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Humidified micro gas turbines for domestic users: An economic and primary energy savings analysis

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A B S T R A C T

Micro Gas Turbines (mGTs) offer valuable advantages for small-scale Combined Heat and Power (CHP) production compared to reciprocating Internal Combustion Engines (ICEs): lower maintenance costs per kWh_e, cleaner exhaust, lower vibration levels and concentration of the residual heat in a single source (the exhaust gases). Nevertheless, mGTs have lower electrical efficiencies, fact that has prevented them from penetrating in the CHP market. Hot liquid water injection—by means of a saturation tower within the micro Humid Air Turbine (mHAT) cycle—allows both improving the flexibility of heat production and the electrical efficiency of mGTs; two qualities that if enhanced would increase the economic feasibility of the technology. Although the advantages of mHAT technology have been proven from a thermodynamic point of view, its economic performance has not yet been fully investigated. This paper presents a comparison of the economic profitability and the primary energy savings of an mGT, an ICE and an mHAT unit operating in real network conditions. Our aim is to investigate whether the increase in flexibility and electrical efficiency, achieved when transforming an mGT into an mHAT, allows this technology to economically outperform ICEs. Results show that the three units are viable in scenarios with high electricity and low natural gas prices. For the cases in which investment is feasible, the revenues with mHAT are the highest: thanks to their flexibility in heat generation, mHAT units are able to run all year long. On the other hand, the greatest primary energy savings are achieved with ICE units—which have the highest overall efficiencies—while mHAT savings are substantially lower.

1. Introduction

Micro Gas Turbines offer important advantages for small scale (up to a few hundred kilowatt) Combined Heat and Power (CHP) compared to reciprocating Internal Combustion Engines (ICEs): lower vibration level, a smaller number of moving parts, cleaner exhaust and lower maintenance costs per kWh_e [1]. In addition, the usable heat in Micro Gas Turbines (mGTs) is concentrated in the high temperature exhaust gases, while in ICEs it is distributed between the cooling jacket, the exhaust gases and the lubricant oil, making it more complicated to collect [2]. Both mGTs and ICEs running on natural gas have high cogeneration efficiencies (of ~80 and 85% respectively). Nevertheless, the electrical efficiency of mGTs is limited to 30%, whereas values for reciprocating ICEs go up to 34–35% [3]. Hence, whenever the external heat demand is low and the only useful output of the unit is the generated electricity, the overall efficiency is reduced to the electrical efficiency. Although this is a problem common to all CHP technologies, the fact that mGTs have lower electrical efficiencies than ICEs means that they have an even greater disadvantage. Therefore, operation with a reduced external heat demand may not be economical; consequently, mGTs in such situations need to be shut down. This, in turn, negatively affects their profitability [4,5].

In order to increase the electrical efficiency for periods of low external heat demand, the exhaust gases—instead of blown off—can be used to warm up water to then re-inject it back into the cycle, following the same principle as the Humid Air Turbine (HAT) developed by Rao [6]. Several authors have investigated the

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Nomenclature

Acronyms

CHP	Combined Heat and Power
ICE	Internal Combustion Engine
IRR	Internal Rate of Return
mGT	micro Gas Turbine
mHAT	micro Humid Air Turbine
NPV	Net Present Value
O&M	Operation and Maintenance Costs
PES	Primary Energy Savings
TIT	Turbine Inlet Temperature
TOT	Turbine Outlet Temperature
VUB	Vrije Universiteit Brussel
WAC	Water Atomising inlet air Cooling

Greek symbols

$\eta_{el,ref}$	Reference electrical efficiency
$\eta_{th,ref}$	Reference thermal efficiency

Roman symbols

$CHP_{\eta_{el}}$	Total electricity production of the CHP unit during the year divided by its yearly consumption
$CHP_{\eta_{th}}$	Total heat production of the CHP unit during the year divided by its yearly consumption
B_n	Cash flow in year n
C_0	Initial capital costs
C_n	Cost in year n
N	Lifetime of the project

beneficial effect of converting an mGT into a micro Humid Air Turbine (mHAT), both from a numerical and an experimental perspective [7–13]. Parente et al. carried out a thermodynamic assessment of the mHAT cycle, concluding that an existing mGT can be operated as an mHAT without major re-design [7]. Nikpey et al. predicted a 1.7% efficiency increase when transforming an mGT into an mHAT [8]. Zhang and Xiao studied the off-design performance of 90 kW_e humidified cycles, confirming that mHAT had stable off-design behaviour [9]. Dodo et al. built a 150 kW_e mGT with a water saturation air line and also coupled with a Water Atomizing Inlet Cooling (WAC). Experiments resulted in stable operation at 32% electrical efficiency and reduced NO_x emissions in the exhaust [10]. Thereafter, Nakano et al. showed, by performing water injection experiments, that the combination of WAC and HAT brought about a 3% absolute efficiency increase [11]. More recently, Wei et al. experimentally investigated the off-design behaviour of a small-sized (25 kW_e) mHAT. Test results at constant fuel flow rate and constant Turbine Inlet Temperature (TIT) indicated power output increases of 3 and 9.5 kW_e respectively [12]. Newly, our research group was able to run an mHAT based on the Turbec T100 mGT with water injection and in a stable way [14,15].

Despite the aforementioned studies on the technical performance of micro gas turbine based humid cycles, there is little literature available on the economic performance of this 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 [16]. A total of 4000 running hours per year was assumed for all cases. They concluded that the mHAT cycle offered a great potential for increased thermoeconomic performance. Delattin et al. performed an economic analysis of steam-injected micro gas turbines considering different dry running hours per year [5]. They derived that the required dry operating hours when steam-injection took place are reduced by about 1500 h per year compared to the traditional mGT cycle operation. It is important to note that both of these analyses assumed a certain amount of yearly running hours and developed, from this standpoint, the economic assessment. Stathopoulos et al. also implemented an economic analysis of a steam-injected mGT for a domestic and a public user, but accounting for detailed heat and electricity demand data during the year [17,18]. In their analyses, the user's demand and market conditions were taken as a given, and a model was developed in Aspen Plus to find the exact microturbine size that maximised the profitability of the investment. They concluded that, in the current German market and with the feed-in tariffs that the government offers, the retrofit of micro gas turbines with steam injection makes sense from an economic and a thermodynamic point of view.

Some of the authors of this paper recently investigated the economic performance of mGT and mHAT cycles in a wide variety of electricity and natural gas price scenarios for two domestic users with distinctive demand profiles [4]. Our study confirmed that for those scenarios where investment in mGT technology is feasible, it is worth transforming the mGT into an mHAT as the latter yields higher profits. Once the supremacy of mHAT over mGT is proved for domestic users, the logical step is to investigate whether the improved performance of mHAT allows this technology to outperform mGT's main competitor: the ICE. In the present work, we have therefore extended our economic study to ICEs. Our aim is twofold: on the one hand, we explore whether the flexibility of water injection in mGTs results in a better economic performance compared to ICEs, accounting for real household demands. On the other hand, we examine the effect of water injection in mHAT primary energy savings to determine if this advanced cycle would still qualify as high-efficiency cogeneration according to European standards.

2. The T100 mHAT cycle

The Turbec T100 mGT is, as the majority of mGTs, a recuperated Brayton cycle. The nominal electrical and thermal power outputs of the T100 are 100 kW_e and 165 kW_{th}. The T100 has an electrical efficiency of 30% and a heat generation efficiency of 50%, which means that the total energy efficiency of the unit is 80% [19].

At Vrije Universiteit Brussel (VUB) the Turbec T100 mGT has been coupled with an innovative spray saturation tower [20], and transformed into an mHAT following the layout shown in Fig. 1. In the current mHAT configuration, the incoming air is compressed in a radial compressor until it reaches a temperature of 175 °C. Subsequently, the air flow is passed through the saturation tower, where it is humidified with the hot water (at a temperature of 80 °C) coming from the economiser. As air advances through the saturator, the water vapour content rises: during the process both air enthalpy and air mass flow are increased while heat is extracted from the circulating water below boiling temperature. Subsequently, the humidified air is pre-heated by the exhaust gases in the recuperator up to 560 °C and mixed with natural gas in the combustion chamber, where the fuel is burnt until a TIT of 890 °C is reached. The TIT of the mHAT cycle is lower than that of the original T100 mGT due to the effect of the controller DePaepe:zr. Thereafter, the exhaust gases are expanded in the turbine, down to a Turbine Outlet Temperature (TOT) of 645 °C. The exhaust gases leave the recuperator at 185 °C. Thereafter, the remaining energy in the flue gas is used to warm up water in the economiser. This hot water is then routed towards the saturation tower, where it is sprayed over the air coming from the compressor. Only 2% of the sprayed water actually evaporates in the saturator, the rest is pumped back to the economiser. In order to make up for the evaporated water,