Available online at www.sciencedirect.com

Energy Procedia 00 (2016) 000–000

Energy Procedia

www.elsevier.com/locate/procedia

The 8th International Conference on Applied Energy – ICAE2016

Thermodynamic analysis of water injection in a micro gas turbine: Sankey and Grassmann diagrams

Marina Montero Carrero[a]*, Ward De Paepe[a], Svend Bram[a], Francesco Contino[a]

[a]Vrije Universiteit Brussel, Mechanical Engineering Dept, BURN Research Group, Brussels, Belgium

Abstract

Despite appearing as a promising technology for decentralised Combined Heat and Power (CHP), the rather low electrical efficiency of micro Gas Turbines (mGTs) prevents them from being attractive for users with a variable heat demand. Hot water injection in mGTs, achieved by transforming the cycle into a micro Humid Air Turbine (mHAT), allows increasing the electrical efficiency of the units in moments of low heat demand— therefore decoupling heat and electricity production. In spite of previous research regarding simulations, experiments and economic assessments of mHAT technology, the detailed enthalpy and exergy flows between the components remained to be investigated. In the present paper, we introduce and compare the Sankey (enthalpy flow) and Grassmann (exergy flow) diagrams of an mGT based on the Turbec T100 and the corresponding mHAT cycle. Results show that the electrical efficiency of the T100 increases by 2.5 % absolute points with water injection, while the total exergy efficiency decreases by only 4.1 %. Although there is an enthalpy gain in the saturation tower, exergy actually decreases in this component due to the increase in entropy related to the evaporation of water. The benefits of water injection mostly rely on the increased heat capacity of the air-vapour mixture, the lower fuel consumption, the higher heat recovered in the recuperator, and the reduced power required by the compressor.

Keywords: micro Gas Turbine; micro Humid Air Turbine; Sankey diagram; Grassmann diagram.

Nomenclature

CHP	Combined Heat and Power
HAT	Humid Air Turbine
mGT	micro Gas Turbine
mHAT	micro Humid Air Turbine

---

* Corresponding author. Tel.: +32 2 6293182; fax: +32 2 6292865.
E-mail address: marina.montero.carrero@vub.ac.be.

TIT	Turbine Inlet Temperature
TOT	Turbine Outlet Temperature

1. Introduction

Micro Gas Turbines (mGTs) appear as a promising technology for small-scale, decentralised Combined Heat and Power (CHP) thanks to their total energy efficiencies of around 80 %. Nevertheless, mGTs have a rather low electrical efficiency (~30 %): therefore, their operation is driven by the heat demand. For users with variable electricity and heat consumption, in moments of low heat demand running the unit so as to only produce electricity may not be economical, eventually leading to shutdown [1]. This is the case, for example, for domestic users during the summer months.

In order to improve the electrical efficiency of mGTs whenever the user does not require heat, an option is to heat up water with the high temperature exhaust gases. However, instead of being used to fulfil the heat demand, this warm water can be injected back into the mGT, at the back of the compressor. Such cycle—illustrated in Fig. 1 and based on the Humid Air Turbine (HAT) proposed by Rao and Day [2] —is known as the micro Humid Air Turbine (mHAT).

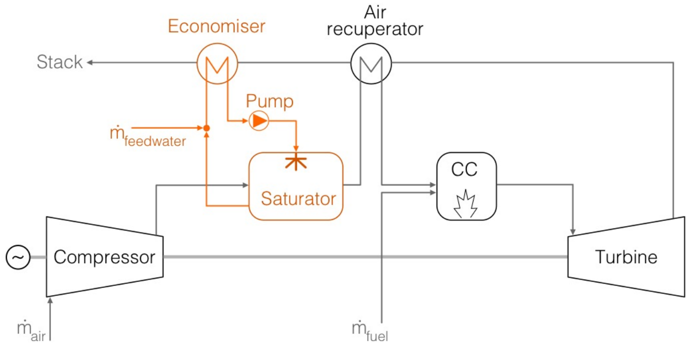

Fig. 1. The main components of an mGT cycle are depicted in black. By adding a humidification unit (in orange) after the compressor, the air is saturated with hot water coming from the economiser, leading to an increase in electrical efficiency.

The performance of the mHAT cycle has been investigated by several authors—including the ones of this paper—through simulations [3-7], experiments [8-11] and economic analyses [1, 12-13]. Nevertheless, the energy and exergy flows of an mHAT have never been thoroughly assessed. Such assessment would allow identifying the components that could be optimised to reduce exergy destruction as well as better understanding the mechanisms that lead to an increase in electrical efficiency. In this article, we will present the Sankey and Grassmann diagrams of an mGT based on the Turbec T100 and its corresponding mHAT cycle assuming that the unit is equipped with the spray saturation tower explained in Ref. [14]. Our objective is to analyse how the injection of water affects the performance of the different components of the cycle in order to achieve an electrical efficiency increase.

2. Methodology

The mGT and mHAT cycles based on the Turbec T100 have been simulated in Aspen Plus, using the mGT and mHAT models developed and validated by our research group and presented in Ref. [6].

The focus of the simulations is to analyse the temperature, pressure, enthalpy and exergy before and after the components of the mGT and mHAT units. Neither mechanical losses nor the power electronics consumption have been accounted for in the present study; hence, the obtained efficiency values are slightly higher than those of the commercial T100 unit. Nevertheless, these losses and auxiliaries' consumption will equally affect the mGT and mHAT cycles. The simulations are therefore considered suitable for this study given that the objective is to compare the performance and energy and exergy flows of the mGT and mHAT units.

3. Results and discussion

We have analysed and compiled the outcome of the simulations in two types of diagrams: the Sankey, which illustrates the enthalpy flows between components, and the Grassmann, which depicts exergy flows. In the following subsections, we compare the graphs and the results for both the mGT and the mHAT cycles.

3.1. Sankey diagrams

The beneficial effect of water injection—in terms of electrical efficiency—can be clearly appreciated when comparing the Sankey diagrams of the mGT (Fig. 2) and mHAT cycles (Fig. 3). For the same electrical power output (100 kW_e), the mGT requires 309 kW of fuel input while the mHAT consumes only 286 kW. The electrical efficiency therefore increases from 32.5 % to 34.9 % when using water injection.

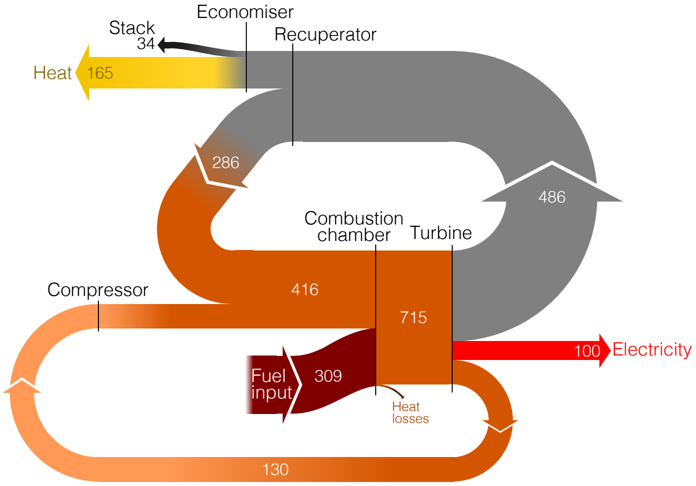

Fig. 2. Sankey diagram of the mGT cycle. All enthalpy values are provided in kW. The electrical efficiency (given that mechanical losses and power electronics consumption have not been accounted for in the model) is 32.4 % while the total efficiency is 85.7 %.

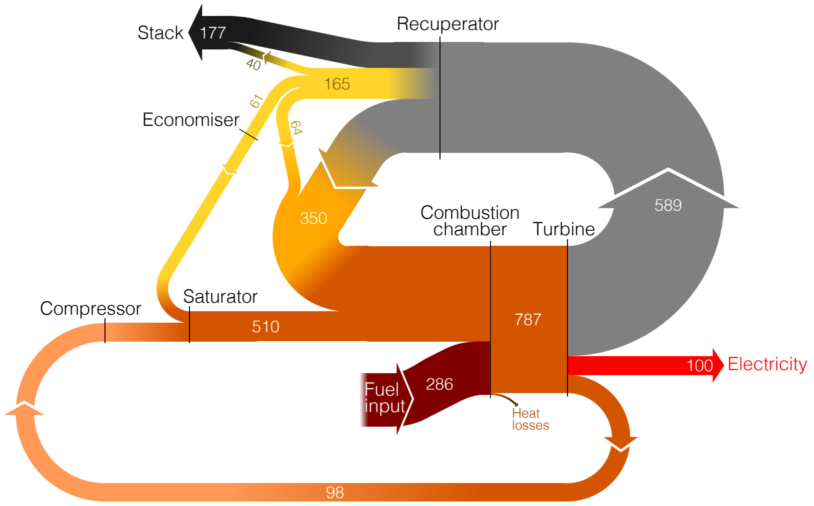

Fig. 3. Sankey diagram of the mHAT cycle. All enthalpy values are provided din kW. Only part of the remaining heat in the exhaust gases is actually directly recovered in the saturation tower, the rest is further retrieved in the recuperator or lost in the stack.

In order to maximise efficiency while protecting the recuperator, the controller of the T100 mGT aims at keeping the Turbine Outlet Temperature (TOT) constant at around 645 °C. To do so while also maintaining the electrical power output at 100 kW, the controller modifies the rotational speed along with the fuel flow rate. In the mHAT cycle, the exhaust gases have a high water content and therefore a higher heat capacity. Hence, for a constant TOT and a power output of 100 kW_e, the required Turbine Inlet Temperature (TIT) is lower than in the mGT case (890 °C vs 950 °C) and so it is the fuel input in the combustion chamber. In addition, the rotational speed decreases from 70000 rpm to 63300 rpm, which translates to a lower power consumption in the compressor.

Of the 165 kW_{th} that correspond to the thermal power output of the T100, only 61 kW are actually recovered in the saturation tower. As shown in the mHAT Sankey (Fig. 3), 64 kW are further retrieved in the recuperator, while the rest (40 kW) are eventually lost in the stack. In the saturation tower, water at 80 °C is sprayed over the compressed air, which is at 180 °C. As a result of the heat and mass transfer in this component, the air at the outlet is saturated but its temperature decreases to 80 °C. A lower inlet temperature in the cold side of the recuperator leads, in turn, to a greater amount of heat transferred to the wet air in this heat exchanger (which amounts to 350 kW as opposed to 286 kW in the mGT).

3.2. Grassmann diagrams

While a Sankey diagram represents a useful tool to examine energy flows in cycles, the information it provides is not sufficient to properly assess and compare the mGT and mHAT cycles. As previously mentioned, water injection in an mGT makes sense when there is no external heat demand and thus the only useful output of the unit is electricity. By solely analysing the energy output of mGT and mHAT technoogies, we are comparing the total efficiency of the mGT—electrical plus heat production, 85.7 % in the case analysed in this paper—to the efficiency of the mHAT—only electrical, amounting to 34.9 %. However, this is not a fair comparison because electricity has a far higher exergy (or useful work potential) than heat. Therefore, not taking this difference into account gives a distorted image of the advantages that water injection brings about. A better way of assessing the performances of mGT and mHAT is thus to analyse the exergy flows, which is possible in a Grassmann diagram. Such analysis can also reveal where exergy is destructed in the cycle and provide valuable insights for possible cycle improvement. The corresponding Grassmann diagrams of the mGT and mHAT cycles studied in the current paper are shown in Fig. 4 and Fig. 5.

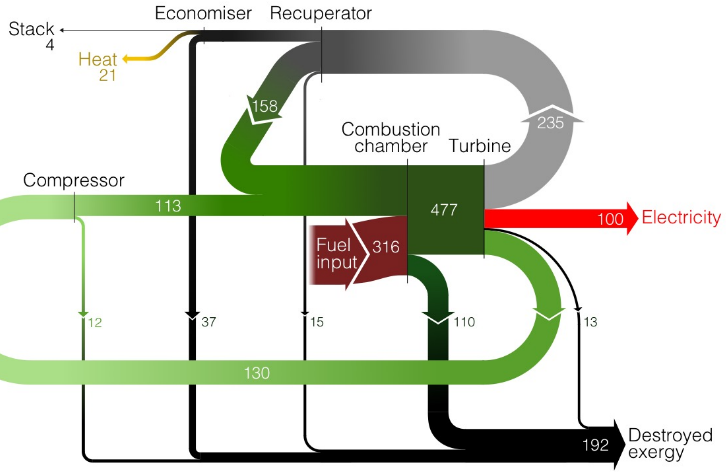

Fig. 5. Grassmann diagram of the mGT cycle. All the exergy values are provided in kW. The exergy efficiency is 38.1 %.

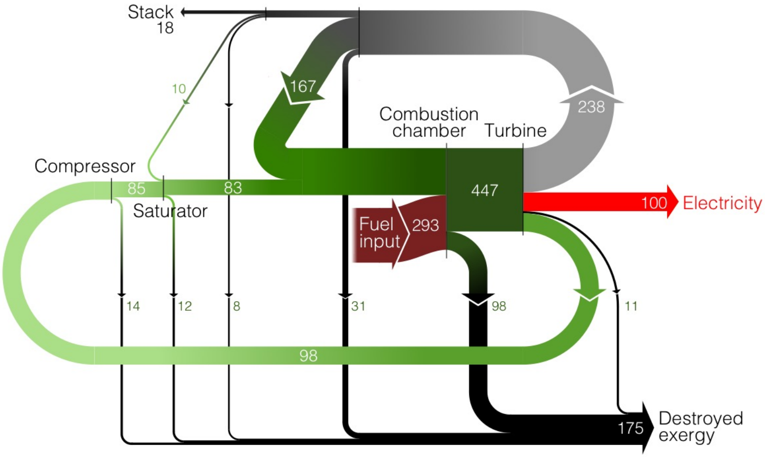

Fig. 4. Grassmann diagram of the mHAT cycle. All values are provided in kW. The exergy efficiency is 34.0 %.

The exergy efficiency of the mGT cycle is 38.1 %, of which 31.5 % correspond to the electricity output. The thermal power output (165 kW_{th}) has an exergy content of only 21 kW. In contrast, the exergy efficiency of the mHAT unit is 34.0 %. Thus, as expected, the most efficient operation mode of the mGT is 'dry' at nominal conditions. However, when the heat demand decreases, water injection allows increasing the electrical efficiency by 2.5 % absolute points while decreasing the total exergy efficiency by only 4.1 %. This unlocks heat and electricity production dependence at low efficiency cost, enabling flexible operation of mGTs.

Contrarily to what could be initially believed, in the saturation tower there is a net exergy loss: 10 kW are gained from the water coming from the economiser but 12 kW are destroyed. Despite the enthalpy and mass gain in the saturator, the evaporation of water leads to an increase in entropy which, in turn, translates to a loss of exergy. The actual advantage of water injection is appreciated by an increase in exergy recovered in the recuperator and by the reduction in compressor consumption, given the lower air flow rate and rotational speed. This, together with the reduced required TIT in the mHAT case, allows for a lower fuel consumption compared to the mGT.

4. Conclusions and future work

The analysis of the Sankey and Grassmann diagrams of the mGT Turbec T100 and its corresponding mHAT cycle reveals that the benefits of water injection are not perceived in the saturation tower itself. In fact, the enthalpy gain in the saturator is 61 kW but there is a net exergy loss of 2 kW associated to the entropy increase due to the evaporation of water. Water injection brings about a reduction in fuel consumption due mainly to three factors. First, the required TIT in the mHAT, in order to achieve the same nominal power output as in the mGT, is lower. Second, at the outlet of the saturation tower the air is fully saturated but its temperature is significantly reduced. This, in turn, allows for a better recovery of the heat in the exhaust gases to the saturated air in the recuperator. Finally, the rotational speed and the air flow rate decrease in the mHAT unit; therefore, so it does the power required by the compressor.

Although the current model in Aspen Plus enables an accurate study of the thermodynamic variables of the mGT and mHAT cycles, there are some minor aspects that are presently disregarded. In the near future, we plan to include mechanical losses as well as the consumption of power electronics in the simulations. This, together with a more accurate estimation of the heat losses in the combustion chamber, would allow fine-tuning the model and obtaining results that better fit the original values of the T100. In addition, the Grassmann diagram of the mGT and mHAT units will be further analysed to determine the components whose potential for improvement is the highest and how this enhancement could be achieved.

Acknowledgements

The work leading to the results of this study has been supported by Electrabel S.A. under the project FlexiHAT.

References

[1] Montero Carrero M, De Paepe W, Parente A, Contino F. T100 mGT converted into mHAT for domestic applications: Economic analysis based on hourly demand. *Applied Energy* 2016;**164**;1019-1027.

[2] Rao A, Day W. HAT cycle status report. In: *Eleventh conference on gasification power plants*; 1992.

[3] Parente J, Traverso A, Massardo A. Micro Humid Air Cycle. Part A—Thermodynamic and technical aspects. In: *Proceedings of ASME Turbo Expo 2003*. GT2003-38326, 2003.

[4] Nikpey H, Mansouri Majoumerd M, Assadi M, Breuhaus P. Thermodynamic analysis of innovative micro gas turbine cycles. In: *Proceedings of ASME Turbo Expo 2014*. GT2014-26917, 2014.

[5] Zhang S, Xiao Y. Steady State Off-Design Thermodynamic Performance Analysis of a Humid Air Turbine Based on a Micro Turbine. In: *Proceedings of ASME Turbo Expo 2006*. GT2006-90335, 2006.

[6] De Paepe W, Contino F, Delattin F, Bram S, De Ruyck J. Optimal waste heat recovery in micro gas turbine cycles through liquid water injection. *Applied Thermal Engineering*;**70**;846-856

[7] Montero Carrero M, Ferrari ML, De Paepe W, Parente A, Bram S, Contino F. Transient simulations of a T100 micro gas turbined converted into a micro humid air turbine. In: *Proceedings of ASME Turbo Expo 2015*. GT2015-43277.

[8] Dodo S, Nakano S, Inoue T, Ichinose M, Yagi M, Tsubouchi K, Yamaguchi K, Hayasaka Y. Development of an advanced microturbine system using humid air turbine cycle. In: *Proceedings of ASME Turbo Expo 2004*. GT2004-54337.

[9] Nakano S, Kishibe T, Araki H, Yagi M, Tsubouchi K, Ichinose M, Hayasaka Y, Sasaki M, Inoue T, Yamaguchi K, Shiraiwa H. Development of a 150kW microturbine system which applies the Humid Air turbine cycle. In: *Proceedings of ASME Turbo Expo 2007*. GT2007-28192, 2007.

[10] Wei C. Zang H. Experimental investigation on the off-design performance of a small-sized humid air turbine cycle. *Applied Thermal Engineering* 2013;**51;**166-176**.**

[11] De Paepe W, Montero Carrero M, Bram S, Contino F. T100 micro gas turbine converted to full humid air operation—a thermodynamic performance analysis. In *Proceedings of ASME Turbo Expo 2015* .GT2015-43267, 2015.

[12] Parente J, Traverso A, Massardo A. Micro Humid Air Cycle. Part B—Thermoeconomic analysis. In: *Proceedings of ASME Turbo Expo 2003*. GT2003-38328, 2003.

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

[14] De Paepe W, Contino F, Delattin F, Bram S, De Ruyck J. New concept of spray saturation tower for micro Humid Air Turbine applications. *Applied Energy;* **130**; 723-737.

Biography

Marina Montero Carrero holds an electro-mechanical engineering degree from Universidad Politécnica de Valencia and an MSc in Sustainable Energy Futures from Imperial College London. She has worked as a researcher at the London School of Economics and at the European Commission. Currently, she carries out her PhD—focused on flexible heat production through water injection in micro gas turbines—at the University of Brussels (VUB).