Applied Thermal Engineering 52 (2013) 371–384

Contents lists available at SciVerse ScienceDirect

Applied Thermal Engineering

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

Optimum design of dual pressure heat recovery steam generator using non-dimensional parameters based on thermodynamic and thermoeconomic approaches

Sanaz Naemi [a], Majid Saffar-Avval [a,*], Sahand Behboodi Kalhori [b], Zohreh Mansoori [c]

[a] Mechanical Engineering Department, Amirkabir University of Technology, Hafez Ave., P.O. Box 15875-4413, Tehran, Iran
[b] Lab. for Alternative Energy Conversion, Mechatronic Systems Engineering, School of Engineering Science, Simon Faser University, Canada
[c] Energy research center, Amirkabir University of Technology, Iran

HIGHLIGHTS

► Presenting thermodynamic and thermoeconomic optimization of a heat recovery steam generator.
► Defining an objective function consists of exergy waste and exergy destruction.
► Defining an objective function including capital cost and cost of irreversibilities.
► Obtaining the optimized operating parameters of a dual pressure heat recovery boiler.
► Computing the optimum pinch point using non-dimensional operating parameters.

ARTICLE INFO

Article history:
Received 14 May 2012
Accepted 6 December 2012
Available online 21 December 2012

Keywords:
Heat recovery steam generator
Exergy analysis
Optimum pinch point temperature
Thermoeconomic analysis

ABSTRACT

The thermodynamic and thermoeconomic analyses are investigated to achieve the optimum operating parameters of a dual pressure heat recovery steam generator (*HRSG*), coupled with a heavy duty gas turbine. In this regard, the thermodynamic objective function including the exergy waste and the exergy destruction, is defined in such a way to find the optimum pinch point, and consequently to minimize the objective function by using non-dimensional operating parameters. The results indicated that, the optimum pinch point from thermodynamic viewpoint is 2.5 °C and 2.1 °C for *HRSGs* with live steam at 75 bar and 90 bar respectively. Since thermodynamic analysis is not able to consider economic factors, another objective function including annualized installation cost and annual cost of irreversibilities is proposed. To find the irreversibility cost, electricity price and also fuel price are considered independently. The optimum pinch point from thermoeconomic viewpoint on basis of electricity price is 20.6 °C (75 bar) and 19.2 °C (90 bar), whereas according to the fuel price it is 25.4 °C and 23.7 °C. Finally, an extensive sensitivity analysis is performed to compare optimum pinch point for different electricity and fuel prices.

1. Introduction

Due to global energy crisis, an increasingly attitude to efficient energy conversion technologies especially Combined Cycle Power Plants (*CCPPs*) have seen in recent decades, in which gas turbine operating in open cycle is integrated with a steam cycle by means of a Heat Recovery Steam Generator (*HRSG*). Hereupon, *HRSG* provides the critical connection between the gas turbine topping cycle and the steam turbine bottoming cycle. Undoubtedly, the optimum design of *HRSG* has a particular interest to improve the performance of heat recovery for maximizing the power generated by steam cycle. Besides, it reduces the environmental impacts of pollutant emissions. In the design of *HRSGs*, the method to obtain the optimum design usually is a combination of the thermodynamic and economic point of views. The exergy method, which uses the conservation of mass and energy principles together with the second law of the thermodynamics, is a useful tool to identify the locations, types and magnitudes of losses.

In the past decade, coupled energy and exergy analyses of different thermal systems have been carried out. Dincer and Rosen

* Corresponding author. Tel.: +98 21 66405844; +98 21 66419736.
E-mail addresses: sanaz_n@aut.ac.ir (S. Naemi), mavval@aut.ac.ir (M. Saffar-Avval), sbehbood@sfu.ca (S. Behboodi Kalhori), z.mansoori@aut.ac.ir (Z. Mansoori).

1359-4311/$ – see front matter © 2012 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.applthermaleng.2012.12.004

Nomenclature

A	heat transfer area (m^2)
A_f	fin surface areas (m^2/m)
A_t	total surface area (m^2/m)
A_i	inside surface area (m^2/m)
A_o	obstruction surface area (m^2/m)
A_w	area of tube wall (m^2/m)
B	factor used in Grinson's correlation
b	fin thickness (m)
c_I	specific cost of exergy loss (US \$/kWh)
c_p	specific heat (kJ kg^{-1} k^{-1})
$Cost$	cost of each heat transfer section (US \$)
$Cost_{E,j}$	cost of economizer joints (US \$/kg)
$Cost_{E,m}$	cost of tubes and fins (economizer) (US \$/kg)
$Cost_{E,w}$	cost of welding (economizer) (US \$/kg)
$Cost_{S,b}$	cost of bending (superheater) (US \$/kg)
$Cost_{S,m}$	cost of tubes and fins (superheater) (US \$/kg)
c_1	specific heat of water in low pressure economizer (kJ kg^{-1} K^{-1})
$\acute{c}_1$	specific heat of water in high pressure economizer1 (kJ kg^{-1} K^{-1})
c_1''	specific heat of water in high pressure economizer2 (kJ kg^{-1} K^{-1})
c_2	specific heat of steam in low pressure superheater (kJ kg^{-1} K^{-1})
$\acute{c}_2$	specific heat of steam in high pressure superheater (kJ kg^{-1} K^{-1})
d	tube outer diameter (m)
d_i	tube inner diameter (m)
f	friction factor
ff_i	inside fouling factors (m^2 s K kJ^{-1})
ff_o	outside fouling factors (m^2 s K kJ^{-1})
f_{EC}	thermoeconomic objective function
f_{th}	thermodynamic objective function
G	gas mass velocity (kg m^{-2} s^{-1})
h	fin height (m)
h_c	convection heat transfer coefficient (W m^2 K^{-1})
h_i	inside heat transfer coefficient of tubes (W m^2 K^{-1})
h_o	outside heat transfer coefficient of tubes (W m^2 K^{-1})
h_N	nonluminous heat transfer coefficient (W m^2 K^{-1})
k_m	metal thermal conductivity (W m K^{-1})
L	latent heat of vaporization (kJ/kg)
$L_{EC,w}$	length of welding (m)
$LMTD$	logarithmic mean temperature difference (for evaporator) (K)
$\dot{m}$	mass flow rate (kg s^{-1})
M_E	mass of tube and fins (economizer) (kg)
$M_{E,j}$	joint mass for economizer (kg)
M_S	mass of tube and fins (superheater) (kg)
N_b	number of bending in superheater
N_d	number of tubes per row
N_w	number of tube rows
n	number of fins per meter
NTU	number of transfer units
P_0	ambient pressure (kPa)
Q	heat transferred (kW)
S_L	longitudinal pitch (m)
S_T	transferred pitch (m)
St	Stanton number
$\dot{S}_{gen}$	rate of entropy generation (kW/K)
T_g	temperature of flue gas at the considered location (K)
T_0	ambient temperature (K)
T_{out}	flue gas temperature at the economiser outlet (K)
T_{sat1}	saturation temperature of water or steam (low pressure boiler) (K)
T_{sat2}	saturation temperature of water or steam (high pressure boiler) (K)
T_{sup1}	temperature of superheated steam (low pressure superheater) (K)
T_{sup2}	temperature of superheated steam (high pressure superheater) (K)
T_w	temperature of water at the considered location (K)
$\acute{T}_{w,in}$	temperature of water at the entrance of high pressure economizer2 (K)
U_o	overall heat transfer coefficient (W m^2 K^{-1})
V	flue gas velocity (m/s)
V^*	non-dimensional gas velocity
X_1	ratio of heat capacities of water and gas stream (*LE*)
X_1'	ratio of heat capacities of water and gas stream (*HE*2)
X_1''	ratio of heat capacities of water and gas stream (*HE*1)
X_2	ratio of heat capacities of steam and gas stream (*LS*)
X_2'	ratio of heat capacities of steam and gas stream (*HS*)

Greek symbols

ΔP_g	pressure drop (kPa)
η	fins efficiency
τ	non-dimensional hot flue gas inlet temperature difference ratio
τ_{s1}	non-dimensional water saturation temperature (*LP* drum) difference ratio
τ_{s2}	non-dimensional water saturation temperature (*HP* drum) difference ratio
τ_{h1}	non-dimensional *HP* superheated steam temperature difference ratio
τ_{h2}	non-dimensional *LP* superheated steam temperature difference ratio

Subscripts

g	gas
HB	high pressure boiler (evaporator)
*HE*1	high pressure economizer1
*HE*2	high pressure economizer2
HS	high pressure superheater
HRSG	heat recovery steam generator
I	irreversibility
in	inflow
LB	low pressure evaporator
LE	low pressure economizer
LS	low pressure superheat
out	outflow
w	water
w_1	water in low pressure economizer
w_2	water in high pressure economizer

[1] reviewed application of exergy approach, to analyze and design a wide range of energy conversion systems. Shi and Che [2] conducted energy and exergy analyses of an improved liquefied natural gas fuelled *CCPP* with a waste heat recovery, considering mass, energy and exergy balances for each component. Cihan et al. [3] preformed energy and exergy analyses of a *CCPP* investigating the potential for improving system efficiency. They indicated that, while the greatest energy loss takes place at the stack, the greatest exergy loss takes place in the combustion chamber of gas turbine and *HRSG*.