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Waste heat recovery optimization in micro gas turbine applications using advanced humidified gas turbine cycle concepts

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HIGHLIGHTS

- Water injection in micro gas turbine (mGT) cycles has a large potential for waste heat recovery.
- Current humidified mGT cycles do not fully exploit the potential for waste heat recovery.
- Different cycle concepts of large scale gas turbines are applied on the small scale mGT to find the optimal cycle.
- The cycle concept allowing the highest water injection rate and lowest stack temperature recovers most waste heat.
- The REVAP cycle concept with preheat was identified as the optimal cycle.

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ABSTRACT

Introduction of water in a micro Gas Turbine (mGT) has proven to be a very effective method to recover waste heat into the cycle, since it increases the mGT electrical efficiency significantly. Different routes exist for water introduction in the mGT cycle. Classical routes, like injection of steam/preheated water or the micro Humid Air Turbine (mHAT) concept, where water is introduced in the cycle by means of a saturation tower, have shown to have high potential. However none of the previously mentioned cycles exploits the full thermodynamic potential for waste heat recovery through water introduction. More advanced humidified Gas Turbine (GT) cycles have been proposed and studied for large scale GTs. So far, none of these concepts have been applied on mGT scale, despite their high potential.

In this paper, we study the impact of these different, more advanced, humidified GT cycle concepts on the mGT performance. The different selected cycles – next to the classical steam injection or injection of (preheated) liquid water in the recuperated cycle and the mHAT – were: micro Humid Air Turbine Plus (mHAT+), Advanced Humid Air Turbine (AHAT) and the REgenerative EVAPoration (REVAP®) cycle concept. The impact of these concepts on the mGT cycle performance has been studied on the Turbec T100 mGT.

Simulations indicated that humidifying the air of the mGT has a significant beneficial effect on cycle performance due to the increased waste heat recovery, resulting in a higher electrical power output (at constant rotational speed) or reduced fuel consumption (at constant power output), both leading to an increased electrical efficiency. Depending on the different cycle layout used, more or less waste heat could be recovered from the exhaust gas. The REVAP® concept with feedwater preheat was identified as the optimal cycle layout within the selected options. By applying this concept to the Turbec T100, most waste heat could be recovered, achieving the highest electrical efficiency increase.

1. Introduction

Despite the potential of micro Gas Turbines (mGTs) for small-scale (up to 500 kW_e) Combined Heat and Power (CHP) production [1,2], they never fully penetrated the mGT market [3]. The heat-

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Nomenclature

Acronyms

AHAT	Advanced Humid Air Turbine
CAF	Corrected Air Flow
CHAT	Cascaded Humidified Advanced Turbine
CHP	Combined Heat and Power
GT	Gas Turbine
HAT	Humid Air Turbine
HRSG	Heat Recovery Steam Generator
ICE	Internal Combustion Engine
mGT	micro Gas Turbine
mHAT	micro Humid Air Turbine
mHAT+	micro Humid Air Turbine Plus
REVAP®	REgenerative EVAPoration
STIG	STeam Injected Gas Turbine
PIT	Turbine Inlet Pressure
TIT	Turbine Inlet Temperature
TOPHAT®	TOP Humid Air Turbine
TOT	Turbine Outlet Temperature
WAC	Water Atomizing inlet air Cooling

Roman symbols

A	cross section area
k	heat capacity ratio
$\dot{m}$	mass flow rate
R	universal gas constant

Greek symbols

η	efficiency
π	pressure ratio

Subscripts

is	isentropic
turb	turbine

Superscripts

$*$	properties of standard air

driven operation of CHP units in general, in combination with the lower electrical efficiency of the mGT compared to its main competitor, the Internal Combustion Engine (ICE) [4], was identified in the past as their major drawback. Since the mGT has still a relative high specific investment cost [5], any forced shutdown of the installation during periods with limited or no heat demand, has a negative effect on the economic performance [6]. By introducing water in the mGT cycle during periods with low heat demand to increase the electrical efficiency, the economic performance can be improved significantly [7–11].

In past research, several routes for mGT cycle humidification for waste heat recovery have been proposed and studied. Many researchers focussed on classical steam injection [6,10–13] or water injection [12,14] by studying these different options on different mGTs. All researchers reported a significant electrical efficiency increase (and possible electrical power output increase, when operated at constant rotational speed). This increase depends on the mGT size, the injection method (liquid water or steam) and on the injection point in the cycle. Finally, the concept of steam injection in the mGT cycle has already been validated experimentally for the Capstone C60 [13] and for the Turbec T100 [15–18], showing the potential for mGT humidification.

Next to the more classical humidification methods of steam and liquid water injection, Parente et al. proposed the micro Humid Air Turbine (mHAT) concept [19]. This mHAT concept is based on the Humid Air Turbine (HAT) cycle, proposed by Rao [20], but modified for the mGT cycle by excluding the inter- and aftercooling. This mHAT cycle was identified, by our research group, as a perfect candidate for waste heat recovery through humidification, based upon its high efficiency in combination with the rather limited necessary cycle modifications [21]. These findings were confirmed by Nikpey et al. [22] and Majoumerd et al. [23], who also simulated the conversion of the Turbec T100 mGT into a mHAT. The mGT can easily be converted into a mHAT by introducing a saturation tower in between compressor outlet and recuperator inlet [24]. The high potential of the mHAT cycle was confirmed experimentally by our research group by transforming a Turbec T100 into a mHAT by introducing a spray saturation tower in the cycle [25–27].

Exergy analysis however indicated that the thermodynamic limit for water addition in the mGT is much higher than what can be achieved with the steam/water injection in mGTs and the mHAT cycle [28]. As a consequence, the exergy loss at the stack is significant, even for the mHAT cycle (19 kW exergy loss at nominal power output of 100 kW_e), as it can be clearly observed from the analysis of the exergy flows in a Grassmann diagram [29]. The main problem with the existing options for humidification, is the limited heat recovery from the stack, especially the recovery of the water latent heat in the flue gases. The latter is only released at low temperatures (below 67 °C), thus requiring a cooling stream ensuring a sufficient temperature difference (at least 10 °C lower with respect to the minimum temperature difference). In addition, such a stream should allow for the absorption of the heat, which requires that the stream remains at this temperature during the heat transfer process. This is only possible if the cold stream has a mass flow rate that is several orders of magnitude larger than the flue gas mass flow rate or if it is combined with a phase-change process. None of the above-mentioned cycles displays these options.

In this paper, the potential of several more advanced humidified Gas Turbine (GT) cycle concepts on mGT scale will be presented. The aim of the study presented in this paper is to identify which of these more advanced humidified GT concepts has the largest potential for application on mGT scale for waste heat recovery and approaches the thermodynamic limit, which is defined based upon first and second law analysis. Based on the overview work of Jonsson and Yan, which discusses the different humidified GT cycles [30], a selection of possible large scale humidified GT concepts that can be applied on mGT scale, is made. The application of these cycles on mGT level is simulated on a typical mGT, the Turbec T100, by using Aspen Plus® [31]. This analysis allows for a full comparison of the performance of the different cycle concepts on mGT scale and identification of the optimal solution (from a thermodynamic point of view). The final feasibility study, taking into account investment and operating costs and possible technological challenges (e.g. material constraints) [32], is not within the scope of this paper.

In the following sections, first the different selected cycles are presented. Second, the simulation approach for the humidified cycles is discussed, followed by the presentation of the results of the different simulations. Finally, the main findings of this study are summarized in the conclusion.

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