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A simulation study on the operating performance of a solar–air source heat pump water heater

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Abstract

A simulation study on the operating performance of a new type of solar–air source heat pump water heater (SAS-HPWH) has been presented. The SAS-HPWH used a specially designed flat-plate heat collector/evaporator with spiral-finned tubes to obtain energy from both solar irradiation and ambient air for hot water heating. Using the meteorological data in Nanjing, China, the simulation results based on 150 L water heating capacity showed that such a SAS-HPWH can heat water up to 55 °C efficiently under various weather conditions all year around. In this simulation study, the influences of solar radiation, ambient temperature and compressor capacity on the performance of the SAS-HPWH were analyzed. In order to improve the overall operating performance, the use of a variable-capacity compressor has been proposed.

Keywords: Solar energy; Heat pump; Water heater; Energy efficiency; Simulation

1. Introduction

With the increased demand for energy use, how to improve energy efficiency and utilize renewable energy effectively have become key issues for sustainable development. In China, a large percentage of building energy use was for domestic water heating, with ~10% to 40% in commercial buildings and ~20% to 30% in residential buildings. Currently, in many parts of the world, electric and gas water heaters are commonly used. Both use high-grade energy to directly heat water to approximately 50 °C, which does not seem to be reasonable.

Thermosyphon solar water heaters (TSWH) have been used in places where the available solar irradiation is high. However, when available solar radiation is not strong enough, electricity, as a supplementary energy source, will have to be used to take up water heating duty as appropriate, consuming high-grade electrical energy. On using a heat pump water heater, low-grade energy from various sources such as ambient air may be upgraded to an appropriate level for water heating. A heat pump water heater usually has a high efficiency of energy utilization. This is particularly true for a solar-assisted heat pump (SAHP) water heater.

There have been significant interests in studying the application of direct expansion SAHP in major developed countries since 1950s [1–4]. These studies demonstrated theoretically and experimentally that a DX-SAHP could work satisfactorily with a very high efficiency on sunny days. For example, the experimental DX-SAHP system of a 350 W rated heating capacity in a previous study can achieve a COP of 5.3 at noon on a sunny day in winter, when the condenser water inlet temperature was 40 °C [5]. However, a DX-SAHP hot water heater in winter worked with a reasonable COP

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Nomenclature

A_c	surface area of collecting plate of collector/evaporator, m^2
$C_{p,w}$	specific heat of water, J/(kg K)
COP	coefficient of performance
d_i	inside diameter, m
F	heat-transfer area of collector/evaporator, m^2
F'	collector/evaporator efficiency factor
f	friction factor
f_s	solar energy input ratio
G_r	mass velocity of refrigerant, kg/(m^2 s)
h	refrigerant enthalpy, J/kg
h_c	convective heat loss coefficient, W/(m^2 K)
h_r	radiation heat loss coefficient, W/(m^2 K)
I	solar irradiation on the collector/evaporator, W/m^2
l_0	height of fins, m
m	mass flow rate, kg/s
Nu	Nusselt number
Pr	Prandtl number
p	pressure, Pa
p_{cr}	critical pressure, Pa
Q_a	ambient air energy gain by refrigerant, W
Q_c	heat rejection by condenser, W
Q_e	the total energy gain by refrigerant, W
Q_p	solar energy collected by collector/evaporator, W
Q_s	solar energy gain by refrigerant, W
q_L	energy loss per unit area of collector/evaporator per unit time, W/m^2
Re	Reynolds number
R_n	refrigerant-side heat transfer resistance, (m^2 K)/W
R_w	air-side heat transfer resistance, (m^2 K)/W
r	rotational speed of compressor, r/min
r_h, e_h	heat transfer enhancement factor
t_a	ambient air temperature, °C
t_p	surface temperature of collector/evaporator, °C
t_r	refrigerant temperature, °C
t_w	water temperature, °C
t_0	evaporating temperature, °C
U_{LC}	energy loss coefficient of collector/evaporator, W/(m^2 K)
u_w	wind speed, m/s
V_h	theoretic displacement of compressor, m^3
v	specific volume, m^3/kg
X_{tt}	Martinelli number
x	refrigerant dryness fraction

Greek letters

α	absorptance of collector/evaporator, 0.96/ heat transfer coefficient, W/(m^2 K);
β	fin coefficient
δ	tube wall thickness, m
ε	emissivity
η_o	overall efficiency of finned tube
η_v	volumetric efficiency of compressor
λ	thermal conductivity, W/(m K)
μ	viscosity, Pa s
ρ	density, kg/m^3
σ	Stefan–Bolzmann constant, W/(m^2 K^4)

Subscripts

c	condenser
e	evaporator
l	refrigerant liquid
r	refrigerant
i	inside, inlet
o	outside, outlet
sh	superheated region
tp	two-phase region
v	refrigerant vapor
w	water, wind

for a short duration. A recent study [6] also demonstrated that when solar irradiation dropped to below 250 W/m^2, there was not enough heat released by its condenser for water-heating.

There have been other related studies [7–11] and recent attempts to integrate a SAHP and an air-source heat pump to form an integrated heat pump water heater [12,13]. The variation of available solar energy due to the changes in weather conditions suggested that it was not appropriate to use solar energy as the only energy source for a heat pump water heater. On the other hand, the low-grade energy from air source was readily available. Therefore, it was intuitive to develop a new type multi-source heat pump water heater, using the solar energy as its major energy source, and air as its supplementary energy source [14].

This paper reports on a simulation study on the operating performance of an integrated solar–air source heat pump water heater (SAS-HPWH). A description of the detailed configuration and operating principle of the SAS-HPWH is firstly presented. This is followed by reporting the development of a mathematical model of the SAS-HPWH. Finally, the simulation results and their analysis are presented.