Available online at www.sciencedirect.com

SciVerse ScienceDirect

Solar Energy 86 (2012) 1378–1395

SOLAR ENERGY

www.elsevier.com/locate/solener

Thermal analysis and performance optimization of a solar hot water plant with economic evaluation

Young-Deuk Kim [a], Kyaw Thu [a], Hitasha Kaur Bhatia [b], Charanjit Singh Bhatia [c], Kim Choon Ng [b,*]

[a] *Water Desalination and Reuse Center, 4700 King Abdullah University of Science and Technology, Thuwal 23955-6900, Saudi Arabia*
[b] *Department of Mechanical Engineering, National University of Singapore, 9 Engineering Drive 1, Singapore 117576, Singapore*
[c] *Department of Electrical and Computer Engineering, National University of Singapore, 9 Engineering Drive 1, Singapore 117576, Singapore*

Received 22 December 2010; received in revised form 27 December 2011; accepted 11 January 2012
Available online 27 February 2012

Communicated by: Associate Editor S.C. Bhattacharya

Abstract

The main objective of this study is to optimize the long-term performance of an existing active-indirect solar hot water plant (SHWP), which supplies hot water at 65 °C for use in a flight kitchen, using a micro genetic algorithm in conjunction with a relatively detailed model of each component in the plant and solar radiation model based on the measured data. The performance of SHWP at Changi International Airport Services (CIASs), Singapore, is studied for better payback period using the monthly average hourly diffuse and beam radiations and ambient temperature data. The data input for solar radiation model is obtained from the Singapore Meteorological Service (SMS), and these data have been compared with long-term average data of NASA (surface meteorology and solar energy or SSE). The comparison shows a good agreement between the predicted and measured hourly-averaged, horizontal global radiation.

The SHWP at CIAS, which comprises 1200 m^2 of evacuated-tube collectors, 50 m^3 water storage tanks and a gas-fired auxiliary boiler, is first analyzed using a baseline configuration, i.e., (i) the local solar insolation input, (ii) a coolant flow rate through the headers of collector based on ASHRAE standards, (iii) a thermal load demand pattern amounting to 100 m^3/day, and (iv) the augmentation of water temperature by auxiliary when the supply temperature from solar tank drops below the set point. A comparison between the baseline configuration and the measured performance of CIAS plant gives reasonably good validation of the simulation code. Optimization is further carried out for the following parameters, namely; (i) total collector area of the plant, (ii) storage volume, and (iii) three daily thermal demands. These studies are performed for both the CIAS plant and a slightly modified plant where the hot water supply to the load is adjusted constant at times when the water temperature from tank may exceed the set temperature. It is found that the latter configuration has better thermal and economic performances over the conventional design.

Keywords: Solar hot water plant; Solar radiation analysis; Economic evaluation; Optimization

1. Introduction

Solar hot water (SHW) systems are recognized as the most cost-effective way for generating hot water for domestic, agricultural, commercial, and industrial applications. It is environmental friendly and economic viable investment because it reduces the burning of fossil fuels and thus, reduces the emission of pollutants and greenhouse gases. A SHW system can be used in most climate conditions as they harness the solar energy to useful heating. However, system costs vary considerably depending on geographic location, water usage, and utility rates. To assure maximum cost benefit, therefore, the appropriate sizing of each component in the system and operating conditions are important parameters need to be accounted for.

* Corresponding author. Tel.: +65 6516 2214; fax: +65 6516 1459.
E-mail address: mpengkc@nus.edu.sg (K.C. Ng).

0038-092X/$ - see front matter Crown Copyright © 2012 Published by Elsevier Ltd. All rights reserved.
doi:10.1016/j.solener.2012.01.030

Nomenclature

A	area (m^2)
A_a	aperture area per collector (m^2)
A_c	total collector area (m^2)
A_{ch}	channel cross-sectional area, bL_w (m^2)
A_{cs}	cross sectional area of the tank (m^2)
A_{eff}	effective area of plate, L_hL_w (m^2)
A_{HX}	total heat transfer area of the plate heat exchanger (m^2)
A_i	anisotropy index
A_l	lateral area of control volume (m^2)
b	mean flow channel gap, p–t (m)
c_1	global heat loss coefficient (W/m^2 °C)
c_2	temperature dependence of global heat loss coefficient (W/m^2 °C^2)
c_3	effective thermal capacity (kJ/m^2 °C)
c_p	mean specific heat capacity (kJ/kg °C)
C_B	boiler cost coefficient (S$)
C_c	fluid heat capacity rate in primary circuit (W/°C)
C_C	collector cost coefficient (S$/$m^2$)
C_D	collector area dependent cost (S$/$m^2$)
C_F	fuel cost coefficient (S$/kW h)
C_h	fluid heat capacity rate in secondary circuit (W/°C)
C_I	collector area independent cost (S$)
C_{IC}	instrumentation and control cost coefficient (S$/$m^2$)
C_{HX}	heat exchanger cost coefficient (S$/$m^2$)
C_{max}	maximum heat capacity rate (W/°C)
C_{min}	minimum heat capacity rate (W/°C)
C_{PS}	pump and support structure cost coefficient (S$/$m^2$)
C_{RF}	capital recovery factor (1/y)
C_S	total cost of plant (S$)
C_T	storage tank cost coefficient (S$/$m^3$)
C^*	dimensionless heat capacity rate ratio
D_e	channel equivalent diameter, $2b/\phi$ (m)
e	fuel inflation rate (%)
f	modulating factor
F	control function
$F(X)$	objective function (years)
G	mass flow rate per unit area of collector (kg/m^2s)
G_b	monthly average hourly beam irradiance on a tilted plane (W/m^2)
G_{ch}	mass flux velocity, $\dot{m}_{ch}/A_{ch}$ (kg/m^2s)
G_d	monthly average hourly diffuse irradiance on a tilted plane (W/m^2)
G_T	monthly average hourly global irradiance on a tilted plane (W/m^2)
h	heat transfer coefficient (W/m^2 °C)
H/D	height to diameter ratio of storage tank
H_d	monthly average daily diffuse irradiation on a horizontal plane (J/m^2)
H_h	monthly average daily global irradiation on a horizontal plane (J/m^2)
i	interest rate (%)
i'	effective interest rate (%)
i''	effective interest rate for fuel (%)
I_b	monthly average hourly beam irradiation on a horizontal plane (J/m^2)
I_d	monthly average hourly diffuse irradiation on a horizontal plane (J/m^2)
I_h	monthly average hourly global irradiation on a horizontal plane (J/m^2)
I_o	monthly average hourly extraterrestrial irradiation on a horizontal plane (J/m^2)
I_T	monthly average hourly global irradiation on a tilted plane (J/m^2)
j	inflation rate (%)
k_w	thermal conductivity of water (W/m °C)
k_p	thermal conductivity of plate (W/m °C)
K_T	monthly average daily clearness index
$K_{\theta b}$	beam radiation incidence angle modifier
$K_{\theta d}$	diffuse radiation incidence angle modifier
L_h	effective plate length (m)
$LMTD$	logarithmic mean temperature difference (°C)
L_w	effective plate width (m)
$\dot{m}_{ch}$	mass flow rate per channel, $\dot{m}_p/N_{ch}$ (kg/s)
$\dot{m}_l$	desired load mass flow rate (kg/s)
$\dot{m}_p$	mass flow rate in primary circuit, A_cG (kg/s)
$\dot{m}_r$	makeup water mass flow rate (kg/s)
$\dot{m}_s$	mass flow rate in secondary circuit, A_cG (kg/s)
$\dot{m}_t$	mass flow rate from storage to load (kg/s)
n	life cycle of plant (years)
N_c	number of collectors
N_{ch}	number of channels per pass, $(N_{pl} - 1)/(2N_{pass})$
N_{pass}	total number of passes
N_{pl}	total number of plates, $A_{HX}/A_{eff} + 2$
N_{ht}	number of heat transfer plates, $N_{pl} - 2$
Nu	Nusselt number, hD_e/k_w
p	plate pitch (m)
Pr	Prandtl number, $\mu C_p/k_w$
q_a	auxiliary energy required (W)
Q_a	auxiliary energy required over a year (J)
Q_l	desired hot water load over a year (J)
Q_r	solar energy incident on the collector over a year (J)
q_s	load met by solar energy (W)
Q_s	load met by solar energy over a year (J)
q_u	solar useful heat gain rate (W)
Q_u	solar useful heat gain rate over a year (J)
R_b	ratio of beam radiation on a tilted plane to that on the horizontal plane