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Methodology to determine the appropriate amount of excess air for the operation of a gas turbine in a wet environment

R. Lugo-Leyte[a], J.M. Zamora-Mata[a], M. Toledo-Velázquez[b], M. Salazar-Pereyra[c,*], A. Torres-Aldaco[a]

[a] *Universidad Autónoma Metropolitana-Iztapalapa, Departamento de Ingeniería de Procesos e Hidráulica, San Rafael Atlixco 186, Col Vicentina 09340, Iztapalapa, México, D.F., Mexico*

[b] *Instituto Politécnico Nacional, Escuela Superior de Ingeniería Mecánica y Eléctrica, Sección de Estudios de Posgrado e Investigación, Laboratorio de Ingeniería Térmica e Hidráulica Aplicada, Unidad Profesional Adolfo López Mateos, Edificio 5, 3er piso SEPI-ESIME, C.P. 07738, Col. Lindavista, México D.F., Mexico*

[c] *Tecnológico de Estudios Superiores de Ecatepec, División de Ingeniería Mecatrónica e Industrial, Posgrado en Ciencias en Ingeniería Mecatrónica, Av. Tecnológico s/n, Col. Valle de Anáhuac, C.P. 55210, Ecatepec de Morelos, Estado de México, México*

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A B S T R A C T

This paper addresses the impact of excess air on turbine inlet temperature, power, and thermal efficiency at different pressure ratios. An explicit relationship is developed to determine the turbine inlet temperature as a function of excess air, pressure ratio and relative humidity. The effect of humidity on the calculation of excess air to achieve a pre-established power output is analyzed and presented. Likewise it is demonstrated that dry air calculations provide a valid upper bound for the performance of a gas turbine under a wet environment.

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1. Introduction

The thermal cycle of a power plant is affected by the conditions that are present at the place where it is installed, mainly ambient temperature, atmospheric pressure and the air's relative-humidity. All these parameters have impact in the generated electric-power and the heat-rate during operation [1] and [2]. Among these variables, the ambient temperature causes the greatest performance variation during operation.

According to Felipe and Electo [3], while the air's relative-humidity increases, the power generated by the combined-cycle plants also increases, provided the other parameters remain constant. In this case, the gas-turbine's efficiency is slightly reduced, as well as its power. However, the temperature of the gas-turbine's exhaust-gases increases, and therefore the power generated by the steam cycle is increased. Nevertheless, the operation and performance of the thermal cycle depends on great measure of the place's environmental conditions as well as the design condition [4]. Improvements in the design and operation of gas turbines have come along with advances in aerodynamics, thermodynamics and metallurgy. Such relationship has made possible for today's gas turbines to withstand temperatures in the 1700 °C range, pressure ratios up to 34:1, internal compressor and turbine isentropic efficiencies up to 90 percent, and overall thermal efficiency up to 40 percent [5]. In the same way, the number of stages required in a compressor to achieve a specific pressure ratio, and consequently the overall gas turbine size, has been reduced allowing more compact and efficient gas turbines for a given power output.

However, the most important improvement that the gas turbine has experimented is, perhaps, an increase of the turbine gas inlet temperature. This has been possible thanks to recent developments on cooling techniques for turbine blades, and metallurgical advances [6]. The turbine inlet gas temperature is, of course, linked to exhaust temperature from the combustion chamber. It is a well known fact that the temperature during steady combustion in the combustion zone could greatly exceed the maximum allowable temperature by the turbine blades placed on the first stage of the turbine. In order to lower the temperature of the combustion gases to a tolerable level, an important amount of excess air is continuously supplied in the latter sections of the combustion chamber (Fig. 1).

The main objective of this work is to develop a systematic methodology to quantify the amount of excess air that needs to be supplied in order to keep the turbine inlet temperature at acceptable levels during steady state operation. To determine this amount of excess air, the humidity of the atmospheric air for the combustion

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* Corresponding author. Tel.: +52 55 50002329.
E-mail address: msalazar@tese.edu.mx (M. Salazar-Pereyra).

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Nomenclature

DA	dry air, [mol]
C_p	specific heat at constant pressure, [kJ/(kg K)]
$\bar{h}$	enthalpy, [kJ/kmol]
N	number of moles, [mol]
p	pressure, [bar]
R	gas constant, [kJ/(kg K)]
T	temperature, [°C, K]
WA	wet air, [mol]
x	mole fraction, [-]
ε	relative pressure losses, [-]
η	efficiency, [%]
ϕ	relative humidity, [%]
λ	excess air, [%]
π	pressure ratio, [-]

Subscripts

DA	dry air
f	fuel
H_2O	water
i	i-th component in natural gas
m	hydrogen atoms number
n	carbon atoms number
sat	saturation
sic	compressor
sit	turbine
th	thermal
WA	wet air
λ	with excess air
0	ambient conditions
1	compressor inlet
2	compressor outlet
3	turbine inlet
4	turbine outlet

needs to be taken into consideration. The effect of relative humidity on the operation of a gas turbine has been previously discussed by Usiyama [8]; there, the effect of ambient conditions, like temperature, pressure and humidity, over the gas turbine performance is analyzed. Usiyama's work concludes that the effect of humidity must be considered in accurate calculations when the ambient temperature is above 30 °C, and the relative humidity is over 70 percent. The paper presented by Rice [9] concurs with the conclusions presented in [8]. Due to the importance of relative humidity in the determination of the amount of excess air required for the safe operation of a gas turbine, its role and effects are considered in this paper. Firstly calculations considering dry air are presented and used as a point of reference, then the actual amount of excess air required for operation in a wet air environment is determined. It must be pointed out that previous works in the literature considering the effect of the relative humidity analyze only the effect over the plant's global thermal efficiency, but do not consider the impact on the turbine inlet temperature, which is a point of major concern in this article. Previous works also disregard an analysis of how the thermal efficiency and the work output depend on pressure ratio and excess air [10,7]. Bussman and Baukal [12] analyzed the effect of ambient conditions on the process heater efficiency.

2. System description

Fig. 1 shows a schematic diagram of a combustion chamber with its main components, combustion and cooling zones. Depending on turbine blade materials, and the availability and design of the turbine cooling systems, the combustion gas temperature at the turbine inlet ranges from 800 to 1700 °C. In order to attain these temperatures, excess air in the order of 600–100 percent needs to be supplied. However, large amounts of excess air cause the combustion in the turbine to become un-steady. That is why combustion chambers are divided in two sections, the combustion zone, and the mixture and dilution zone [11], as Fig. 1 shows. In the combustion zone, fuel is sprayed and stabilized by swirling vanes; primary air is mixed with fuel, making the combustion mixture approximately stoichiometric, which ignites the flame and keeps a steady temperature at approximately 2200 °C, depending on the type of utilized fuel. In the first stage of the mixture and dilution zone, secondary air is forced into the flame tube through small holes on the tube wall in order to achieve a complete combustion, and also to lower the temperature of the neighboring combustion zone. In the second stage of the mixture and dilution zone, tertiary air is supplied to further lower the temperature of the gases coming out from the combustion zone. The total amount of air that is delivered should be large enough to reach a permissible temperature value at the first stage of blades in the turbine.

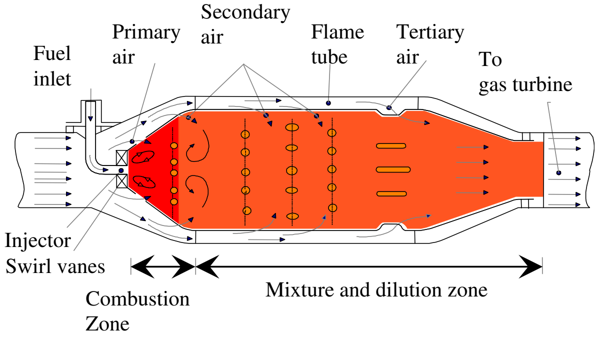

Fig. 1. Schematic diagram of a continuous combustion chamber.

3. Dry air composition

Atmospheric air is basically an Oxygen and Nitrogen mixture with slight quantities of Carbon Dioxide, Argon and Water Steam. Its composition slightly varies with humidity and altitude. When the presence of water steam is not considered in atmospheric air composition, the latter is known as dry air. This work considers the dry air composition as 21 percent Oxygen and 79 percent Nitrogen. Thus, the 79 percent N_2 fraction refers to the mixture of N_2, CO_2 and Ar, which is known as atmospheric Nitrogen. Therefore, it is assumed that one mol of dry air contains 0.21 mol of Oxygen, and 0.79 mol of Nitrogen. This is the typical composition of the atmospheric air that is utilized in the design, and analysis of internal combustion machines.

4. Wet air characterization

Wet air is simply a mixture of dry air and water steam. Here, let us assume that wet air behaves as an ideal gas, and also that the liquid phase embedded in the wet air mixture does not contain any dissolved gas. To determine the appropriate amount of excess air

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