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Enhancing micro gas turbine performance in hot climates through inlet air cooling vapour compression technique

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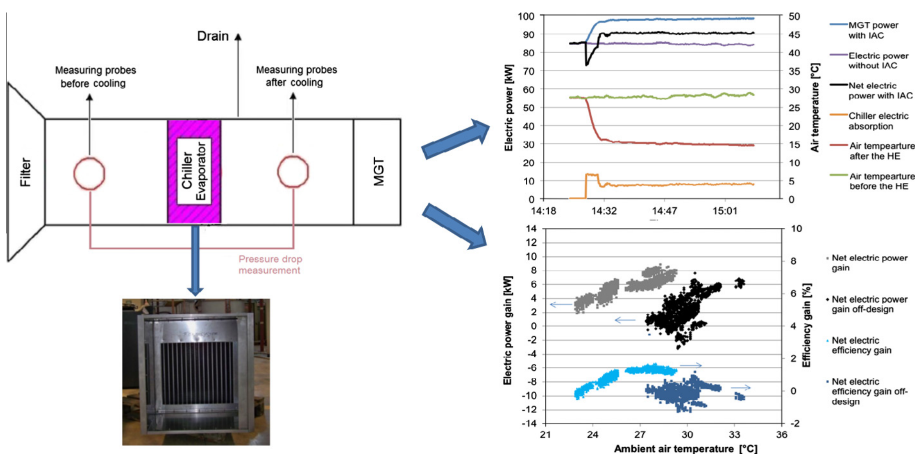
HIGHLIGHTS

- A test bench has been designed to test direct expansion IAC technique to a MGT.
- The COP of the chiller ranged between 2.2 and 2.5.
- Electric power gain depends on ambient conditions and it reached up to 8.5%.
- Electric efficiency gain depends on ambient conditions and it reached up to 1.6%.
- Performance gains are higher in drier climates and with more performing chillers.

GRAPHICAL ABSTRACT



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ABSTRACT

Microturbines (MGTs) are power generation devices showing very interesting performance in terms of low environmental impact, high-grade waste heat and very low maintenance cost. One of the main issues that affect the output of MGTs is their strong sensibility to inlet air temperature. Both in literature and in practical applications, several solutions have been applied to control the inlet air conditions and reduce the sensibility of this kind of machines to ambient conditions. One of the most interesting technology is the refrigerating vapour compression technique. This solution has already been used for medium/large GTs, but there are very limited inlet air cooling applications on MGTs and few experimental data are documented. This paper describes a test bench that has been designed to apply the direct vapour expansion technique to a 100 kWe MGT and reports the power and efficiency augmentation of the machine when operating in hot summer days.

The chiller was designed to treat the MGT's air flow rate under specific working conditions and cool the inlet air temperature down to 15 °C. Thanks to the reduction of the inlet air temperature, the MGT showed a benefit in terms of electric power gain up to 8% with respect to the nominal power output in ISO conditions while the electric efficiency increased by 1.5%. Results indicate that an almost linear trend can be obtained both in the electric power increase and in the electric efficiency increase as a function of the inlet air temperature when the chiller operates under nominal working conditions.

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When the IAC device operates at a higher temperature or a higher humidity than the design one, the gain is limited; in some working conditions with high relative humidity, most of the beneficial effect can even be lost.

1. Introduction

Among the energy production devices that can be adopted in the distributed generation (DG) market, Microturbines (MGTs) could play a significant role [1–4] since their electric output varies from 25 kW to 500 kW, which is a particularly interesting range for cogeneration applications in the service sector, households and small industry. Even if the electric efficiency of MGTs is generally smaller than that of internal combustion engines [5,6] they can be profitably applied in DG, thanks to their high power density, low pollutants' concentration, low operation and maintenance (O&M) costs and multi fuel capability [7]. A significant limitation on the application of MGTs, especially in hot climates, is the strong dependence of their performance, namely the electric output and the electric efficiency, on the ambient conditions, being the hot ambient temperature the most affecting parameter. This characteristic, that is also recorded for larger GT, does not allow to exploit the full potential of these machines which are normally rated in ISO conditions (15 °C, 101.3 kPa, 60% RH) [8].

Literature is rich of documents reporting the influence of atmospheric conditions on industrial scale GTs' performance. Several works evaluated the performance loss of these machines in hot climates: depending on the size and the characteristics of the GT, the electric power output can decrease by 0.5–0.9%/°C [9–11]; even greater losses are recorded for GTs of smaller capacities as reported in a paper by Mohanty [12]. Amell and Cadavid [13] also investigated this issue and they attributed this behavior of smaller GTs not only to the air density reduction with higher ambient temperature but also to a volumetric flow reduction.

As for MGTs, the effect of the inlet air temperature on their performance has been investigated in a limited number of works [14–18]. This specific problem was already approached by the authors of this paper: we designed a specific test bench to evaluate the cogeneration performance of MGTs [19] and we adopted the artificial neural networks (ANNs) methodology [20] as well as analytical models [21] to quantify the effect of ambient conditions on the output of the machine. Air pressure and relative humidity do not affect significantly the performance of the machine while air temperature strongly affects both the electric output and the electric efficiency. In numerical terms, a reduction of about 1.22%/°C for the electric power and a reduction of about 0.51%/°C for the electric efficiency was assessed for Turbec100 kWe MGT if compared to the ISO ratings.

Since the performance of GTs is so sensible to ambient temperature variations, the so-called Inlet Air Cooling (IAC) techniques have been studied and applied to reduce its impact. There are several works in literature that presented a series of solutions and the beneficial results that can be obtained by reducing the compressor inlet air temperature.

A work by Al-Ibrahim et al. [22] describes the most used IAC techniques that can be applied to enhance the performance of GTs: (i) wetted media evaporative cooling; (ii) high-pressure fogging; (iii) absorption chiller cooling using the GT's exhaust gas; (iv) and refrigerative vapour compression cooling.

In some cases, it is also possible to have a combination of the abovementioned technologies and obtain hybrid solutions in order to use the most performing one depending on the environmental conditions. A study by Al-Ansary et al. [23] showed that, combining vapour compression cooling and fogging technologies, it is possible to meet the requirements of both dry and humid climates and optimize the effectiveness of the IAC technique. Of course a drawback of this solution is that the initial cost and the complexity of the plant are increased.

Among all the possible IAC technologies, the high-pressure fogging system shows a good compromise in terms or effectiveness, pay-back period and application simplicity [24]. It is particularly suitable for hot and dry climates where it is possible to exploit maximally the advantage of the adiabatic saturation. On the other hand, it is not possible to control the temperature of the air downstream the fogging nozzles as it is limited by the wet bulb temperature of the ambient air. The characteristics of this technology have been analyzed in several works. Sanaye [25] developed an analytical approach to evaluate the compressor map working point when high-pressure fogging is applied to GTs and combined cycle plants: a significant enhancement in the net power output was reported as well as a general trend of the compressor operating point towards the surge line. Besides the inlet fogging upstream the compressor, Roumeliotis [26] also studied the water/steam injection in the combustor and applied to several commercial GTs showing results on both performance augmentation and engine operability. As regards the Brayton regenerated cycles, Kim [27] reported on the chance of adopting the fogging technique to enhance the performance of low-compression ratio GTs.

As regards the absorption cooling technique, the chance of adopting an absorption chiller fed by the GT's exhaust to treat the inlet air of the gas compressor was investigated by Najjar [28]. Khaliq [29] conducted an energetic and exergy analysis of an absorption inlet cooling cogeneration plant with evaporative after cooling showing significant advantages with respect to the original basic cycle. Popli et al. [30] compared the positive effect of evaporative cooling and absorption chiller to a GT installed in an oil and gas installation in Abu Dhabi. IAC techniques are also applied to more complex combined cycles where the exhaust of the GT are used to feed a bottoming steam cycle: Yang [31] developed an analytical method to evaluate the influence of fogging and absorption cooling techniques on the performance of a combined cycle plant; he also suggested a range of ambient air temperature and humidity where the IAC technologies can be favorably applied.

With regard to vapour compression techniques, a specific work was carried out by Chacartegui [32] that evaluated the energetic and economic advantage of applying direct expansion cooling to several commercial cogeneration GTs. Mohapatra [33] compared the positive effect of vapour compression and vapour absorption chillers applied to a combined cycle plant, also evaluating the effect of ambient humidity on the performance of the IAC techniques.

Besides the theoretical evaluations of the benefits of the application of the above mentioned solutions, IAC techniques are increasingly applied in many installations, especially in hot climates. Their application to commercial GTs has been investigated by Kitchen et al. [34] who also calculated the achievable capacity increase; a detailed discussion of the available cooling techniques and the main advantages and drawbacks of each of them were discussed by Giourof [35], De Lucia et al. [36], ASHRAE [37], and Anderpont [38]; finally, a design guide was proposed by Stewart [39].

Another interesting solution to enhance MGT output is hot water or steam injection in the combustion chamber, even though