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Ceramic tubes membrane technology as a new humidification technique for gas turbine inlet air cooling

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ABSTRACT

An experimental study is conducted to cool ambient air using a new humidification technique. A wind tunnel is built with a test section comprising a matrix of ceramic tubes. These ceramic tubes are of porous design to achieve air cooling by humidification. Ambient air passes over the ceramic tubes matrix (cross flow) whereas water passes through the ceramic tubes. Air temperature and relative humidity data are measured upstream and downstream of the ceramic tube bundle used to humidify the ambient air for several air and water flow velocities. Air velocity is measured at different locations along the centerline of the rectangular wind tunnel's cross section before the test section. Results show that the ambient temperature drops by about 10 °C when the relative humidity increases from 2% to 5.4%. Heat and mass transfer analyses are made and show good agreement with correlations available in the literature. It is noticed that the evaporation process does not follow the isenthalpic lines. Therefore, heat is transferred from the air as latent and sensible heats. A 25% decrease in the duct air outlet temperature is obtained as the water velocity increased to 0.0347 m/s (9.81×10^{-7} m^3/s). The results also show that the maximum estimated evaporative cooling system efficiency of the test section is about 45%.

1. Introduction

Cooling the air at compressor inlet is a well known technology used to increase gas turbine capacity and efficiency. Air humidification can be used to cool the air at compressor inlet. This technology is inexpensive, simple to apply and its power consumption is low. Humidification is normally carried out by spraying water in air flow upstream of the compressor inlet. Using this method requires high quality water to avoid corrosion and erosion of the compressor blades, and scale off composition on compressor blades. Furthermore, droplet drift can increase water consumption in the conventional humidification process. Membrane evaporation is a new technology used in many applications such as desalination and juice concentration. Using this technology in air humidification eliminates blade problems mentioned above and droplet drift. In addition, low quality water can be used in the humidification process. Inlet air cooling markedly enhances the performance of combustion turbines [1–6]. The turbine power increases at a lower cost per kW, and as an added benefit the heat rate also improves. Various approaches to cooling the turbine inlet air have been employed. The two most common approaches (evaporative cooling and mechanical refrigeration) have been extensively applied, and are well developed and documented. Combustion turbines have ambient temperature sensitivity: both the capacity and efficiency decrease as the ambient temperature increases. The power demand of the compressor section of the turbine is proportional to the absolute temperature of the inlet air. The compressor capacity is proportional to the density of the inlet air, which is inversely proportional to the absolute temperature. Therefore higher ambient temperatures negatively affect both capacity and efficiency of the turbine. Turbine manufacturers supply curves detailing both the power output and heat rate as a function of ambient temperature.

Erickson et al. [3] reported that a 300-refrigeration ton aqua ammonia refrigeration unit is required to cool the inlet of a 5 MW gas turbine from 35 °C to 5 °C. This cooling increases the power output by 1 MW, and the added power is at a marginal efficiency of 39%, compared to 29% for the base turbine power. Alhazmy and Najar [5] reported that the spray coolers appear to be capable of boosting the power and enhancing the efficiency of the gas turbine power plant in a way that is less expensive than cooling coils. Although the performance of spray coolers is deeply influenced by the ambient temperature and humidity, they operate efficiently during hot and dry climatic conditions. The analysis of Alhazmy and

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Nomenclature

A	tube bank surface area, m^2
ATS	after test section
BTS	before test section
C_p	specific heat at constant pressure, J/kg K
C_w	specific heat of water, J/kg K
d	tube diameter, m
D_v	mass diffusivity of water vapor in air, m^2/s
F	correction factor
h_e	evaporative heat transfer coefficient, W/m^2 K
h_{fg}	latent heat of vaporization, J/kg
h_m	convective mass transfer coefficient, m/s
J_D	Colburn mass transfer group
J_H	Colburn heat transfer group
k	thermal conductivity, W/m K
k_m	mass transfer coefficient, kg/m^2 s
$\dot{m}_{ev}$	evaporation rate, kg/s
$\dot{m}$	flow rate, kg/s
n	constant
Nu	Nusselt number
Pr	Prandtl number
Pr_s	Prandtl number at surface temperature
Q	heat transfer, W
RH	relative humidity
Re	Reynolds number
Sc	Schmidt number
Sc_s	Schmidt number at surface temperature
Sh	Sherwood number
S_L	distance between the tube bank centers parallel to the flow, m
S_T	distance between the tube bank centers normal to the flow, m
T	temperature, °C
u_{max}	water maximum velocity through the tube bank, m/s
v	velocity, m/s

Greek symbols

ΔP	pressure loss, Pa
μ	absolute viscosity, Pa s
ρ	density, kg/m^3
ρ_{am}	average air density, kg/m^3
ω	humidity ratio, kg (vapor)/kg (dry air)
ω_m	average humidity ratio, kg (vapor)/kg (dry air)
ω_s	humidity ratio at the tube surface, kg (vapor)/kg (dry air)

Subscripts

a	air
d	dry
di	dry bulb at inlet
do	dry bulb at outlet
ew	outlet water
i	inlet
iw	inlet water
m	mean
o	outlet
s	at the tube surface
w	water
wb	wet bulb
win	wet bulb at inlet

Najar [5] have shown that the spray cooler reduces the temperature of incoming air by 3–15 °C, enhancing the power by 1–7% and improving the efficiency by 3%.

Membrane evaporation is a new technology which utilizes the evaporative cooling technique in air conditioning, water desalination, juice concentration and other applications [7–12]. Microporous hydrophobic membranes have been examined by Loeb [7] for possible use as containers in the evaporative cooling of water, particularly in desert climates. An experimental determination was made of the overall heat and mass transfer coefficients of these membranes while surmounting contained water and with air flowing over the surface of the membranes. Recently, Zhang [13] has reported a numerical and experimental study about parallel-plates membrane cores used in air-to-air heat exchangers for fresh air heat and moisture recovery. His results indicated that for these membrane structures, when the channel pitch is below 2 mm, the flow distribution is quite homogeneous and the sensible and latent heat performance deteriorations due to flow maldistribution are below 9% and can be neglected. However, when the channel pitch is larger than 2 mm, the maldistribution is quite large and the consequent thermal and latent performance can deteriorate by 28%. More recently, a numerical simulation for mass transfer through a porous membrane of parallel straight channels has been reported by Lu and Lu [14]. In their study, two types of flows, channel flow and ultra-filtration flow, were physically described. Their results displayed the flow and solute distribution patterns inside channels, described the ultra-filtration profiles along the surface of the porous membrane and disclosed an existent nano-scale reverse osmosis problem. Ceramics and ceramic matrix composites for heat exchangers in advanced thermal systems have been reviewed by Sommers et al. [15]. In their paper, the current state-of-the-art of ceramic materials for use in a variety of heat transfer systems was reported. It should also be mentioned that other methods of cooling the inlet air are known as wet media evaporative cooling technology, which offer 85–90% evaporation efficiency, and may not require high water quality but they need huge amounts of water. These methods offer reduced risk of erosion to the compressor blades and corrosion to turbine inlet duct structure. It should be noted that the current suggested method presents a new interesting engineering concept to enhance the performance of the gas turbine in spite of its low efficiency. Therefore, further research needs to be performed to improve the efficiency of the proposed technology, such as increasing the number of tubes and reducing their diameters, which leads to increase the exchange surface between the ceramic tubes and air flow. Another advantage is the possibility of using recycled water (chemically treated water) since the fresh water in arid areas like Saudi Arabia is mostly available through desalination plants and commonly used for human consumption.

In this paper, evaporation technology is used to humidify the air for cooling before it enters to the compressor of a gas turbine. A wind tunnel is built and a matrix of ceramic tubes is used as a test section where water passes through in cross flow configuration. The relative humidity, pressure loss, air velocity and water velocity are measured before and after the test section. Heat and mass transfer analyses are made. Results show that the proposed technology has an efficiency not to exceed 45%. Therefore, this study can be considered of preliminary nature and more detailed technical study including economic aspects will need to be examined for the proposed method to be implemented in real life applications.