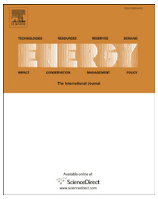
Energy xxx (2014) 1–15

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy



Thermal–economic–environmental analysis and multi-objective optimization of an ice thermal energy storage system for gas turbine cycle inlet air cooling

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ARTICLE INFO

Article history:
Received 8 August 2013
Received in revised form
15 February 2014
Accepted 18 February 2014
Available online xxx

Keywords:
Ice thermal energy storage system
Gas turbine
Inlet air cooling
Exergy
Economic
Multi-objective optimization

ABSTRACT

In this study, a mathematical model of an ice thermal energy storage (ITES) system for gas turbine cycle inlet air cooling is developed and thermal, economic, and environmental (emissions cost) analyses have been applied to the model. While taking into account conflicting thermodynamic and economic objective functions, a multi-objective genetic algorithm is employed to obtain the optimal design parameters of the plant. Exergetic efficiency is chosen as the thermodynamic objective while the total cost rate of the system including the capital and operational costs of the plant and the social cost of emissions, is considered as the economic objective. Performing the optimization procedure, a set of optimal solutions, called a Pareto front, is obtained. The final optimal design point is determined using TOPSIS decision-making method. This optimum solution results in the exergetic efficiency of 34.06% and the total cost of 28.7 million US\$ y^{-1}. Furthermore, the results demonstrate that inlet air cooling using an ITES system leads to 11.63% and 3.59% improvement in the output power and exergetic efficiency of the plant, respectively. The extra cost associated with using the ITES system is paid back in 4.72 years with the income received from selling the augmented power.

1. Introduction

Gas turbines are constant volumetric flow rate machines which, based on their design, move a given volume of air at a given shaft speed. Owing to the fact that the required air for combustion is supplied directly from the environment, weather conditions significantly impact their performance [1]. In fact, thermodynamic analyses reveal that the net output power and thermal efficiency of a gas turbine considerably decrease with increased humidity and ambient temperature [2]. This takes place due to the reduction of air density and, thus, mass flow rate [3]. Finding an alternative solution to address this issue is crucial – specifically in locations where peak electrical demand coincides with hot, humid conditions. Cooling the compressor inlet air flow is one possible solution to solve this by keeping the inlet temperature into the gas turbine constant [4]. In fact, inlet air cooling increases inlet air density and air mass flow rate, enhancing the gas turbine's power output and efficiency (especially during the summer season) [5]. Several direct inlet air cooling methods have been proposed, including: vapor compression refrigeration, absorption chiller cooling, and evaporative cooling [6]. These cooling methods can also be utilized indirectly through cold thermal energy storage (CTES) systems. In this configuration, energy is taken from the plant to cool the storage medium during off-peak hours (during the night) and later utilized for inlet air cooling during on-peak hours (during daytime) [5]. Thus, a CTES shifts the cooling input from on-peak periods (where electricity prices are high) to off-peak periods (where electricity consumption and prices are at their lowest) [7].

TES systems are divided into two major categories including sensible heat storage and latent heat storage [8]. In sensible heat storage systems, energy is stored by changing the temperature of the energy storage media (without phase change). For latent heat storage units, energy is stored by changing the phase of energy storage media at a constant temperature [9]. For the same volume and reasonable operation ranges, latent heat storage systems can store more energy than sensible heat storage systems [10]. Accordingly, for inlet air cooling, latent TES systems based

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http://dx.doi.org/10.1016/j.energy.2014.02.071
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Please cite this article in press as: Shirazi A, et al., Thermal–economic–environmental analysis and multi-objective optimization of an ice thermal energy storage system for gas turbine cycle inlet air cooling, Energy (2014), http://dx.doi.org/10.1016/j.energy.2014.02.071

Nomenclature

A	heat transfer surface area (m^2)
c_{elec}	electricity unit cost (US\$ kWh^{-1})
COP	coefficient of performance
c_p	specific heat at constant pressure ($kJ\ kg^{-1}\ K^{-1}$)
CRF	capital recovery factor
$\dot{C}_{env}$	social cost of air pollution (US\$ s^{-1})
$\dot{C}_{tot}$	total cost rate (US\$ s^{-1})
e	specific exergy ($kJ\ kg^{-1}$)
$\overline{e}$	molar specific exergy ($kJ\ kmol^{-1}$)
E	exergy (kWh)
$\dot{E}$	exergy flow rate (kW)
F	logarithmic mean temperature difference correction factor
h	specific enthalpy ($kJ\ kg^{-1}$)
i	interest rate (%)
i_{ph}	melting latent heat ($kJ\ kg^{-1}$)
k	specific heat ratio
LHV	low heating value ($kJ\ kg^{-1}$)
$\dot{m}$	mass flow rate ($kg\ s^{-1}$)
$\dot{n}$	molar flow rate ($kmol\ s^{-1}$)
N	operational hours in a year
n	system life time (year)
NTU	number of transfer units
p	pressure (Pa), extra cost payback period (year)
$\dot{Q}$	the time rate of heat transfer (kW)
Q_C	cooling load (kWh)
$\dot{Q}_C$	cooling load (kW)
R_{th}	thermal resistance ($m^2\ K\ kW^{-1}$)
s	specific entropy ($kJ\ kg^{-1}\ K^{-1}$)
$\overline{R}$	universal gas constant ($kJ\ kmol^{-1}\ K^{-1}$)
r_p	pressure ratio
T	temperature (°C or K)
TIT	turbine inlet temperature (K)
U	overall heat transfer coefficient ($kW\ m^{-2}\ K^{-1}$)
x	molar fraction
u	specific internal energy ($kJ\ kg^{-1}$)
V	volume (m^3)
$\dot{W}$	the time rate of energy transfer by work (kW)
x	molar fraction
y	year
Z	capital cost (US\$)
$\dot{Z}$	capital cost rate (US\$ s^{-1})

Greek symbols

ε	effectiveness
η	isentropic efficiency
$\overline{\lambda}$	molar fuel to air ratio
ν	specific volume ($m^3\ kg^{-1}$)
ρ	density ($kg\ m^{-3}$)
Φ	maintenance factor
ϕ	relative humidity
ψ	exergetic efficiency
ω	absolute humidity (kg water vapor kg^{-1} dry air)

Subscripts

a	air
AC	air cooler
Av	average
C1	air compressor
C2	refrigeration compressor
REC	recuperator
CC	combustion chamber
amb	ambient
C	cooling load
CH	chemical
ch	charging
GT	gas turbine
Cond	condenser
CT	cooling tower
cv	control volume
CW	chilled water
D	destruction
dc	discharging
EV	evaporator
EX	expansion valve
f	final, fuel
FP	freezing point
g	gas
i	inlet
int	initial
LMTD	logarithmic mean temperature difference
o	outlet
op	operational
PH	physical
tot	total
w	water
l	leakage
r	refrigerant
ST	ice storage tank
t	time
WB	wet-bulb

on ice storage have received the most attention in the recent years [11].

Numerous studies have been conducted in recent years in the fields of CTES systems and gas turbine inlet air cooling techniques. Saito [12] reviewed the recent advances in the field of CTES units. In that study, various types of CTES systems were compared and their merits and drawbacks were presented. Li et al. [13] reviewed the recent development of available cold storage mediums for subzero applications and discussed their possible issues. Dincer [8] presented various technical aspects and criteria for CTES systems and their applications which showed that thermal load profiles, electrical costs, building type and occupancy are often overlooked parameters that are actually very important to system operation. Ezan et al. [14] conducted energy and exergy analyses on an ice-on-coil TES system for the charging period. The results revealed that the design parameters of the modeled TES system should be achieved by taking into account both energetic and exergetic behavior of the system. A review of the methods by which the Saudi Electric Company enhanced power generation from its combustion turbines during summer peaking hours using inlet air cooling was conducted by Al-Ibrahim and Varnham [15]. Vapor compression refrigeration inlet air cooling system using chilled water or ice thermal storage was determined to be the most suitable method for use in the desert climate of Saudi Arabia. Habeebullah [16] carried out an investigation on the economic feasibility of installing an ITES (ice thermal energy storage) system for the unique air conditioning plant of the Grand Holly Mosque of Makkah in Saudi Arabia where both operational and capital costs of the ITES system were taken into account. The results showed that employing ice storage technology under an incentive tariff model has reasonable daily savings

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