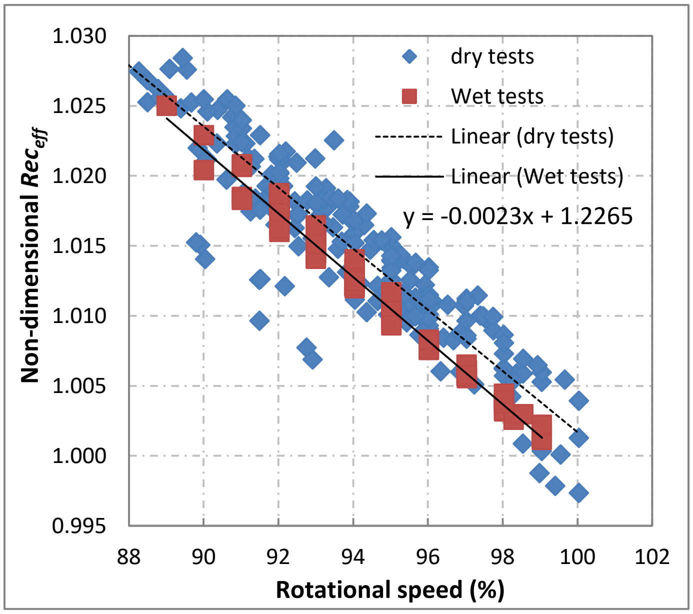

Figure 7. Recuperator off-design effectiveness with variable load in wet and dry mode

Finally, the recuperator performance degradation of the VUB-mHAT system, as a result of the performed dry and wet tests, has been assessed using the AE-T100 model. The model has been applied on the dry test results of experiments conducted over the past five years (test shown in Figure 3) on the VUB-mHAT system. For this purpose, model has been tuned (following the same tuning paractice as shown in Model tuning) and validated based on the same parameters as presented in Table 1 and 2, to get the new set of design condition. Afterwards, the actual recuperator design effectiveness ,which was determined based on the new set of design conditions at full load (or close to the full load), is compared with the initial value provided by the supplier, to see the degradation under the dry operation over the last five years (Table 3and Figure 8).

The analysis of the dry recuperator effectiveness indicates clearly that, over the past 5 years, the recuperator has degraded significantly (Table 3 and Figure 8). The non-dimensional value of the effectiveness, obtained by comparing the current value with the initial design effectiveness, has decreased by 2.01% as a result of the continuous tests in dry and wet operation. Although, only a limited amount of wet experiments have been carried out on the mHAT-VUB test rig so far (see Figure 4), the recuperator effectiveness is already degrading in the range of 0.1% to 0.4 % per year.

Table 3. Estimation of the recuperator performance degradation in dry operation

Time (dd/mm/yyyy)	Rotational speed (%)	Number of tests included in each time interval	Degradation (%)
08/05/2012	100	36	0.14
04/09/2012	100	51	0.42
29/08/2013	99.67	29	0.87
27/03/2014	100	21	1.10
29/09/2015	99.04	45	1.65
21/09/2016	100	20	1.87
17/03/2017	99.55	12	2.01

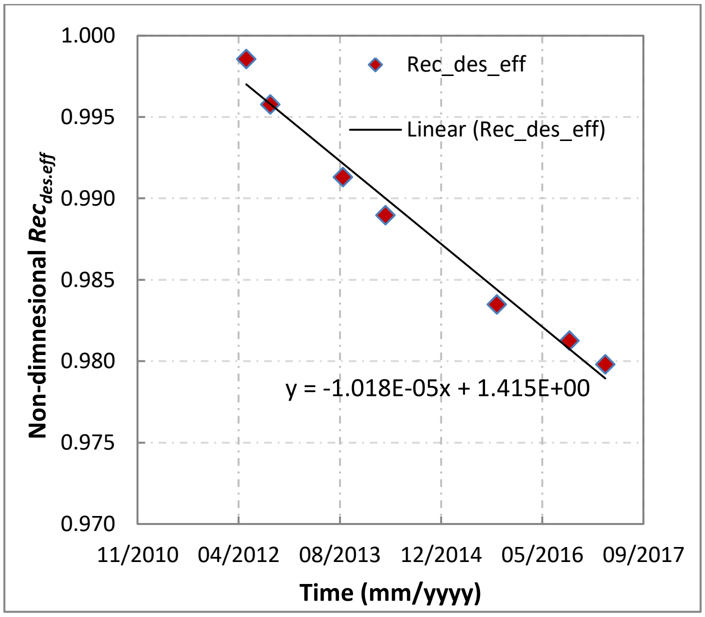

Figure 8. Recuperator performance degradation in dry mode over five years of tests

In addition, the change in recuperator design effectiveness is almost linear with time, although, it depends on several factors such as, the number of tests carried out on the test rig between tim inteveral; the total duration of the test conducted; the operating conditions; the ambient conditions and fuel parameters and finally any possible modification applied to the test rig. Finally, we also notice that this linear effectiveness reduction already started before the wet experiments had been started i.e effectiveness had decreased by 1.65% until the year 2015 . This indicates that the degradation is not only a result of the wet operation, but also of the dry operation. A more in-depth analysis is however necessary when more wet experiments have been conducted over a longer period, to see if this will have an impact on the degradation rate of the recuperator.

Similar to the dry case, the recuperator performance degradation in the wet mode can also be analysed. However, at present, the lack of experimental data, captured over a longer time period of wet operation, does not allow for a complete diagnostics of this novel cycle through the AE-T100 tool. Hence, the preliminary assessment of the degradation in dry mode already provides a basis for a more advanced diagnostic application of the AE-T100 tool. Finally, this advanced diagnostic application of the AE-T100 tool will allow us to report the recuperator degradation and to estimate the impact of air humidifcation on the recuperator effectiveness.

CONCLUSION

The AE-T100 model is a steady state simulation tool that also possesses the diagnostics capability of the mGT cycle. In this work, the AE-T100 model is applied to simulate the mHAT system located at Vrije Universiteit Brussel (VUB). This involves modification in the basic AE-T100 model (since this has been designed to simulate the dry operation of AE- T100 machine) according to the VUB-mHAT cycle configuration. Afterwards, the modified model has been tuned following a routine based on the RMSE criterion, to estimate the correct set of design conditions. Once the model has been validated in real operating conditions at full load, it is applied to analyze the mHAT cycle over the set of several experiments conducted at the nominal and part load in both dry and wet operation mode, with particular focus on the recuperator performance. The recuperator design effectiveness is determined based on the new set of design conditions.

To see the degradation/change in the recuperator performance with time, the new recuperator design effectiveness is compared with initial design value from the supplier. However, since the VUB-mHAT cycle is a novel cycle, there is not yet enough experimental data available to do a full diagnostics in wet mode, hence, we applied it for all the dry tests conducted over past five years (2012-2017) on the VUB- mHAT test rig, to demonstrate the first diagnostic application of the AE-T100 tool. The analysis on the dry experiments highlighted that, although a limited amount of wet tests have been conducted on the VUB-mHAT system so far, already a clear recuperator effectiveness degradation could be reported (2.01% over the time period).

In conclusion, this preliminary analysis of the recuperator performance in dry mode provides the basic pathway or algorithm that can be applied for more detailed diagnostics of the mHAT cycle in future, under wet operation over longer time scale. This work also highlights the necessity of more parameters measurement (like pressure drops at certain points of the mHAT cycle) from experiments, to help the model validation further.

FUTURE WORK

In this paper, we have proven the capability of the AE-T100 tool to adapt to a different plant layout i.e mHAT cycle in this case. It also indicated the potential of the AE-T100 tool to be used as a diagnostic tool and predict the performance degradation of the VUB-mHAT test rig, with particular focus on the recuperator. On this test rig, in the past, several other test campaigns with steam and water injection have already been performed. In addition, currently, a large measurement campaign is ongoing to study the dynamic behavior of the mHAT and its capacity to operate in a larger DG network by controlling the mHAT based on the thermal load. This campaign involves intensive water injection experiments spanning over several weeks/months. After this test campaign, a more in-depth analysis of the mGT and more specifically the recuperator performance degradation is planned using the AE-T100 tool, with all tests data captured over the years. Hence, this preliminary analysis together with further experimental data, will be used for more detail diagnostics of the mHAT cycle, to predict the degradation of the recuperator under wet operation, and by doing so, allowing to predict the lifetime of the recuperator under wet operation.

ACKNOWLEDGMENTS

The authors are grateful to Vrije Universiteit Brussel (VUB) for authenticating the use of experimental data obtained from VUB-mHAT facility. The first author acknowledges the financial support provided by National University of Sciences And Technology (NUST) Pakistan to conduct this research activity.

REFERENCES

1. Cochran, J., Bird, L., Heeter, J., and Arent, J.D., 2012. “Integrating Variable Renewable Energy In Electric Power Markets: Best Practices From International Experience”. NREL/TP-6A00-53732. http://www.nrel.gov/docs/fy12osti/53732.pdf. Last access on 20.01.2018.
2. Arnold, S., Schatz, M., 2014. “Exploiting Waste Heat In Small And Medium-Sized Combined Heat And Power Plants Using Steam Injection”. ASME paper GT2014-25222.
3. Abdollahi, S. E., and Vahedi, A., 2005. “Dynamic Modeling of Micro-Turbine Generation Systems Using Matlab/Simulink”. The Renewable Energy & Power

Quality Journal, **1** (3). http://www.icrepq.com/full-paper-icrep/243-abdollahi.pdf. last access on 20-01-2018.

4. Rossi I., Sorce A., Traverso A., Gas turbine combined cycle start-up and stress evaluation: A simplified dynamic approach. Applied Energy, 190 (2017) 880–890.
5. Delattin, F., Bram, S., Knoops, S., and De Ruyck, J., 2008, "Effects of Steam Injection on Micro turbine Efficiency and Performance". Energy, 33(2), pp. 241-247.
6. Ofualagba, G., 2012. "The Modeling and Simulation of a Microturbine Generation System". International Journal of Scientific & Engineering Research, **2**(2), ISSN 2229-5518.
7. Kaikko, J., and Backman, J., 2007, "Technical and Economic Performance Analysis for a Microturbine in Combined Heat and Power Generation," Energy, 32(4), pp. 378- 387.
8. De Paepe, W., Montero Carrero, M., Bram, S., Parente, A., and Contino, F., "Towards Higher Micro Gas Turbine Efficiency and Flexibility: Humidified mGTs- A Review", ASME. J. Eng. Gas Turbines Power. 2017. doi:10.1115/1.4038365..
9. Jonsson, M., and Yan, J., 2005, "Humidified Gas Turbines – a Review of Proposed and Implemented Cycles," Energy, 30(7), pp. 1013-1078.
10. Dodo, S., Nakano, S., Inoue, T., Ichinose, M., Yagi, M., Tsubouchi, K., Yamaguchi, K., and Hayasaka, Y., 2004, "Development of an Advanced Microturbine System Using Humid Air Turbine Cycle," ASME Paper GT2004-54337, pp. 167-174.
11. De Paepe, W., Contino, F., Delattin, F., Bram, S., and De Ruyck, J., 2014, "Optimal Waste Heat Recovery In Micro Gas Turbine Cycles Through Liquid Water Injection". Appl.Therm. Eng. 70 (1), pp. 846–856.
12. Lee, J. J., Jeon, M. S., and Kim, T. S., 2010, "The Influence of Water and Steam Injection on the Performance of a Recuperated Cycle Microturbine for Combined Heat and Power Application," Applied Energy, 87(4), pp. 1307 - 1316.
13. Traverso A., and Massardo A.F., "Thermoeconomic Analysis of Mixed Gas-Steam Cycles". Applied Thermal Engineering, 22 (2002), pp: 1-21.
14. Stathopoulos, P., and Oliver Paschereit, C., 2016, "Operational Strategies of Wet-Cycle Micro Gas Turbines and Their Economic Evaluation", J. Eng. Gas Turbines Power 138(12), 122301. Paper No: GTP-15-1289; doi: 10.1115/1.4033999
15. Montero Carrero, M., De Paepe, W., Parente, A., Contino, F., 2016. "T100 mGT Converted Into mHAT For Domestic Applications: Economic Analysis Based on Hourly Demand". Appl. Energy 164, pp: 1019–1027.
16. Parente, J., Traverso, A., Massardo, A.F., 2003. "Micro Humid Air Cycle Part A: Thermodynamic and Technical Aspects", ASME paper GT-2003-38326.
17. Parente, J., Traverso, A., Massardo, A.F., 2003. "Micro Humid Air Cycle Part B: Thermoeconomic analysis", ASME Paper 2003-GT-38328.
18. De Paepe, W., Delattin, F., Bram, S., and De Ruyck, J., 2012, "Steam Injection Experiments in a Microturbine – a Thermodynamic Performance Analysis," Applied Energy, 97, pp. 569-576.
19. De Paepe, W., Delattin, F., Bram, S., Contino, F., and De Ruyck, J., 2013. "A Study on the Performance of Steam Injection in a Typical Micro Gas Turbine". ASME paper GT2013-94569.
20. Ferrari, M. L., Pascenti, M., Traverso, A. N., Massardo, A.F., 2012. "Hybrid System Test Rig: Chemical Composition Emulation With Steam Injection", Applied Energy 97 (2012), pp: 809–815.
21. Traverso, A., 2010 "Humidification Tower For Humid AirGas Turbine Cycles: Experimental Analysis", Energy 35, pp; 894–901.
22. Montero Carrero, M., Ferrari, M.L., Paepe, W.D., Parente, A., Bram, S., and Contino, F., 2015. "Transient Simulations Of A T100 Micro Gas Turbine Converted Into A Micro Humid Air Turbine". ASME Paper GT2015-43277.
23. Traverso, A., 2005. "TRANSEO Code for the Dynamic Performance Simulation of Micro Gas Turbine Cycles". ASME Paper GT2005-68101
24. Parente, Joao O.S., Traverso, A., Massardo, A.F., 2003, "Saturator Analysis For An Evaporative Gas Turbine Cycle", Applied Thermal Engineering, 23 (10), pp: 1275-1293.
25. Pedemonte, A.A., Traverso, A., Massardo. A.F., 2008. "Experimental Analysis Of Pressurized Humidification Tower For Humid Air Gas Turbine Cycles. Part A: Experimental Campaign", Applied Thermal Engineering, Vol. 28, pp. 1711-1725.
26. Pedemonte, A.A., Traverso, A., Massardo. A.F., 2008. "Experimental Analysis Of Pressurized Humidification Tower For Humid Air Gas Turbine Cycles. Part B: Correlation Of Experimental Data", Applied Thermal Engineering, Vol. 28, pp. 1623-1629.
27. De Paepe, W., Carrero, M.M., Bram, S., Contino, F., 2014, "T100 Micro Gas Turbine Converted To Full Humid Air Operation: Test Rig Evaluation". ASME Paper GT2014-26123.
28. De Paepe, W., Carrero, M.M., Bram, S., Contino, F., 2015, "T100 Micro Gas Turbine Converted To Full Humid Air Operation – A Thermodynamic Performance Analysis". ASME Paper GT2015-43267.
29. Montero Carrero, M., De Paepe, W., Magnusson J., Parente, A., Bram, S., and Contino, F., 2017, "Experimental Characterization of a Micro Humid Air Turbine: Assessment of the Thermodynamic Performance". Applied Thermal Engineering 118, pp: 796-806.
30. Rodgers, C., 2000. "25-5 kWe Micro Turbine Design Aspects". ASME Paper 2000-GT-626, pp: 1–11.
31. Lara-Curzio, E., Trejo, R., More, K., Maziasz, P., and Pint, B., 2004. "Screening and Evaluation of Materials for

Micro Turbine Recuperators". ASME paper GT2004-54254, pp. 145–157.

32. Mahmood, M., Martini, A., Traverso, A., Bianchi, E., 2016. "Model Based Diagnostics of AE-T100 Micro Gas Turbine", ASME Paper GT2016-57671.
33. Mahmood, M., Martini, A., Traverso, A., 2017. "Fault Detection Through Model Based Diagnostics of AE-T100 Micro Gas Turbine". ASME Paper GT2017- 64619.
34. De Paepe, W., Contino, F., Delattin, F., Bram, S., and De Ruyck, J., 2014. "New Concept Of Spray Saturation Tower For Micro Humid Air Turbine Applications". Applied Energy, 130, pp. 723–737.