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Thermoeconomic optimization of an ice thermal storage system for gas turbine inlet cooling

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ABSTRACT

The gas turbine power output and efficiency decrease with increasing ambient temperature. With compressor inlet air cooling, the air density and mass flow rate as well as the gas turbine net power output increase. The inlet cooling techniques include vapor or absorption refrigeration systems, evaporative cooling systems and thermal energy storage (TES) systems. In this paper the thermoeconomic analysis of ice (latent) thermal energy storage system for gas turbine inlet cooling application was performed. The optimum values of system design parameters were obtained using genetic algorithm optimization technique. The objective function included the capital and operational costs of the gas turbine, vapor compression refrigeration system, without (objective function I) and with (objective function II) corresponding cost due to the system exergy destruction. For gas turbines with net power output in the range of 25–100 MW, the inlet air cooling using a TES system increased the power output in the range of 3.9–25.7%, increased the efficiency in the range 2.1–5.2%, while increased the payback period from about 4 to 7.7 years.

1. Introduction

Gas turbines are considered as constant volume flow rate rotating equipment. Therefore with increasing the atmospheric temperature, the air density and mass flow rate entering the compressor (and passing through the gas turbine) as well as net power output and cycle efficiency decrease. The gas turbine inlet cooling increases the air density and therefore inlet air mass flow rate which increases the gas turbine power output and efficiency. This provides the required power without need for installation of new gas turbines and their corresponding investment cost. There are several inlet air cooling systems such as: Vapor compression or absorption refrigeration, evaporative cooling (inlet fogging, media & air washer), and thermal energy storage (TES).

Thermal energy storage systems are in two major categories of sensible and latent heat types. In the first type, water and sand/stone are used to store the energy. The cost of the energy storage media (water or stone) is low in this case. In the second type, the energy storage media change its phase from solid to liquid when it receives energy, and from solid to liquid when it rejects energy. Considering the same volume, the latent type of energy storage systems can store more energy in comparison with the sensible type [1,2].

Henze [3] described the simulation based results of an investigation for a commercial cooling plant with an ice storage system. The investigation was carried out to determine the performance of four control strategies with change of the operation cost, total energy consumption, on-peak and off-peak demand, chiller types, as well as building and weather types. Habeebullah [4] investigated the economic feasibility of installing an ice thermal storage for the unique air conditioning plant of the Grand Holly Mosque of Makkah in Saudi Arabia. The objective function in his economic analysis included both operation and capital investment costs of the ice storage system.

Gareta et al. [5] modeled different gas turbine inlet air cooling systems including evaporative coolers, mechanical chillers, absorption chillers and ice storage. They presented the results of their economic analysis in a certain location.

Chen et al. [6] also studied the optimization of an ice storage air conditioning system for the minimum life cycle cost as well as the maximum value of COP for its refrigeration system. They used dynamic programming algorithm with sum of initial and operation costs as the objective function. The performance of chiller was analyzed to obtain the optimum values of chiller and ice storage tank capacity.

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Nomenclature

A	heat transfer surface area [m^2]
a_{ij}	coefficients in the cost functions
c	the cost per unit of exergy
C_c	cold water heat capacity [kJ/s K]
C_{fuel}	fuel cost per unit of energy [$/MJ]
c_p	specific heat at constant pressure [kJ/kg K]
c_v	specific heat at constant volume [kJ/kg K]
c_r	stored liquid specific heat [kJ/kg K]
d	diameter [m]
$\dot{D}$	cost flow rate [$/s]
$\dot{E}$	exergy flow rate [MW]
$\dot{E}^{PH}$	physical exergy flow rate [MW]
$\dot{E}^{CH}$	chemical exergy flow rate [MW]
$\dot{E}_D$	exergy destruction in a component [MW]
f	friction factor
F	logarithmic mean temperature difference correction factor
FA	fuel to air ratio
H_f	fin height [m]
h	specific enthalpy [kJ/kg]
i	interest rate [%]
i_{ph}	melting latent heat [kJ/kg]
K_f	pressure drop factor due to the friction
k	specific heat ratio, number of flow line
L	length [m]
LHV	lower heating value [kJ/kg]
$\dot{m}$	mass flow rate [kg/s]
n	system life time
n_t	number of tubes in transversal direction
n_r	number of tubes in longitudinal direction
N	number of tubes, operational hours in a year
NTU	number of transfer units
Nu	Nusselt number
P	payback period [year]
p	pressure [Pa]
P_1, P_2	tube pitches
Pr	Prandtl number
$\dot{Q}_C$	air cooler heat transfer rate [kW]
$\dot{Q}_H$	condenser heat transfer rate [kW]
$\dot{Q}_L$	evaporator heat transfer rate [kW]
Q_r	reservoir available heat [kJ]
$\overline{R}$	universal gas constant [kJ/kmole K]
Re	Reynolds Number
R_f	fouling factor [m^2 K/W]
r_C	compressor pressure ratio
r_T	turbine pressure ratio
s	specific entropy [kJ/kg.K], fin spacing [m]
T	temperature [K]
t_c	charging time [s]
t_h	discharging time [s]
t_w	tube wall thickness [m]
U	overall heat transfer coefficient [W/m^2 K]
$\dot{V}$	volumetric flow rate [m^3/s]
V_{ST}	storage tank (ice bank) volume [m^3]
w	fin width or thickness [m]
$\dot{W}_C$	compressor power consumption [MW]
$\dot{W}_{net}$	net power output with TES [MW]
$\dot{W}_T$	turbine power output [MW]
X	molar fraction
Z	capital cost [$]
$\dot{Z}$	capital cost rate [$/s]
ΔT_{LMTD}	logarithmic mean temperature difference [°C]
η	isentropic efficiency
μ	dynamic viscosity [N s/m^2]
ρ	density [kg/m^3]
Ω	absolute humidity $\left[\text{kg water vapor/kg dry air}\right]$

Subscripts

a	air
AC	air cooler heat exchanger
C_1	air compressor
C_2	refrigeration compressor
CC	combustion chamber
Cond	condenser
CT	cooling tower
CW	chilled water
EV	evaporator
EX	expansion valve
f	fin
fuel	fuel
g	gas
i	tube inside
ref	refrigerant
ST	storage tank
T	turbine
o	tube outside

Seyyedi et al. [7] proposed a new criterion for the residues cost allocation which was based on the entropy distributed in the components, and not on the entropy generated along the process.

Thermoeconomic or exergoeconomic analysis may be performed by various methodologies such as “the theory of the exergetic cost” with applying cost balance equations and obtaining the exergetic unit cost defined based an a specific principle. These methodologies combine economic and thermodynamic analyses by applying the cost concept to exergy which accounts for the quality of energy [8]. Generally the objectives of thermoeconomic are: 1) to compute separately the costs of each product generated by a system. 2) to understand the cost formation process and flow of costs in the system. 3) to optimize specific variables in a single component. 4) to optimize the overall thermal system [9]. Therefore thermoeconomic optimization technique combines exergy analysis and economic principles to obtain an optimum configuration of a thermal system (exergy-aided cost minimization) [10].

Badar et al. [11] as well as Domanski and Fellah [12] applied a thermoeconomic optimization technique in design of TES systems. They minimized the sum of entropy generation cost and annualized capital cost of system components. The optimal sizes of cold storage equipment and refrigeration units were analyzed by Meyer and Emery [13].

In addition to the above mentioned theories, a new methodology in evaluating energy systems in three fields of cost allocation, cost optimization, and cost analysis has been introduced recently [14]. The new introduced concept is wonergy which is the energy that can equally evaluate the worth of each product as one equation. Any type of energy, including enthalpy or exergy, can be applied to the wonergy concept.

This paper covers a thermoeconomic analysis to find the optimum design parameters of a described TES system. To implement this job the system thermal modeling was performed, then an objective function (the sum of capital or investment cost as well as operational cost) without and with the corresponding cost of