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Research paper

Gas turbine evaporative cooling evaluation for Lagos – Nigeria

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HIGHLIGHTS

- The paper models the performance improvement of GTs with evaporative cooling.
- Economic impact evaluation of evaporative cooling is applied to a GTGE 9E.
- A practical limit for the width of the cooling potential interval is given.
- CAPEX at which evap. cooling results in increased electricity income is shown.
- GTs fitted with evaporative cooling have better performance.

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ABSTRACT

Evaporative cooling is widely recognised as one of the available gas turbine power augmentation tools. Due to its inherent characteristics evaporative cooling is thought as being only effective in geographic areas with high ambient air dry bulb temperature and low relative humidity. This paper clarifies, via literature review and thermal modelling examples, the fact that there is still potential for evaporative cooling in high temperature and relative humidity areas. The paper also estimates the maximum cost of the evaporative cooling installation that will yield a positive return of investment to plant owners in the decision of retrofitting evaporative cooling systems for the particular location of Lagos in Nigeria. In consequence power plant operators, especially those whose power generation assets are located on coastal environments, should be aware of the prospective benefits associated with such cooling technology.

1. Introduction

There is a general misconception that evaporative cooling cannot be implemented in regions where air relative humidity is high. Such misconception impedes power plant operators to take advantage of a relatively affordable way to augment the power generated by Gas Turbines on warm days or during the warmest hours of day. Gas Turbine Generators (GTGs) are constant volumetric machines [1] except those using Inlet Guide Vanes (IGVs), meaning that the volume flow of ingested air is fixed by the internal geometry and the rotation speed of the shaft. By increasing the mass flow rate of ingested air, the power generated by the GTG will increase.

One of the options to increase the mass flow rate of compressor ingested air is to increase the density of the combustion air by reducing its temperature, thereby increasing the GTG power output. The air density increase is accomplished by evaporating water into the inlet air, which decreases its temperature, following an adiabatic heat and mass exchange process, which correspondingly increases its density. The water vapour passes through the turbine, causing a negligible increase in fuel consumption [2].

Since the compressor absorbs approximately 2/3 of the GTG power production, a reduction in power consumption on the GTG compressor by means of reducing the inlet air temperature, for the same GTG fuel consumption, will result in a proportional increase in GTG power generation capacity and heat rate decrease, with the accompanying commercial benefits. There are different alternatives to accomplish a reduction in the incoming air stream temperature, namely wetted media evaporative cooling, spray cooling, inlet fogging or mist cooling and mechanical chiller air cooling (including thermal storage and absorption chiller technology). Of all these different technologies, only water evaporation based technologies will be analysed on this paper.

When dealing with evaporative cooling technologies, the reader should keep in mind, that there is an inherent limitation of such

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Nomenclature

Acronyms

Atm	101.325 kPa
bar(a)	100.000 kPa
PLC	Programmable Logic Controller
GTG	Gas Turbine Generator
IGV	Inlet Guide Vanes
USD	United States American Dollar
RH	Relative Humidity %
DBT	Dry Bulb Temperature, K
WBT	Wet Bulb Temperature, K
MW	Molecular Weight, kg/mol
kWh	Kilowatt hour, 3600 kJ

Variables

p	partial pressure, Pa
P	total mixture pressure, Pa
n	number of moles
cp	specific heat J/(kg K)
$\dot{m}$	mass flow, kg/s
W	power, kW
w	water
V	total mixture volume, m^3
$\dot{V}$	volumetric flow rate, m^3/s
T	absolute temperature, K

Subscripts

comp	compressor section
turb	turbine section
da	dry air
w	water vapour
air	air
g	gas
comb	combustion products
n	total number of moles in the mixture, mol R
$2 \rightarrow 1$	change between compressor section outlet and inlet
$3 \rightarrow 4$	change between turbine section inlet and outlet

Constants

R	universal gas constant, 8314.41 J/(kmol K)
Rg	specific gas constant, J/(kg mol K)

Greek symbols

ρ	gas density kg/m^3
Δ	increase

technologies, which is that the lowest attainable air temperature is set by the air wet bulb temperature and therefore this limit is established by atmospheric conditions rather than human controlled parameters. Changing atmospheric conditions, as for example increasing air relative humidity, will limit the potential evaporative cooling hours, and we will see that there are specific parts of the day in which using evaporative cooling is more beneficial than others.

2. Literature review

There are many different authors that have analysed evaporative cooling applications to gas turbines all under diverse approaches. Johnson [2], provides the dimensioning equations for inlet media evaporative coolers. Cataldi et al. [7] and Chaker and Meher-Homji [4] analyse in detail the thermodynamics of fogging systems. Preliminary climatic analysis is undertaken by Chaker [5] and McNeilly [15], this analysis should be always carried out to determine the evaporative cooling potential of a specific given location. Scheibel [6], provides a comprehensive and detailed review of the different available evaporative cooling processes applicable to GTGs. The different options for very hot and humid climates are evaluated under Al-Ibrahim and Varnham [8].

Farzaneh-Gord and Deymi-Dashtebayaz [9], evaluated different options one with evaporative cooler and another with mechanical chiller, and a novel method in which a turbo-expander is used to decrease the inlet air temperature by utilising the temperature drop caused by the Joule-Thomson effect on natural gas expansion.

Diogo et al. [10], analysed the Liquefied Petroleum Gas (LPG) cooling potential available on the regasification facilities in which the glycol solution that circulates on the gas vaporiser is used as refrigerant for the gas turbine air inlet stream on a mechanical chiller system.

The designer of gas turbine evaporative cooling systems, and especially of fogging systems, needs to be aware of the risk of water drop entrainment into the compressor section of the GTG. Droplets beyond the critical size, will cause premature erosion of the blade suction side of the first compressor stages. Further information on water droplet evaporation, residence time and water entrainment was thoroughly discussed by Perez-Blanco et al. in Ref. [11].

Under a mechanical integrity point of view, the reduction on compressor surge margin when using evaporative cooling and/or fogging systems must be accounted for. For a given compressor running line, when the evaporative cooling and/or fogging system is in operation the air mass flow increases. Such mass flow increase entails a rise of the compressor back pressure, which in turn results in a reduction of the compressor surge margin. For fogging systems the water injection rate must be regulated to maintain the pressure ratio below the surge line. In the author's experience most heavy duty gas turbines have a “dry” surge margin for transient operations that varies between 10 and 15%. The “wet” surge margin is defined by the gas turbine manufacturer on case by case basis and implemented on the GT controllers.

Finally, surge margin discussions, along with a comprehensive review of humidified gas turbines and their applications, was provided in the paper by Jonsson and Yan [12].

3. Evaporative cooling theory

One of the available methods to increase the mass flow rate of ingested air, on a gas turbine, is to reduce the incoming air temperature. In evaporative cooling, sensible heat from the air is transferred to the water, via an isenthalpic process, becoming latent heat as the water evaporates. During the air–vapour mixing process the water vapour becomes part of the bulk air and carries the latent heat with it. The air dry-bulb temperature is decreased because it gives up sensible heat. The air wet bulb temperature is not affected by the absorption of vapour latent heat since the water vapour temperature coincides with the air wet-bulb temperature [2].

Moist air is a mixture of two independent perfect gases: water vapour and dry air, each of these two gases is assumed to conform to the perfect gas equation of state as follows: