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Optimal waste heat recovery in micro gas turbine cycles through liquid water injection

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HIGHLIGHTS

- Adiabatic black box method was used to find the optimal route for waste heat recovery through water injection.
- Full water recovery was added as a constraint for the black box analysis.
- Composite curve theory was used to design the heat exchange and injection network.
- Direct injection of water results in an absolute efficiency increase of 4.6%.
- Stack temperature needs to be below 26 °C to have full recovery of water.

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ABSTRACT

Water injection in the compressor exhaust, to recuperate waste heat, is considered a possible route to improve the electric efficiency and overall performance of the micro Gas Turbine turbine (mGT). Many research exists on water injection in mGTs, however a generic study to determine the optimal route for waste heat recovery is still missing. To determine the optimal cycle settings for waste heat recovery through water injection, we have performed simulations using a two-step method. In a first step, the thermodynamic limit for water injection is sought using a black box method. In a second step, the cycle layout is designed by means of composite curve theory.

This paper summarizes the results of two scenarios. In the first scenario, the black box is considered as adiabatic and no fixed stack temperature is imposed (thus allowing condensation of the exhaust gasses). One of the major concerns when injecting water is the water consumption, which can be compensated in some cases through condensation and recycling the condensate. Therefore, in the second scenario, the cycle is made self-sufficient with water. In this case, the black box is no longer considered adiabatic and heat exchange with the environment is allowed for condensation of the flue gasses.

Black box simulations showed that lowering the stack temperature to 53 °C results in an injection of 17 %wt of water and an increase in electric efficiency of 9% absolute. To keep the mGT cycle layout simple, low cost and not too complex, a maximum of two heat exchangers was imposed for the heat exchanger network design. Although black box analysis indicated a large potential for water introduction, this potential could not be achieved with the considered networks in this paper. Finally, injection of pre-heated water was identified as the optimal water injection scheme for waste heat recovery resulting in 4.6% absolute electric efficiency increase and a final stack temperature of 62 °C. Results of simulations of the second case indicate that the stack temperature needs to be lowered under 26 °C in order to make the cycle self-sufficient with water.

1. Introduction

micro Gas Turbines (mGTs) offer a number of advantages compared to Internal Combustion Engines (ICEs) for small-scale (up to 500 kW_e) power production, for example, a small number of moving parts, compact size and light weight, lower emissions and

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lower electricity costs [1]. Particularly for the small-scale Combined Heat and Power (CHP) production, mGTs offer great potential [2]. The major drawback is their lower electric efficiency. A lower heat demand mostly leads to a forced shutdown of the mGT, due to the low electric efficiency because producing only electricity with the mGT is more expensive than taking the necessary power from the grid. This forced shutdown reduces the total amount of yearly running hours, making the investment less attractive [3].

A way to improve the overall economic performance of a mGT CHP unit is to improve the electric efficiency of the mGT. Increasing the electric efficiency will make the mGT more competitive against the ICE engine.

Electric efficiency can be improved by increasing the efficiency of the components of the mGT. The two parameters that have potential for efficiency increase are increased Turbine Inlet Temperature (TIT) and higher recuperator effectiveness [4]. Since cooling of the small radial flow turbine is difficult, the TIT can only be increased if thermal resistant – ceramic – materials are introduced in the mGT. The use of these ceramic materials allows for a higher TIT, resulting in considerable energy savings [5]. McDonald and Rodgers indicated that a ceramic recuperator and a ceramic radial turbine are necessary to achieve 40% efficiency in a 200 kW_e mGT [6]. Campanari and Macchi showed that the high electric efficiency levels achievable with future advanced ceramic mGTs would improve dramatically the economic competitiveness of the application, as well as the primary energy savings and environmental benefits [7]. By using a heat resistant coating technology, Kim and Lee were able to increase the TIT of their home made mGT by 100 °C, resulting in 20% more power output and 6% absolute increase in electric efficiency [8]. Increasing the recuperator efficiency is very straight forward, but will however result in a dramatically increase in recuperator size, weight and cost [4]. Pressure drop over the recuperator should be limited, since a 1% pressure loss increase will decrease the turbine efficiency by 0.33% absolute [9]. McDonald proposes a basic concept for better heat exchanger design [10]. Finally, Galanti and Massardo indicated that increasing turbine and compressor efficiency by two percentage points would increase the global mGT efficiency without affecting costs in a significant manner [11].

Another way to improve the electric efficiency of the mGT is to introduce water (vapour/liquid) in the cycle. Water injection is considered a successful way to increase electric efficiency of Gas Turbine (GT) cycles [12]. In periods with a low heat demand, the lost thermal power can be recovered by introducing auto-raised steam/heated water inside the mGT cycle, resulting in a more profitable investment [3]. The beneficial effect of steam/water introduction in a mGT on its performance has already been studied several times [13–20]. Lee et al. showed by means of simulations the beneficial effect of steam injection on the performance of a recuperated mGT cycle [13]. Dodo et al. equipped a 150 kW_e mGT with a Humid Air Turbine (HAT) line and Water Atomizing inlet air Cooling (WAC) line. Experiments showed stable runs at 32% electric efficiency and reduced NO_x exhaust [14]. Mochizuki et al. performed steam injections experiments on a Capstone C60 mGT. At 60 kW_e and injection up to 6 wt% steam/air ratio, thermal efficiency could be improved by 3–4% [15]. Parente et al. studied the thermodynamic [16] and the thermo-economic performance of the micro Humid Air Turbine (mHAT) [17]. Ferrari et al. injected steam in a hybrid system test rig to study the effect of a steam rich mass flow on engine behaviour. Test results showed that the mGT accepted the injected steam mass flow rate without surge problems [18]. More recently, Wei and Zang experimentally investigated the off-design behaviour of a small-sized (25 kW_e) HAT cycle. Test results at constant fuel flow rate and constant TIT indicated significant power output increases of 3 kW_e and 9.5 kW_e [19]. Our research group simulated [3] and validated the effects of steam injection on the performance of a Turbec T100 mGT [20]. Recently, the authors of this paper indicated that by converting the T100 mGT into a mHAT, electric efficiency will increase by 2% absolute [21].

None of the previous mentioned studies however identified the most optimal route for water introduction in a mGT cycle to recuperate the lost thermal power. Our research group developed a general two-step approach for optimal humidified GT cycle development [22]. In this procedure, the thermodynamic potential of water injection is first determined using an adiabatic black box method. In a second step, the final cycle layout is designed, using composite curve theory. This two-step approach showed its potential by identifying the HAT, as proposed by Rao [23], as the most optimal layout for a humidified cycle. This two-step approach also led to the development of a new humidified GT, without using a saturation tower, the REgenerative EVAPoration cycle (REVAP®) [24]. This cycle has about the same net efficiency as the HAT cycle (54%) [12]. We applied this two-step method to the mGT cycle to identify the most optimal way for water introduction in a mGT cycle.

In this paper, the results of two different scenarios concerning the water injection in a mGT, using the two-step procedure, are presented. In the first scenario [Scenario 1 (S1)], the black box is considered as adiabatic and no fixed stack temperature is imposed (thus allowing condensation of the exhaust gasses). Since water consumption is a major issue for mixed air/water GTs, in the second scenario [Scenario 2 (S2)], the cycle is made self-sufficient with water. In the first scenario (S1), we did not control the amount of condensed water. In the second scenario (S2), we add a new constraint to condense exactly the amount of water introduced in the mGT cycle (not all water present in the flue gasses). The main goal of S1 and S2 is to identify the thermodynamic limit for water introduction in a mGT under these considered boundary conditions. By using composite curve theory, different ways for water introduction in a mGT cycle for waste heat recovery could be developed. The performance of each cycle is then compared with the black box results in order to check if the full potential for waste heat recovery is exploited. The cycle that approaches the black box results the closest is then identified as the most optimal way for waste heat recovery through water injection in a mGT. Both selection procedure and final cycle lay-out will be presented in this paper.

2. Approach

The Turbec T100 microturbine CHP system is a typical recuperated mGT system (Fig. 1). The inlet air enters the compressor (1), where it is compressed. The compressed air is preheated in the air recuperator by the hot flue gasses (2). In order to obtain the best performance, the compressed air is heated until maximal TIT (950 °C) by burning natural gas in the combustion chamber (3). The hot gasses will expand over the turbine (4), which is connected to the compressor and a high-speed generator. After preheating the compressed air, the excess heat, available in the flue gasses, is used to heat water for heating purposes (5). A brief summary of the mGT performance is given in Table 1.

By changing the shaft speed, the T100 mGT control system keeps the produced electric power output constant at a user defined set point (between 60 and 100 kW_e). The compressor and turbine operate thus at the same variable shaft speed, which results in variable mass flow rate and pressure ratio. Besides the shaft speed, the fuel flow rate is also controlled in order to maintain TIT at its maximal value. The variable shaft speed and constant TIT allow the T100 to operate at high part load electric efficiency [25]. The produced thermal power can be controlled by routing part of the