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Modeling and experimental validation of a solar-assisted direct expansion air conditioning system

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ABSTRACT

Continuous increase in global electricity consumption, environmental hazards of pollution and depletion of fossil fuel resources have brought about a paradigm shift in the development of eco-friendly and energy-efficient technologies. This paper reports on an experimental study to investigate the inherent operational characteristics of a new direct-expansion air conditioning system combined with a vacuum solar collector. Mathematical models of the system components are firstly derived and then validated against experimental results. To investigate the potential of energy savings, the hybrid solar-assisted air-conditioner is installed and extensively equipped with a number of sensors and instrumentation devices, for experimentation and data collection. The influence on the system energy usage of the average water temperature, storage tank size and room set-point temperature are then analyzed. Once the air-conditioned room has achieved its desired temperature, the compressor turns off while the cooling process still continues until the refrigerant pressure no longer maintains the desired temperature. The advantages of the proposed hybrid system rest with the fact that the compressor can remain off in a longer period by heat impartation into the refrigerant via the water storage tank. Results show an average monthly energy saving of about between 25% and 42%.

1. Introduction

Growing demand for heating, ventilating and air conditioning (HVAC) systems has nowadays imposed a considerable increase in electricity, which represents approximately 50% of total building energy consumption [1]. For air conditioning, one commonly-used type of HVAC systems is the direct expansion (DX) wall-mounted air-conditioner with a vapor compression cycle. When compared to the chilled water based air conditioning systems, the use of DX systems is more advantageous due to simpler operation and less maintenance cost [2–5]. While this system is energy-efficient and highly comfortable for residential and commercial buildings in different types of climatic conditions, their combination with free energy sources in order to reduce the power consumption has been an interesting topic for researchers. In fact, as the typical value of coefficient of performance (COP) for vapor compression systems is between 2 and 3 [6], combining these systems with any type of renewable energy resources can certainly increase their COP. To this end, it has been found that the electric compression and absorption systems have very high energy saving potential when utilizing the availability of solar energy [7].

Among different types of renewable source of energy available, solar thermal energy is abundantly present and environmentally sustainable. Advantages include significant reductions in energy usage as well as ozone depletion (ODP), and smaller contribution to greenhouse effects and lower CO_2 emission compared to electrically-operated plants. These have therefore promoted the design alternative of using solar collectors for HVAC systems [8–10]. Over the past decade, investigation has been carried out on the feasibility and energy saving potential of different hybrid air conditioning systems [11–14]. Bilgili [15] proposed a solar electric-vapor compression refrigeration system and investigated its performance for different evaporating temperatures, nevertheless without considering the cost of photovoltaic solar panels. A solar-assisted ejector cooling/heating system was developed by Huang et al. [16], wherein the solar ejector cooling system was connected to a conventional inverter type air conditioner to reduce the condensing temperature and hence increase the system COP. Fong et al. [7] proposed a solar hybrid air conditioning system using adsorption refrigeration, chilled ceiling and desiccant dehumidification. Their simulation results showed that the proposed system can satisfy the necessary indoor conditions for office use with a year-round primary energy usage up to 47.3% lower than consumption of a conventional air conditioning system. However, the system would be quite expensive and suitable only for large buildings. A hybrid solar-assisted air conditioner has been recently developed

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Nomenclature

A	cross-sectional area (m^2)
C_P	heat capacity (kJ/(kg °C))
D_i	inside diameter of tube (m)
D_o	outside diameter of tube (m)
h	enthalpy (kJ/kg)
I_t	total solar radiation (kW/m^2)
k	polytropic index of the refrigerant vapor
L	length (m)
$\dot{m}$	refrigerant mass flow rate (kg/s)
M	mass (kg)
p_c	condenser pressure (kPa)
p_e	evaporator pressure (kPa)
T	temperature (°C)
t	time (min)
U	overall heat loss coefficient (kW/(m^2 °C))
V_D	displacement volume of the compressor (m^3/s)
W_{in}	electrical power consumption of the compressor (kW)
α_i	heat transfer coefficient between tube wall and refrigerant (kW/(m^2 °C))
α_o	heat transfer coefficient between tube wall and air (kW/(m^2 °C))
α_s	collector absorptance value
$\bar{\gamma}$	mean value of void fraction
η_{comp}	total efficiency of the compressor
η_v	volumetric efficiency of the compressor
ϑ_{suc}	specific volume at the compressor inlet (m^3/kg)
τ_s	collector transmittance value
ρ	density (kg/m^3)

Subscripts

a	air
c	condenser
cap	capillary tube
comp	compressor
c	condenser
col	collector
ds	de-superheat
e	evaporator
f	water inside storage tank
g	saturated vapor
hx	heat exchanger
i	inlet
int	interface
l	saturated liquid
o	outlet
r	refrigerant
sc	subcool
sh	superheat
t	tank
tp	two-phase
w	wall

in Al-Alili et al. [17], consisting of a solid desiccant wheel cycle and a conventional vapor compression cycle. Their results showed that the COP of the proposed solar-assisted plant is higher than that of a vapor compression cycle powered by photovoltaic panels and a solar absorption cycle. However, as solar thermal energy is obviously more efficient than photovoltaics in HVAC, research effort has been devoted to its use in hybrid air-conditioning for further improving the system energy efficiency and COP. Modeling and control of such systems remain of an increasing interest. For this purpose, a synergetic framework of system identification, empirical modeling, optimization and control has been proposed [18,19]. In this new hybrid solar system, in addition to a conventional compressor used to increase the pressure on the gas, forcing it into a liquid in the condenser coil, a hot water storage tank integrated with a vacuum solar collector is installed after the compressor to supply superheat to the refrigerant and increase its kinetic energy. A larger condenser is used to reject the additional heat obtained from the water storage tank. Therefore, when the room temperature achieves its desired set-point, the compressor will turn off and the additional refrigerant temperature resulting from the hot water storage tank will help it to stay off longer. This method reduces the compressor duty cycle, while fulfilling the building cooling demand, to eventually result in overall energy saving. It is observed that there has been to date no reported research work on comprehensive modeling and experimental validation for the performance of a hybrid solar DX air-conditioner where a solar thermal collector is installed after its compressor.

In this paper, the objectives are to develop reliable mathematical models for components of a direct expansion solar-assisted DX air-conditioner with solar thermal collectors being installed after its compressor, and validate them experimentally via their thermal performance. To this end, mathematical models based on dynamic heat transfer through the system components are developed and incorporated into a transient computer tool, TRNSYS [20], using FORTRAN codes. An iterative numerical procedure is implemented to solve simultaneously heat transfer equations for various components of the system. Experimental results are then compared with simulation prediction to validate the system's mathematical models. A key element of this work is to monitor the system performance in order to quantify energy saving potential for optimal usage of the system. Parametric study of the system has also been performed to understand the influence of the principal parameters of the system on its performance. For this purpose, the system is extensively equipped with sensors and several data logger devices to record its performance data over time. The system is operated over a wide range of climatic conditions for two typical summer weeks. Results showed monthly average energy saving of 25–42%, compared to the energy consumption of a conventional air-conditioner.

The remainder of the paper is organized as follows. After the introduction, Section 2 presents the system description and details the component-wise models of the system. The experimental test rig and model validation are described in Section 3. Results and discussion are given in Section 4. Finally a conclusion is drawn in Section 5.

2. System modeling

This section describes the system configuration and derives mathematical models for its components.

2.1. System configuration

The single-stage vapor compression solar air-conditioner consists of six major components: a compressor, an air-cooled condenser, an expansion device, a DX evaporator, a solar vacuum collector and a hot water storage tank. The schematic diagram of the arrangement is shown in Fig. 1. The cycle starts with a mixture of liquid and vapor refrigerant entering the evaporator (point 1). The heat from the warm air is absorbed by the evaporator coil. During this process, the state of the refrigerant is changed from liquid to gas and becomes superheated at the evaporator exit. The superheat vapor enters the compressor (point 2), where the increasing pressure raises the refrigerant temperature. A vacuum solar panel