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Enhancing micro gas turbine performance through fogging technique: Experimental analysis

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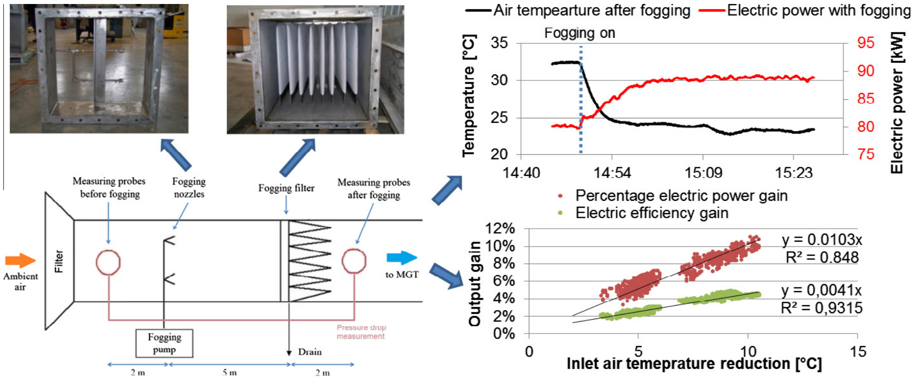
HIGHLIGHTS

- A test bench that has been designed to implement the fogging IAC technique to a MGT.
- Electric power gain depends on ambient humidity and it ranges from 5% to 13%.
- Electric power enhancement is 1.03 kW/°C of inlet air temperature reduction.
- Electric conversion efficiency increases by about 0.41%/°C.
- Performance gains are the higher, the hotter and drier the climate is.

GRAPHICAL ABSTRACT



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ABSTRACT

This paper describes a test bench that has been designed to implement the fogging inlet air cooling technique to a 100 kWe Microturbine (MGT) and reports the power and efficiency increase of the machine. Indeed, one of the main issues of MGTs, which has also been observed and documented in large sized gas turbines, is their strong sensibility to inlet air temperature. One of the most interesting technology in terms of low plant complexity to limit the MGTs performance loss is the high pressure fogging. Although cooling down the inlet air temperature with this technique has already been analyzed for medium/large gas turbines systems, there are very limited reports available on MGTs and few experimental data are documented.

Results show that the machine's electric power gain depends on ambient humidity and it ranges from 5% to 13% (corresponding to an inlet temperature drop between 4 and 10 °C) in the location where the plant is installed. Power enhancement corresponds to 1.03 kW for each Celsius degree of inlet air temperature reduction. As regards the electric conversion efficiency, the increase reaches about 0.41%/°C. Being the inlet air saturation the thermodynamic limit, the absolute power and efficiency gains are the higher, the hotter and drier the climate is.

1. Introduction

Microturbines (MGTs) are a relatively new technology that is currently attracting a lot of interest in the distributed generation (DG) market [1–4]. Their electric output varies from 25 kW to 500 kW, which is a power range particularly well suited for

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Nomenclature

$\dot{m}$	mass flow rate (kg/s)
n	rotational speed (rpm)
p	pressure (Pa)
T	temperature (K)
x	specific humidity (g/kg)

Subscripts

air	air
H_2O	water
nom	nominal
sat	saturated

Abbreviations/acronyms

DG	distributed generation
GT	gas turbine
HP	heat and power
IAC	inlet air cooling
ICE	internal combustion engine
MGT	micro gas turbine
RH	relative humidity
RHE	recovery heat exchanger

cogeneration applications in the service sector, households and small industry. MGTs are generally preferred to ICEs [5,6] even if they are less efficient in generating electricity, thanks to their high power density, low environmental impact in terms of pollutants, low operation and maintenance costs and multi fuel capability [7]. One of the biggest drawbacks of this kind of machines, which is also reported in larger GT, is the strong dependence of their performance, mainly output power and electric efficiency, on the ambient conditions, being the ambient temperature the most affecting parameter. This substantially limits their application in hot climates and does not allow to exploit the full potential of the machine which is normally rated in ISO conditions (15 °C, 1013 hPa, 60% RH) [8].

The influence of atmospheric conditions on medium/large GTs performance is well known and widely documented in literature. As regards large sized GT, the power output loss has been evaluated in several works and it ranges between 0.5 and 0.9%/°C depending on the machine type [9–11]. For GTs of smaller capacity, Mohanty [12] reported that power output loss with hot ambient temperature can be even greater than in larger GTs. This evidence is also reported by Amell and Cadavid [13]: they explained that this behavior of smaller GTs is due not only to the air density reduction but also to the volumetric flow decreases with temperature.

Being the effect of ambient temperature on the performance of GTs so significant, several Inlet Air Cooling (IAC) techniques have been studied and applied to reduce its influence. Literature is rich of works that evaluated a series of solutions both theoretically [14–19] and experimentally [20–25].

In particular, Al-Ibrahim et al. [14] reported an interesting review listing the following main technical solutions: (i) wetted media evaporative cooling; (ii) high-pressure fogging; (iii) absorption chiller cooling; (iv) refrigerative cooling and (v) thermal storage together with their key benefits and drawbacks. In particular they highlight that the techniques based on water evaporation in the inlet air stream are simple and reliable in design, have low unit capital and operational costs, do not introduce significant parasitic power consumption but yield limited power gain due to the ambient wet-bulb limitation on inlet air temperature and require large amounts of purified water. The techniques using an heat exchanger placed upstream of the compressor are not sensitive to ambient-air wet-bulb temperature and thus guarantee greater performance increase than evaporative or fogging, but have higher unit capital and operational costs. Refrigerative cooling are relatively simple and reliable in design and operation but require large electric power (that can be reduced using thermal storages to cool the inlet air during peak-power demand). Absorption chiller cooling techniques have minimum parasitic electric power demand as they can recover energy from the GT exhausts but are complex systems requiring expertise in design, operation and maintenance.

Al-Ansary et al. [15] proposed a hybrid solution using a combination of vapor compression cooling and fogging showing that it can meet the requirements of both dry and humid climates and maximize the effectiveness of the IAC technique. On the other hand, the initial cost and the complexity of the plant are high.

Najjar [16] evaluated the chance of adopting an absorption chiller fed by the GT exhausts to treat the inlet air of the gas compressor. Khaliq [17] reported the energetic and exergetic analysis of a cogeneration plant with absorption inlet air cooling combined with evaporative aftercooling showing significant advantages with respect to a traditional basic cycle. Chacartegui [18] described the energetic and economic advantages of applying different kinds of IAC solutions to a commercial cogeneration GT. Yang [19] developed an analytical method to figure the influence of two IAC techniques (fogging and absorption cooling) on the performance of a combined cycle plant and he suggests a range of ambient parameters (namely air temperature and humidity) where the IAC technologies can be favorably applied. Kitchen et al. [20] examined several commercial GTs and evaluated the potential capacity increase applying inlet air cooling techniques; a detailed discussion of the available cooling techniques and the main advantages and drawbacks of each of them were discussed by Giourof [21], De Lucia et al. [22], ASHRAE [23], and Anderpont [24]; finally, a design guide was proposed by Stewart [25].

Literature on high pressure fogging systems applied to medium/large GTs is rich.

Chacartegui et al. [18] analyze the use of this technique in a cogeneration power plant evidencing that it represents a good compromise in terms or effectiveness, pay-back period and application simplicity and it is particularly suitable for hot and dry climates where it is possible to exploit maximally the advantage of the adiabatic saturation.

An analytical approach in the evaluation of the compressor map working point with fogging IAC has been reported by [26] for GTs and combined cycle plants: the results of this analysis indicate a significant increase in the net power output of the studied plants and a general trend of the compressor operating point towards the surge line.

Roumeliotis [27] investigated the effect of both inlet fogging upstream the compressor and water/steam injection in the combustor applied to several commercial GTs showing results on both performance augmentation and engine operability.

A paper by Kim [28] reports on the chance of adopting cycle regeneration and fogging to enhance the performance of GTs. In particular, the thermodynamics of the droplets evaporation is described and the effects on the cycle efficiency as a function of the compression ratio is evaluated. Practical considerations and experimental aspects have been discussed in [29,30] with particular reference to droplet thermodynamics and heat transfer issues.