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Research Paper

Experimental characterisation of a micro Humid Air Turbine: assessment of the thermodynamic performance

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HIGHLIGHTS

- A T100 micro gas turbine has been converted into a micro humid air turbine.
- To do so, a unique spray saturation tower was designed and built for the facility.
- We have conducted experiments at constant power and constant rotational speed.
- Experimental results show an electrical efficiency increase of 4.2 percentage pt.

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ABSTRACT

Despite appearing as a promising technology for distributed generation, micro Gas Turbines (mGTs) have not yet managed to penetrate the small-scale Combined Heat and Power (CHP) market. The energy efficiency of mGTs amounts to 80% whenever both heat and electricity are required. However, when the heat demand is low, the hot exhaust gases have to be directly blown off and the electrical efficiency of the unit ($\sim 30\%$) is not high enough to sustain profitable operation. Water injection, achieved when transforming the mGT into a micro Humid Air Turbine (mHAT), allows making use of the exhaust gas heat in such cases, thus increasing electrical efficiency of the technology and improving its feasibility.

Although the enhanced performance of the mHAT cycle has been thoroughly investigated from a numerical point of view, results regarding the experimental behaviour of this technology remain scarce. In this paper, we present the experimental characterisation of the mHAT located at Vrije Universiteit Brussel (VUB) which is based on the T100 mGT equipped with a spray saturation tower. These are the first experimental results of such an engine working at nominal load with water injection. In addition, the control system of the unit has been modified so that it can operate either at constant electrical power output (the default setting) or at constant rotational speed. The latter option allowed better assessing the effect of water injection.

Experimental results demonstrate the patent benefits of water injection on mGT performance: at fixed rotational speed, the power output of the mHAT increases by more than 30% while fuel consumption rises only by 11%. Overall, the electrical efficiency in wet operation increases by up to 4.2% absolute points.

1. Introduction

Distributed energy systems offer solutions to many of the world's most imperative energy and electric issues, including blackouts and brownouts, limitations on emissions, energy security matters, power quality concerns, transmission bottlenecks and the eagerness for larger control over energy costs [1]. In addition to being a distributed energy technology—and due to the efficiency gains inherent to the simultaneous production of electricity and heat—small-scale Combined Heat and Power (CHP) units feature energy efficiencies of around 80%. Therefore, they allow sparing up to one third of the primary energy compared

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Nomenclature

Acronyms

CHP	Combined Heat and Power
CIT	Combustor Inlet Temperature
ICE	Internal Combustion Engine
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 symbols

A	area of the pipe section [m^2]
C_p	heat capacity at constant pressure [$\frac{J}{kg\ K}$]
D	hydraulic diameter of the pipe [m]
f_D	Darcy friction factor [–]
$\dot{m}_{fuel}$	fuel flow rate [$\frac{g}{s}$]
$\dot{V}_{water}$	volumetric water rate [$\frac{m^3}{s}$]
L	length of the pipe [m]
N	rotational speed [rpm]
P_{el}	electrical power output [kW_e]
V	mean flow velocity [$\frac{m}{s}$]

Greek symbols

η_{el}	electrical efficiency [%]
$\eta_{el,corr}$	electrical efficiency, corrected to match the inlet temperature of the corresponding dry case [%]

to the independent production of electricity and heat [2]. However, 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. Although micro Gas Turbines (mGTs) are in several aspects superior to Internal Combustion Engines (ICEs)—they have a cleaner exhaust, lower vibration levels and reduced maintenance costs—their electrical efficiencies are lower (~30% vs 35% for capacities around 100 kW_e) [3–5]. Hence, in moments of curtailed heat demand, running the mGT may not be economical, eventually leading to shutdown of the machine. In turn, a finite number of running hours per year negatively affects the Net Present Value (NPV) of the investment, thus worsening the feasibility of the technology [6].

Turning an mGT into a micro Humid Air Turbine (mHAT) allows increasing the electrical efficiency in periods of no or low external heat demand. To this end, the exhaust gases—instead of being blown off—can be used to warm up water to then inject it back into the cycle, following the same principle as the Humid Air Turbine (HAT) developed by Rao [7].

Several authors have researched the benefits that mHAT technology brings about, both from a numerical and an experimental perspective [8–17]. Parente et al. developed a thermodynamic assessment of the mHAT cycle, deducing that an existing mGT can be run as an mHAT without major re-design [8]. Nikpey et al. predicted a 1.7 pt.% efficiency increase when transforming an mGT into an mHAT [9]. Zhang and Xiao investigated the off-design performance of 90 kW_e humidified cycles, confirming that mHAT had stable off-design behaviour [10]. Dodo et al. performed 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 [11]. Thereafter, Nakano et al. demonstrated by means of water injection experiments that the combination of WAC and HAT led to a 3 pt.% absolute efficiency increase [12]. More recently, Wei et al. experimentally researched the off-design behaviour of a micro (25 kW_e) HAT. Test results at constant fuel flow rate and constant Turbine Inlet Temperature (TIT) illustrated power output rises of 3 and 9.5 kW_e respectively [13]. In addition, our research group has carried out extensive work on the development of an Aspen Plus model of the mHAT cycle [14–16]. Most recent results show that by adding a saturation tower to the Turbec T100 mGT and converting it to an mHAT, water injection would lead to a reduction by 6 pt.% in fuel consumption and an absolute efficiency increase of 2 pt.% if the default settings of the controller are respected [16]. 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 [17].

Despite the potential of mHAT technology, to the knowledge of the authors an mHAT unit coupled with a real saturation tower has never been experimentally tested at nominal conditions. Nevertheless, in the last years, the T100 mGT installed at the VUB laboratory has been adjoined with a spray saturator thus constituting a first-of-its-kind facility. The results of the preliminary tests in this unit have been presented in [18,19]. In this paper, we discuss the first humid full-load experiments in our T100 mHAT working both in constant power output and in constant rotational speed modes. In addition, we assess how water injection affects the components of the cycle and we quantify the beneficial effect of adding water to the mGT in terms of electrical power output and electrical efficiency increase.

2. Experimental set-up and overall methodology

The basis of the test rig is the natural gas-fired mGT Turbec T100. The T100 is, as most mGTs, a typical Brayton cycle with regeneration. At nominal operating conditions and ISO ratings, this unit produces a power output of 100 kW_e and 165 kW_{th} with a rotational speed of 70,000 rpm. Its total energy efficiency is 80%—of which 30% corresponds to the electrical efficiency [20].

The Turbec T100 present at Vrije Universiteit Brussel (VUB) has been converted into an mHAT following the layout shown in Fig. 1. In addition, Table 1 lists all the components of the experimental set-up. In the current configuration—according to simulations performed in Aspen Plus [16]—, the incoming air is compressed in the radial compressor (1) and subsequently humidified in the saturation tower (2), where hot water at around 80 °C is sprayed. The water vapour content of the air rises as it advances through the saturator: during the process both air enthalpy and air mass flow are increased while the heat of evaporation is extracted from the circulating water below boiling temperature. Thereafter, the saturated air is preheated by the exhaust gases in the recuperator (3) before entering the combustion chamber (4) where natural gas is burnt until reaching a Turbine Inlet Temperature (TIT) of ~890 °C—value that corresponds to a Turbine Outlet Temperature (TOT) of 645 °C. The flue gas expands in the turbine (5), which drives the compressor through a single shaft while the extra shaft power is converted into electricity in a high speed generator. The power electronics system transforms this electricity into 400 V and 50 Hz before plugging it in the grid.