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Advanced humidified gas turbine cycle concepts applied to micro gas turbine applications for optimal waste heat recovery

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Abstract

Introduction of water in a micro Gas Turbine (mGT) has proven to be a very efficient way to introduce waste heat in the cycle. The injection of preheated water/steam in the mGT cycle will increase the efficiency of the cycle significantly. Different routes exist for water injection in an mGT cycle. Classical routes, like injection of steam/preheated water or the micro Humid Air Turbine (mHAT) cycle, where water is introduced in the cycle by means of a saturation tower, have shown to have high potential, however do not fully exploit the maximal potential for waste heat recovery. More advanced humidified gas turbine cycles exist on large scale, but these concepts have not yet been applied on mGT scale. In this paper, we study the impact of these different, more advanced, humidified gas turbine cycle concepts on the mGT performance. The different selected cycles – next to the classical Steam Injected Gas Turbine (STIG), injection of (preheated) water and the mHAT – were: mHAT-plus, Advanced Humid Air Turbine (AHAT) and the Regeneration EVAPoration cycle (REVAP®). Simulations indicated that humidifying the air of the mGT has a significant beneficial effect on cycle performance, resulting in increased electrical power output and efficiency. Depending on the different used cycle layout, more waste heat could be recovered from the exhaust gas. The REVAP® cycle with feedwater preheat was identified as the optimal cycle layout within the selected cycles. Using this concept, the stack temperature could be lowered to 53°C, corresponding to an increase in electrical power output of 128.7 kW_e with a maximal absolute efficiency increase of 6.9% compared to the dry cycle layout (100.1 kW_e electrical power output and 35.1% efficiency).

Keywords: micro Gas Turbine (mGT), advanced humidified Gas Turbines, waste heat recovery

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Nomenclature

AHAT	Advanced Humid Air Turbine	mHAT	micro Humid Air Turbine
CHAT	Cascaded Humidified Advance Turbine	REVAP®	REgenerative EVAPoration cycle
CHP	Combined Heat and Power	STIG	STeam Injected Gas turbine
ICE	Internal Combustion Engine	TOPHAT®	TOP Humid Air Turbine
mGT	micro Gas Turbine	WI	Water Injection

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-driven operation of CHP units in general, in combination with the lower electrical efficiency of the mGT compared to their 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 shutdown of the installation when there is 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 and by doing so increasing the electrical efficiency, the economic performance can be improved significantly [7, 8].

In past research, the micro Humid Air Turbine (mHAT) cycle was identified as perfect candidate for waste heat recovery through humidification, based upon its high efficiency in combination with the rather limited necessary cycle modifications [9]. The mGT could easily be converted into a mHAT by introducing a saturation tower in between compressor outlet and recuperator inlet [10]. Exergy analysis however indicated that the thermodynamic limit for water introduction in the mGT is much higher [11]. The main problem with the steam/water injection mGT and mHAT cycles is the limited heat recovery from the stack, especially the recovery of the evaporation heat of the water present in the flue gases. None of the above mentioned cycles allows the recovery of the large amount of evaporation heat that is available in the stack, but only at low temperature.

In this paper, the potential of several more advanced humidified gas turbine cycle concepts will be investigated. A selection of possible candidates was made based upon the overview work of Jonsson and Yan, discussing the different humidified gas turbine cycles [12]. The cycles have been simulated using Aspen Plus®. The basic mGT components – compressor, turbine, generator and combustion chamber – are assumed to be unchanged. For the different heat exchangers, generic components were used to make comparison between the different cycles possible. The aim of this paper is to compare the potential of the different cycle layouts. The final feasibility study, taking into account investment costs, 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 results are summarized in the conclusion.

2. Advanced humidified mGT cycle selection

The Turbec T100 mGT was selected as reference mGT to apply the advanced humidified cycle concepts to. This Turbec T100 mGT is a typical recuperated mGT (Figure 1). The air is first compressed in a variable speed radial compressor (1). By preheating the compressed air in a recuperator using the hot exhaust gases (2), high efficiency can be achieved. The compressed air is heated further in the combustion chamber by

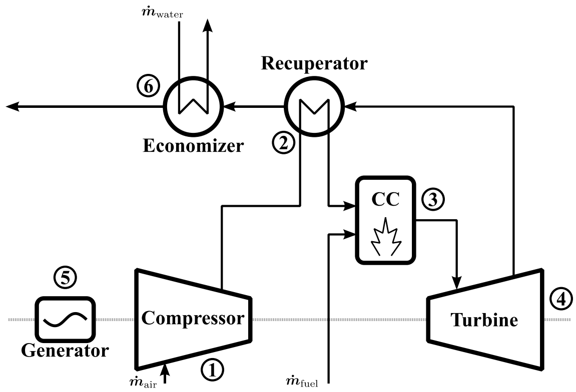

Figure 1: The Turbec T100 mGT, which is a typical recuperated mGT, was used as reference machine for the advanced humidified mGT cycles.

burning natural gas (3). The hot compressed air is then expanded over the turbine (4) to deliver the necessary power to drive the compressor. The remaining power on the shaft in converted into electrical power by a variable speed generator (5). After leaving the recuperator, the remaining heat in the exhaust gases is converted into thermal power by heating water for heating purpose (6).

To recover the waste heat from the exhaust gases, water will be introduced in the cycle. Different possible routes exist to recover the water. Depending on the cycle, the existing heat exchange network of the mGT – consisting of a recuperator and an economizer (components (2) and (6) from Figure 2) – is modified to optimize the waste heat recovery.

From the extensive list of existing humidified cycle layouts described by Jonsson and Yan [12], next to the more traditional cases of Steam Injection Gas turbine (STIG), (preheated) Water Injection (WI) and mHAT cycle, following candidates were selected:

- micro Humid Air Turbine plus (mHAT plus) [13];
- Advanced Humid Air Turbine (AHAT) [14];
- Regenerative EVAPoration cycle (REVAP®) [15].

The different cycle layouts have been selected based upon potential and possible application in the mGT cycle. Important criteria were: the humidification process must be applicable to a single pressure level – one compressor and one turbine; the water is introduced to recover waste heat from the flue gases – injection in the combustion chamber to reduce NO_x exhaust is not considered in this analysis – and water can be introduced before or behind the compressor, however when injecting before the compressor, like in the AHAT case, all water must be evaporated to avoid any damage to the compressor (wet compression is not taken into account). More complex layouts, like the Cascaded Humidified Advance Turbine (CHAT) [16] or the TOP Humid Air Turbine (TOPHAT®) [17], were not considered. The final used cycle layouts are presented in Figure 2.

In a previous study, conducted by our research group, the injection of preheated water and the mHAT were found to be the optimal solution, when respectively assuming the heat exchangers are optimized (WI-pre) or kept the same (mHAT) [11]. However, during this previous work, the number of heat exchangers was limited to 2, to keep the investment cost of the installation low [11]. In the study presented in this paper however, the number of possible heat exchangers in the heat exchanger network is not limited, which should allow for more heat recovery from the stack (both the option of aftercooling and a second economizer to

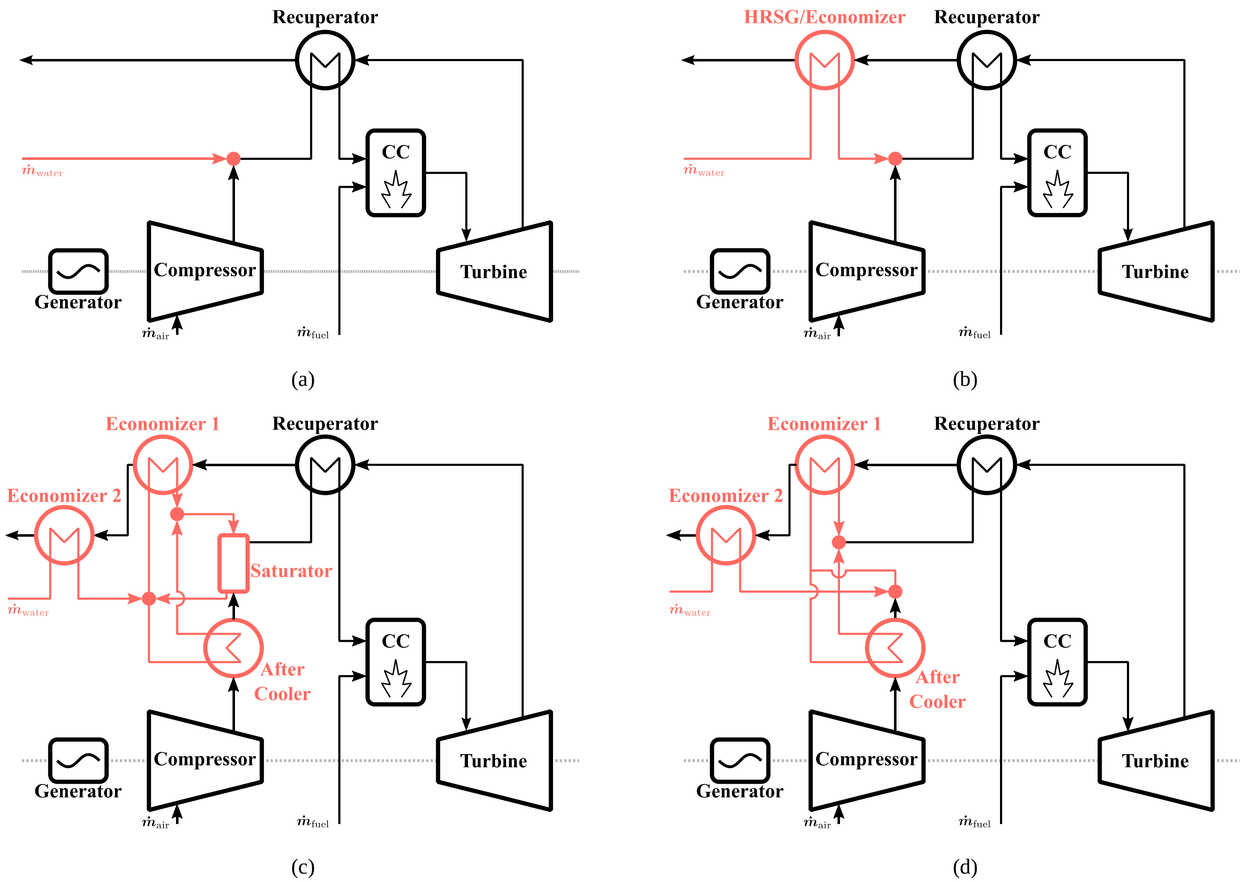

Figure 2: Simulated advanced humidified mGT cycles, covering direct water injection (WI) (a), injection of preheated water (WI-pre) or steam (STIG) (b), mHAT (no aftercooling) or mHAT-plus (with aftercooling), both possibly with or without water preheating (economizer 2) (c) and finally the REVAP® cycle, also possibly with or without water preheat (economizer 2) (d), were used in the analysis in this paper. The newly introduced part necessary for the humidification are indicated in red. The AHAT cycle (not shown) combines the layout of the mHAT (c) with inlet air cooling, using water atomization.

preheat the feedwater are possible in this analysis). This should lead to lower exergy destruction in the network and a final cycle layout approaching the exergetic limit found in previous studies of our research group [9, 11]. This exergetic limit for constant rotational speed (66000 rpm) is a maximal water injection of 120 g/s, corresponding to an electrical power production of 150 kW_e and an electrical efficiency of 46.6%.

3. Advanced humidified cycle modelling

The modelling of the different advanced humidified mGT cycles has been performed with Aspen Plus®. For the modelling of the turbomachinery parts of the mGT, the original compressor and turbine of the Turbec T100 are taken and are assumed to remain unmodified. For the compressor, the actual compressor

Table 1: Boundary conditions used for the advanced humidified mGT cycle development.

Compressor	
Pressure ratio	Variable[1]
Isentropic efficiency	Variable[1]
Rotational Speed	66000 rpm
Inlet air temperature	15°C
Turbine	
Turbine back pressure	40 mbar
Isentropic efficiency	85%
Turbine inlet temperature	950°C
Combustion chamber	
Combustor pressure loss	5%
Combustor heat loss	10 kW_{th}
Heat exchanger network	
Cold side pressure loss	5%
Hot side pressure loss	40 mbar
Heat exchanger pinch (gas/gas)	50°C
Heat exchanger pinch (gas/liquid and gas/gas+liquid)	10°C
Feed water inlet temperature	15°C
Fuel (methane)	
LHV	50 MJ/kg

[1] For the simulations of the compressor and turbine maps of the Turbec T100 are used [18].

map of the T100 [18] is introduced in Aspen Plus®, while the turbine is assumed to be choked and having a dry isentropic efficiency of 85%. The choking condition is corrected for the water injection according to the formula given by Parente et al. [13]. The isentropic efficiency was considered constant, since results of Parente et al. indicated that the humidification of the cycle has little effect on the efficiency of the turbine [13]. The combustion chamber is modelled using a classical Gibbs reactor, with an efficiency of 100% (complete combustion) and 10 kW_{th} heat loss. Pure methane is considered as fuel, to make comparison with the exergy analysis from previous work possible [9, 11]. In this combustion chamber, a 5% pressure loss is introduced (similar to the loss in the actual combustion chamber). To optimize the electrical efficiency of the cycle, the Turbine Inlet Temperature (TIT) is kept constant at 950°C, which is the limit for the material of the turbomachinery. Finally, the heat exchange and water injection network was simulated using generic heat counter flow heat exchanger. As design specification of these heat exchangers, a minimal pinch of 50°C for gas/gas heat exchangers (recuperator), 10°C for gas/liquid or gas/gas-liquid heat exchangers (economizers and aftercoolers) and finally 10°C for the overall system was assumed. Additionally, a typical design pressure loss of 5% on the cold side of the network and 40 mbar at the hot side was considered [19]. Water was assumed to be introduced in the network at 15°C in its liquid form. The details about the used parameters in Aspen Plus® are summarized in Table 1.

The simulations were performed keeping the rotational speed of the compressor and turbine constant (66000 rpm which is the speed at which the mGT delivers nominal power output of 100 kW_e at the same inlet conditions of 15°C and 1.013 bar). In standard operation mode, the Turbec T100 mGT operates at constant power output by adjusting the rotational speed. This means that, when water/steam is introduced in the cycle, the rotational speed will be lowered to keep the power output constant [20]. The first simulation results on the advanced humidified mGT cycles presented in this paper were performed at constant rotational speed. By introducing water while keeping the rotational speed constant, the power output will

Table 2: The REVAP® cycle was identified as the optimal humidified mGT cycle.

	mGT	**WI**	**WI -pre**	**STIG**	**mHAT**	**mHAT plus**	**AHAT**	**REVAP**	**REVAP -pre**
$P_{gen}\ (kW_e)$	100.1	123.1	124.5	116.7	122.3	124.3	127.6	128.7	128.7
$\dot{m}_{fuel}\ (g/s)$	5.7	6.0	6.1	5.9	6.0	6.1	6.2	6.1	6.1
$\eta_{el}\ (\%)$	35.1[1]	40.7	41.1	39.3	40.6	41.0	41.1	42.0	42.0
$\dot{m}_{water}\ (g/s)$	0	49	53	34	48	53	48	64	64
$T_{stack}\ (°C)$	255.9	77.8	65.0	158.5	84.5	83.0	82.1	55.3	55.3

[1] The reported electrical efficiency of the dry mGT simulations is higher than the nominal efficiency of 30% reported by Turbec, due to the use of the same design and control conditions as used for the advanced humidified mGT cycles of Table 1 (for correct comparison) and assuming no losses in the generator and power electronics.

increase due to the additional mass flow rate through the turbine. Simulations of the performance at constant power output are foreseen in a next step.

4. Results

The analysis of the simulation results of the different cycles clearly indicates that the cycle that allows the lowest stack temperature is the one that achieves the most heat recovery and thus the highest efficiency (Table 2). From the selected cycles, the REVAP® concept with water preheat shows the highest efficiency increase. Using this concept, the final stack temperature could be lowered the most (up to 55.3°C), while the highest amount of water (64 g/s) could be injected, resulting in an optimal heat recovery. Using this cycle, a maximal power output of 128.7 kW_e could be achieved with an electrical efficiency of 42%. This is an absolute efficiency increase of 6.9% compared to the dry mGT cycle. Despite the more complex cycle, the performance of the mHAT and mHAT-plus cycles is not superior to the simple water injection with water preheat (40.6% and 41.0% respectively, compared to 41.1%), however the differences are small. The preheated water injection case, however, requires a recuperator that allows two-phase flow (gas+liquid water) on the cold side, which is technically more challenging. Finally, the effect of performing inlet cooling, using water atomization, depends on the conditions of the inlet air. When assuming 0% relative humidity, the mHAT efficiency increases from 40.6% to 41.7% (AHAT case) due to a significant drop in inlet air temperature (by 11°C). When assuming a more common 60% relative humidity, this effect is limited, resulting in a final electrical efficiency of 41.1% (case presented in Table 2).

5. Conclusion

In this paper, several advanced humidified gas turbine concepts have been applied to the mGT cycle to study their potential for waste heat recovery from the stack. The results of this analysis clearly indicated that the cycle which is capable of reducing the stack temperature the most, has the highest waste heat recovery from the exhaust gasses, resulting in the highest electrical efficiency. The key for optimal waste heat recovery lies in the possibility to recover the evaporation heat from the condensing water in the stack. However, to recover this additional waste heat, a much more complex cycle layout is necessary. The optimal heat recovery can be accomplished using the REVAP® cycle concept. Within this concept, the stack can be lowered the most (up to 55.3°C), resulting in a final electrical power output of 128.7 kW_e and an electrical efficiency of 42.0% (increase of 6.9% compared to the dry cycle).

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Biography

Ward De Paepe is a post-doctoral researcher working at both the Vrije Universiteit Brussel and Université Libre de Bruxelles. In 2014, he received his PhD from the Vrije Universiteit Brussel entitled: Flexible Heat Production from a micro Gas Turbine: design and experimental analysis of humidified cycles. His main field of interest is humidified gas turbines and micro gas turbines. Currently, he is working on exhaust gas recirculation in humidified gas turbines.