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Does humidification improve the micro Gas Turbine cycle? Thermodynamic assessment based on Sankey and Grassmann diagrams ☆

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HIGHLIGHTS

- The Sankey and Grassmann diagrams of an mGT and an mHAT are drawn and presented.
- Water injection leads to a 1.4% mGT electrical efficiency increase.
- The saturator acts as an aftercooler enabling greater heat recovery in the recuperator.
- In the saturator there is an enthalpy gain but a net exergy loss due to evaporation.
- The total exergy efficiency of the mGT and mHAT are 35.7% and 30.6% respectively.

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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 these units in moments of low heat demand—therefore decoupling heat and electricity production. This paper introduces and compares 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 1.4% absolute points with water injection, while the total exergy efficiency decreases by 5.1%. Although in the saturation tower there is an enthalpy gain, 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 larger amount of heat recovered in the recuperator and the reduced power required in the compressor.

1. Introduction

Renewable energy, together with energy efficiency, is fundamental to delivering the low-carbon energy future that the international community agreed upon at the United Nations' 21st Conference of the Parties (COP21) in 2015 [1]. Due to the stochastic nature of renewable energy sources like wind and sun, the future electricity system will be forced to become increasingly flexible and able to adapt to fluctuating conditions both on the demand and on the generation side [2].

As a distributed energy technology, micro Gas Turbines (mGTs) (ranging from few to several hundred kW) offer a great potential for adding flexibility to the electricity system. Due to the high temperature of their exhaust gases, mGTs are usually operated as Combined Heat and Power (CHP) units, with cogeneration efficiencies of ∼80% (∼30% electrical plus ∼50% heat production). However,

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Nomenclature

Acronyms

AHAT	Advanced Humid Air Turbine
CHAT	Cascaded Humidified Advanced Turbine
CHP	Combined Heat and Power
CIT	Combustor Inlet Temperature
EvGT	Evaporative Gas Turbine
ICE	Internal Combustion Engine
LHV	Low Heating Value
mGT	micro Gas Turbine
mHAT	micro Humid Air Turbine
TIT	Turbine Inlet Temperature
TOT	Turbine Outlet Temperature
VUB	Vrije Universiteit Brussel
WAC	Water Atomising inlet air Cooling

Roman symbol

k	heat capacity ratio

Greek symbol

η	efficiency

Subscripts

Comp	compressor
CC	Combustion Chamber
el	electrical
ex	exergetic
heat	heat production
is	isentropic
Turb	turbine

this is only true when the heat in the exhaust gases is entirely used for external heating purposes. Whenever there is no or low heat demand (typically during the summer for the case of a domestic user) the heat produced by the small-scale cogeneration unit has to be rejected and the CHP efficiency is cut down to the electrical efficiency. This negatively affects the economic performance of the units, even forcing to shut down. In addition, the rather low electrical efficiency of mGTs means that in order to be profitable, their operation is locked down to those moments when they can run producing both useful electricity and heat, limiting in turn their operational flexibility.

mGT humidification allows increasing the electrical efficiency in periods of no or low external heat demand, therefore decoupling heat and electricity production. Among the different options for humidification of gas turbines (steam injection, water injection that evaporates completely and water injection in a humidification tower), Jonsson and Yan concluded that the Humid Air Turbine (HAT) cycle (i.e. water injection in a saturation tower, as proposed by Rao and Day [3]) offered the highest potential efficiency increase [4]. Various authors have researched the beneficial effect of water injection through a saturation tower in gas turbines, known as the HAT or the Evaporative Gas Turbine (EvGT) cycle. The research spans from investigation of possible cycle layouts [5], modelling of the HAT cycle [6] and studies on the saturation tower performance [7–10]. Only one pilot plant has been constructed and tested in Lund since the development of the HAT cycle layout, achieving a thermal efficiency of approximately 35% [4,11,12]. Thereafter, different variants of the HAT cycle have been proposed, such as the Cascaded Humidified Advanced Turbine (CHAT) [13] and the Advanced Humid Air Turbine cycle (AHAT) [14,15]. However, neither the HAT cycle concept nor any of its variants have been commercialised to date.

This paper addresses water injection in mGTs, which due to their specific features compared to bigger scale gas turbines (radial turbomachinery, inclusion of a recuperator, limited turbine inlet temperature and variable rotational speed) require dedicated investigation. Several authors have researched the benefits of transforming an mGT into a micro Humid Air Turbine (mHAT), both from a numerical and an experimental perspective [16–30]. Parente et al. carried out a thermodynamic analysis of the mHAT cycle, concluding that an existing mGT can be run as an mHAT without major re-design [16]. Lee et al. compared the benefits of water and steam injection in a micro gas turbine, showing that mHAT would lead to a relative increase in power output of 29% and a total efficiency increase of 1.2 pt.% [17]. Nikpey et al. derived that the potential efficiency increase when converting an mGT into an mHAT is 1.7 pt.% [18]. Zhang and Xiao researched the off-design behaviour of 90 kW_e humidified cycles, confirming that mHAT had stable off-design performance [19]. Dodo et al. carried out experiments in a 150 kW_e mHAT coupled with a Water Atomizing inlet air Cooling (WAC) line. The unit was able to attain dry stable operation at 32% electrical efficiency and reduced NO_x emissions in the exhaust [20]. Thenceforth, Nakano et al. proved by means of water injection experiments that the combination of WAC and HAT led to a 3 pt% absolute efficiency increase [21]. More recently, Wei et al. experimentally investigated the off-design behaviour of a 25 kW_e mHAT. Keeping constant the fuel flow rate and the Turbine Inlet Temperature (TIT) their test results showed power output increases of 3 and 9.5 kW_e respectively [22]. Furthermore, our research group has carried out extensive work on the development of an Aspen Plus model of the mHAT cycle [23–25]. The authors of this paper recently modelled the dynamic behaviour of an mHAT based on the T100 mGT concluding that it is possible to vary the requested power output during water injection tests without risk of surge and without modifying the controller of the T100 mHAT [26].

With regard to the viability of mHAT technology, Parente et al. carried out a thermoeconomic analysis of mHAT cycles of several sizes (from 100 to 500 kW_e) compared to recuperated mGTs for an Italian civil user, concluding that the mHAT cycle offered a great potential for increased thermoeconomic performance [27]. The authors of this paper have also worked on an economic assessment of mHAT technology accounting for a variety of natural gas and electricity price scenarios [28–30]. This study confirmed that for scenarios where investment is lucrative, mHAT technology clearly outperforms mGT and Internal Combustion Engines (ICEs). In addition, mHAT is viable for a wider range of electricity and natural gas prices than mGT or ICE.

Despite the available research on humidification of mGTs (and of larger gas turbines), a thorough analysis of the energy and exergy flows between the components of the cycle has not yet been published to the knowledge of the authors. Such analysis is key to understand the thermodynamic mechanisms that lead to an increase in electrical efficiency when water injection takes place, which—as will be shown in the paper—are more complex than presented in the available literature. This paper introduces an exhaustive study of the main thermodynamic properties at all points of the mGT and mHAT engines. The objective is to assess the advantages of water injection both from an energy and an exergy perspective in order to fully comprehend the effect that