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Experimental validation of a theoretical model for a direct-expansion solar-assisted heat pump applied to heating

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A B S T R A C T

This paper discusses the experimental validation of a theoretical model that determines the operating parameters of a DXSAHP (direct-expansion solar-assisted heat pump) applied to heating. For this application, the model took into account the variable condensing temperature, and it was developed from the following environmental variables: outdoor temperature, solar radiation and wind. The experimental data were obtained from a prototype installed at the University Carlos III, which is located south of Madrid. The prototype uses a solar collector with a total area of 5.6 m^2, a compressor with a rated capacity of 1100 W, a thermostatic expansion valve and fan-coil units as indoor terminals. The monitoring results were analyzed for several typical days in the climatic zone where the machine was located to understand the equipment's seasonal behavior. The experimental coefficient of the performance varies between 1.9 and 2.7, and the equipment behavior in extreme outdoor conditions has also been known to determine the thermal demand that can be compensated for.

1. Introduction

The increasing interest in renewable energy and the need to comply with legislation [1,2] have stimulated the commercial market for products that use advanced technologies to derive power from solar radiation, wind or alternative energy sources.

In air-conditioning applications, the refrigerating cycles of mechanical compression are a common way of transporting heat from a cold area to a warm area. The present work develops theoretical and experimental models that combine the technology of mechanical simple compression with solar thermal capture. Using solar radiation to assist the heat pump improves the energy efficiency of the models and diminishes pollutant emissions.

The exterior heat exchangers of conventional heat pumps absorb heat from the cold focus by forced convection with the help of a fan and do not use solar radiation. The DXSAHP (direct-expansion solar-assisted heat pump) replaces the heat exchanger of a finned pipe with solar collectors, which, in contrast to conventional evaporators, absorb solar radiation. It is interesting to consider the comparison Sushil makes between the collector and the standard outdoor fan-coil units, and significant disadvantages are obtained with regard to the DXSAHP [3].

Sporn and Ambrose [4] published the first study on this machine concept in 1952, and several authors have completed studies applying a DXSAHP to DHW (domestic hoot water) and heating for residential use. The water temperature in the consumption circuit is an important parameter in both applications because the condensation temperature and the efficiency depend on this water temperature. For heating applications, low-temperature facilities are usually used [3–11], mainly for floor heating, and the obtained efficiencies have been shown to change according to the environmental variables and the test conditions. Sushil [3] published an experimental validation of the work performed by Chaturvedi [5], with the COP (coefficient of performance) ranging from 2 to 3. Hawlader [6] developed and experimentally validated another simulation model to study the thermal performance. The results indicate that the performance of the system is influenced significantly by the collector area, the speed of the compressor and solar radiation. Kuang [7] also conducted a similar study, and the results indicated that the system performance is governed strongly by the change of solar insulation. Yumrutas [8] performed a study on floor heating to make a daily energy balance using the energy received and the energy absorbed by the system to obtain a coefficient of performance between 2.5 and 3.5. Kong [9] proposed and

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Nomenclature

a	section surface fin (m^2)
A	area (m^2)
C	constant
COP	coefficient of performance
Dg	dragging term
Dt	thermal demand (kWh)
h	heat transfer coefficient (W m^{-2} K^{-1})
i	specific enthalpy (kJ kg^{-1})
k	thermal conductivity (W m^{-1} K^{-1})
L	length (m)
$\dot{m}$	mass rate of flow (kg s^{-1})
P	pressure (Pa)
Q	thermal capacity (kW)
q	thermal power per unit of pipe length (kW m^{-1})
R	solar radiation (kW m^{-2})
S	collector surface (m^2)
Su	useful surface (%)
T	dry bulb temperature (°C, K)
t	thickness (m)
TEV	thermostatic expansion valve
U	global transmission coefficient (kW m^{-2} K^{-1})
V	volume of the collector (m^3)
Vw	wind velocity (m/s)
W	power demand (kW)
x	distance to the pipe in the collector fin (m)

Greek letters

α	absorptivity of the collector
ε	emissivity of the collector
η	efficiency

Subscripts

aux	ancillary
cd	condensation
cv	convection
cp	compressor
el	electric
ev	evaporation
ex	experimental
f	fin
g	global
th	theoretical
ice	ice
in	indoor
m	middle between pipes
n	net
out	outdoor
p	pipe
r	refrigerant
s	surface
uh	useful heat
wp	water pump
1,2,3,4	state

experimentally validated a simulation program based on the models of the components and of the refrigerant charge. Possibly because of the different experimental and environmental conditions, the COP Kong obtained is very different from those presented in the present work. Other authors, such as Kuang [10], studied the possibility that this equipment was multifunctional to satisfy the heating and DHW needs. He obtained efficiencies between 2.1 and 2.7.

In cases in which the system used an interior unit space heater, high temperatures were needed in the circuit that transports the heat up to the condenser. High temperatures in the condenser involve high pressure, so the energy efficiency of the equipment is very low because of the high place consumption of the compressor. Chaturvedi proposes using a two-stage DXSAHP system for high-temperature applications [11], with an efficiency of approximately 2 for this type of application.

Recently, Mohanraj, Jayaraj Muraleedharan [12] and [13], have used ANN (artificial neural networks) to predict the performance and to carry out an exergy analysis of a DXSHAP, using experimental data from Calicut as training data from the network. They have concluded that the use of ANN is quite suitable, obtaining a good correlation between the experimental and the predicted values.

In this work, the theoretical model developed in a previous study by the authors [14] for applications of DHW is validated experimentally for heating applications. To simulate the experimental results, the model determined the variable condensation temperature from the indoor temperature and a dragging term that relates the condensation temperature variation with the evaporation temperature variation.

The experimental study was performed south of Madrid, although the results could be extended to other climatic zones with adjustments for environmental parameters. The system dependence on the exterior conditions is very strong, so it is necessary to perform the study at a particular location to determine the system's seasonal behavior.

The prototype has fan-coils as the terminal units. The indoor temperature according to the RITE [1] must be 20 °C in winter. For this reason, it is not necessary for the condensation temperature to exceed 40 °C, thus assuring an impulsion temperature above 30 °C. The experimental setup was established such that there is no thermal local demand. The fan-coil units always raise the air temperature to 20 °C, and the air impulsion depends only on the machine's instantaneous power. In this paper, the thermal power of the machine in all operating conditions will be investigated. The outside temperature, the solar radiation and other atmospheric phenomena, such as snow, determine the following operating parameters: thermal transferred power, electrical power consumption and efficiency.

The machine tested in this study has no volumetric flow control of the refrigerant and there is not variable flow of water in the consumption subsystem.

2. System description

The proposed experimental setup is shown in Fig. 1. Heat from the atmosphere and solar energy is absorbed by the thermal collection subsystem, which consists of four bare flat-plate solar collectors-evaporators (process 4-1, Fig. 1). The heat is transported up to the condenser by the refrigerant of the heat pump, which has as its main components a reciprocating hermetic compressor and a TEV. The condenser is a plate heat exchanger (process 2-3, Fig. 1) and transfers the heat to the consumption subsystem. For this application, the consumption subsystem consists of two fan-coil units that return the heat to the environment.

The heat is transported by two independent circuits. A primary circuit circulates the refrigerant between the evaporators and the