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Indirect evaporative combined inlet air cooling with gas turbines for green power technology

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ABSTRACT

Different inlet air cooling systems are usually used with gas turbines. A new form of inlet air cooling called the indirect evaporative cooling system (IECS) has been investigated in this work. This system is a combination of a humidifier with a vapor compression or absorption cooling system for part of the total air i.e. the secondary air stream. The net power produced from the gas turbine on a hot day (45 °C) by using combined (IECS) with absorption chillers showed an increase in power and efficiency by 15% and 9%, respectively; its recovery period is suitable for all environmental conditions. For IECS combined with vapor compression mechanical chillers showed an increase in power and efficiency by about 7.81% and 2.24%, respectively, but its recovery period made it suitable only for hot and humid conditions. The IECS has lower chiller's capital cost by about 25% (mechanical chiller) and 40% (absorption chiller).

Refroidissement évaporatif de l'air entrant combiné à des turbines à gaz pour une technologie de production d'électricité écologique

Mots clés : Systèmes de refroidissement de l'air entrant ; Turbines à gaz ; Refroidissement évaporatif indirect (IECS) ; IECS avec refroidisseur à absorption ; IECS avec refroidisseurs mécaniques ; Technologie écologique

1. Introduction

Gas turbines are engines often used to produce electricity. Their capacity and efficiency are lowered as the ambient temperature is increased. At a given shaft speed, they always move the same volume of air, but the power output of such engines depends on the mass flow passing through it. This is precisely the reason why on hot days, when the air is less dense, power output falls off. Many techniques, including evaporation, fogging, vapor

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Nomenclature

Symbols

A	area [m^2]
A_r	ratio of the cooled air mass flow to the total air mass flow rates
Cp	specific heat at constant pressure [kJ (kg K)$^{-1}$]
COP	coefficient of performance
f	fuel air ratio
h	specific enthalpy [kJ kg^{-1}]
IECS	indirect evaporative cooling system
$\dot{m}$	mass flow rate [kg s^{-1}]
$\dot{M}_{weak}$	mass flow rate of weak solution of Li—Br [kg s^{-1}]
P_c	power consumed by compressor [kW]
$P_{G.T}$	net power output from gas turbine [kW]
$Q^{\bullet}$	heat transfer rate [kW]
SFC	specific fuel consumption [kgf kWh^{-1}]
T	temperature [°C]
TIT	turbine inlet temperature [°C]
v	specific volume [m^3 kg^{-1}]
x	concentration of Li—Br [kg LiBr kg^{-1} mix]
rc	pressure ratio

Greek letters

η	efficiency %
ρ	density [kg m^{-3}]
ε	effectiveness
Φ	relative humidity
??	specific heat ratio
ω	humidity ratio [kg_w kg_a^{-3}]

Suffixes

a	air
abs,A	absorber
amb	ambient temperature
cond,C	condenser
comp,c	compressor
db	dry bulb temperature
evap,E	evaporator
g	gas
gen,G	generator
GT	gas turbine
hex	heat exchanger
Li—Br	lithium bromide
ref	refrigerant
sat	saturated
th	theoretical analysis
vc	vapor compression
w	water
wi	inlet water

compression, thermal storage and absorption, have been developed to cool the inlet air to the gas turbine engine (Al-Ibrahim and Varnham, 2010; Alhazmy and Najjar, 2004; Bacigalupo et al., 1993; Bedecarrats and Strub, 2009; Korakianitis and Wilson, 1994; Lucia et al., 1994, 1996; Lukas, 1997; Najjar, 1996; Yokoyama and Ito, 2004). Moreover, unconventional techniques have been suggested (Anonymous, 2002a; El-Hadik, 1990; Khaliq et al., 2010; Liu et al., 2009; Zamzam and Al-Amiri, 2008).

Traditionally, the inlet air is cooled by either direct evaporative system or indirect evaporative system. Evaporative cooling is a simple and effective way of cooling the air stream in a direct evaporative cooler. The air stream to be cooled is directly in contact with a liquid water film and the cooling is accomplished by the adiabatic heat exchange between the air stream and the liquid water film (Jolly, 2000). The evaporation of water in the air stream leads to a reduction in the dry bulb temperature. However, this will also cause an increase of the humidity ratio of the air stream. Johnson (1989) establishes the basic theory, whereas applications are handled in details in the reference (Agren and Westermark, 2003a, 2003b; Anomymous, 2001; Biasi, 2000a; Farmer, 1999, 2009; Robb, 2001).

Another approach for cooling the inlet air to the gas turbine is by introducing liquid water into the suction air. The water droplets will have to be extremely small in size and be in the form of fog to avoid impingement on the blades of the compressor causing erosion (Lukas, 1997).

As the water evaporates within the compressor from the heat of compression, the air being compressed is cooled, which in turn causes a reduction in the compressor work (Anonymous, 2001, 2002b; Biasi, 2000b; Bird and Grabe, 1991; Bucker et al., 003; Chacker et al., 2004a, 2004b; Chaker et al., 2004; Farmer, 2008; Homji and Mee, 1999; Levy et al., 2008; Mee, 1999).

The ideal vapor-compression cycle uses refrigerant as the working fluid to absorb and reject heat energy. The energy transfer allows the vapor-compression cycle to cool the inlet air to the gas turbine (Cengel and Boles, 2010).

Absorption chillers differ from the more prevalent compression chillers in that the cooling effect is driven by heat energy, rather than mechanical energy. Additionally, absorption systems use distilled water and either nontoxic lithium bromide or ammonia, thereby eliminating harmful chlorofluorocarbons (CFCs) common to a vapor-compression systems (Alhazmy and Najjar, 2004; Najjar, 1996). More details of the absorption system with gas turbines are in the reference (Baughn and Kerwin, 1987; Blanco, 1993; Bruno et al., 2005; Hong et al., 2010; Malewski and Holldorff, 1986; Stambler, 1989; Yang and Sato, 1971; Yang et al., 1970, 1971; Yin et al., 2010). Currently, available water-cooled absorption systems use water as the refrigerant and lithium bromide solution as the absorbent material. In the aqua–ammonia systems, ammonia is used as the refrigerant and water as the absorbent.

The indirect evaporative cooling system IECS produces cooling by directly evaporating water into a part of the main air stream (secondary air). This secondary air is then cooled in a refrigeration system before final mixing with primary air (combined system). This supplementary cooling of the air when passing over the evaporator of the refrigeration system will