Renewable Energy 50 (2013) 596–604

Contents lists available at SciVerse ScienceDirect

Renewable Energy

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

Performance analysis of hybrid solar-geothermal CO_2 heat pump system for residential heating

Wonseok Kim [a], Jongmin Choi [b], Honghyun Cho [c,*]

[a] Technology Research & Development Institute, Daelim Industrial Co. Ltd., Seoul 110-732, Republic of Korea
[b] Department of Mechanical Engineering, Hanbat National University, Daejeon 305-719, Republic of Korea
[c] Department of Mechanical Engineering, Chosun University, Seosuk-Dong, Dong-Ku, Gwangju 501-759, Republic of Korea

ARTICLE INFO

Article history:
Received 30 March 2012
Accepted 9 July 2012
Available online 31 August 2012

Keywords:
Carbon dioxide
COP
Heat pump
Solar
Geothermal

ABSTRACT

A simulation study of hybrid solar-geothermal heat pump system for residential applications using carbon dioxide was carried out under different operating conditions. The system consists of a solar unit (concentric evacuated tube solar collector and heat storage tank) and a CO_2 heat pump unit (three double-pipe heat exchangers, electric expansion valve, and compressor). As a result, the differential of pressure ratio between the inlet and the outlet of the compressor increases by 19.9%, and the compressor work increases from 4.5 to 5.3 kW when the operating temperature of the heat pump rises from 40 °C to 48 °C. Besides, the pressure ratio of the compressor decreases from 3 to 2.5 when the ground temperature increases from 11 °C to 19 °C. The operating time of the heat pump is reduced by 5 h as the daily solar radiation increases. As the solar radiation increases from 1 to 20 MJ/m^2, the collector heat rises by 48% and the maximum collector heat becomes 47.8 kWh. The heating load increases by 70% as the indoor design temperature increases from 18 °C to 26 °C. However, the solar fraction is reduced from 11.4% to 5.8% because of the increases of the heating load.

1. Introduction

Recently, hydrocarbon shortage and global energy crisis have aroused great interest in alternative energy supplies. This is especially true for South Korea that badly depends on imported energy resources. However, most alternative energy technologies are faced with difficulties when it comes to application for community facilities because of regional restrictions and operating cost. Therefore, researches on energy saving and optimal operation of residential heat pump systems are urgently required. To this end, using renewable energy (e.g. solar or geothermal) for refrigeration and air conditioning applications becomes increasingly important and draws considerable attention. As for working fluids, carbon dioxide is a natural climate-friendly refrigerant as it does not deplete ozone layer and has a low direct global warming potential with reference value 1. Generally, the performance of a heat pump using carbon dioxide is lower than that of a system using a subcritical cycle refrigerant because of large irreversibility during compression and gascooling. Moreover, system reliability is very low due to large performance variations with operating conditions. Hence, system performance and operating characteristics of a CO_2 heat pump should be investigated according to operating conditions.

During the last decade, a number of studies have been conducted by some researchers on design, modeling and testing of heat pump systems with a view of using solar and geothermal energy for residential heating. The characteristic of an integral-type solar-assisted heat pump (ISAHP) has been examined by Huang and Chyng [1]. Their ISAHP experimental system includes a reverse Rankine refrigeration cycle and a thermosiphon loop that integrated in a combined package heater. Both solar and ambient air energies are absorbed at the collector/evaporator and pumped to the storage tank through the reverse Rankine refrigeration cycle and the thermosiphon heat exchanger. Yumrutas et al. [2] have studied the annual performance of a solar associated heat pump system (SAHPS) with seasonal underground energy storage and annual water temperature distribution in the storage tank using an iterative computational procedure based on the analytical solution of the problem. The results showed that earth type and system size had considerable effects on system performance. Kuang et al. [3] have carried out an experimental study on SAHPS performance and concluded that the thermal storage tank was an important

* Corresponding author. Tel.: +82 62 230 7050; fax: +82 62 230 7055.
E-mail address: hhcho@chosun.ac.kr (H. Cho).

0960-1481/$ – see front matter © 2012 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.renene.2012.07.020

Nomenclature

A	area (m^2)
$A_{t,m}$	minimum throat area (m^2)
$C_1 - C_5$	coefficients in eq. (10)
D_c	fin collar outside diameter (mm)
D_m	hydraulic diameter at orifice throat (m)
D_{ori}	orifice diameter (m)
F_p	fin pitch (mm)
F_R	collector heat removal factor
$F_R\tau\alpha$	intercept of the efficiency curve
h	enthalpy (kJ kg^{-1})
h	convective heat transfer coefficient (W m^{-2} K^{-1})
I_t	solar radiation (W m^{-2})
L	length of needle in the orifice (m)
$\dot{m}$	mass flow rate (kg s^{-1})
N	number of longitudinal tube rows or compressor rotating speed (rpm)
P	pressure (kPa)
ΔP	pressure drop (kPa)
P_l	longitudinal tube pitch (mm)
P_t	transverse tube pitch (mm)
Q	rate of the heat transfer (kW)
Re_{Dc}	Reynolds number based on hydraulic diameter
SH_{sc}	superheat caused in the refrigerant by semi-hermetic compressor refrigeration (°C)
S_h	height of slit (mm)
S_s	breadth of a slit in the direction of air flow (mm)
T	temperature (°C)
T_w	water temperature (°C)
U	overall heat transfer coefficient (W/m^2 K)
U_L	collector overall heat loss coefficient (W/m^2 K)
$\dot{V}_G$	compressor displacement (m^3 h^{-1})
v	specific volume (m^3kg^{-1})
W	compressor work (kW)

Greek symbols

ρ	density (kg m^{-3})
ρ_{pc}	density at pseudo-critical conditions (kg m^{-3})
η	efficiency

Subscripts

air	air or ambient
c	compression
collector	collector
comp	compressor
cont	contact
CO_2	carbon dioxide
crit	critical
db	dry bulb
dis	discharge
f	fin
i	inlet or inner
isen	isentropic
mot	motor or at the inlet port to the electric motor of the compressor
o	outlet or outside
po	pipe outside
suc	suction
v	volumetric
wat	water
wb	wet bulb

component in solar heating systems, which could modulate the mismatch between solar radiation and the heating load. Besides, Chiasson et al. [4] performed a 20-year life-cycle cost analysis to evaluate the economics of ground heat pump systems coupled to thermal solar collectors for six different climates in the U.S. They concluded that GSHP system combined with solar collectors is economically viable for heating-dominated climates. Han et al. [5] investigated different operational modes of a solar assisted GSHP system in the presence of latent heat energy storage tanks, and they indicated that using storage tanks increases system performance by 12.3%. Recently, Kjellsson et al. [6] analyzed five alternatives to supply solar energy to a ground source heat pump(GSHP) system and compared them against a base case without solar collectors. Wang et al. [7] have performance prediction of a hybrid solar ground-source heat pump system(HSGSHPS) and the electrical energy demand of the system could be reduced by 32%. Xi et al. [8] have experiment of long term operation of a solar assisted ground coupled heat pump system for space heating and domestic hot water. Solar assisted heating and solar coupled ground heat pump heating modes are energy saving modes that supply 22% of the total heating load.

Chaturvedi et al. [9] and Aziz et al. [10] have performed thermodynamic analysis of two-component, two-phase flow in solar collectors with application to direct expansion SAHP. Their results showed that changes in the mass-flow rate and the absorbed solar heat flux had significant effects on the collector tube length and refrigerant heat transfer coefficient. Ozgener and Hepbasli [11] have investigated the performance of a solar assisted ground-source heat pump greenhouse heating system (SAGSHPGHS) with R-22 refrigerant in the heating mode by using exergy analysis. Stene [12] has carried out theoretical and experimental study of a residential brine-to-water CO_2 heat pump system for combined space and hot water heating. The CO_2 heat pump was equipped with a unique counter-flow tripartite gas cooler for preheating of domestic hot water (DHW), low-temperature space heating and reheating of DHW.

In earlier studies, however, the performance of the hybrid solar and geothermal heat pump system has been mainly studied assuming CFC or HCFC refrigerant for residential heating. Only few studies have considered heat pump systems with CO_2 refrigerant for hot water and space heating systems. Therefore, it is very important to analyze performance characteristics of the hybrid solar-geothermal CO_2 heat pump system (HSG-CHPS) for residential heating and find out optimal operating conditions for variable conditions.

In this study, a CO_2 heat pump model with solar and geothermal heating system for residential heating has been developed. For efficient use of the CO_2 heat pump, an operating characteristics and performance analysis are required in order to save energy and increase reliability. To address this problem, the performance data of the hybrid solar-geothermal CO_2 heat pump system have been investigated against the pump operating temperature, indoor design temperature, daily solar radiation and outdoor temperature.

2. System modeling

The hybrid solar-geothermal CO_2 heat pump system (HSG-CHPS) consists of a solar heat unit and a CO_2 heat pump unit. The solar heat unit has a concentric evacuated tube collector, and a heat storage tank. The CO_2 heat pump unit consists of two double-pipe heat exchangers (high- and low-temperature), a double pipe type evaporator, an electric expansion valve (EEV) and a semi-hermetic type reciprocating compressor ($Q_{\_cooling}$ = 10.55 kW).