Applied Thermal Engineering 73 (2014) 474–483

Contents lists available at ScienceDirect

Applied Thermal Engineering

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

Numerical analysis and optimization of a solar hybrid one-rotor two-stage desiccant cooling and heating system

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HIGHLIGHTS

- Performance model of a solar cooling/heating system was created in TRNSYS studio.
- Performance analysis of annual data shows that the solar system can operate well.
- Evacuated tube solar air collector was applied in a developed air-conditioning unit.

ARTICLE INFO

Article history:
Received 6 July 2013
Accepted 28 July 2014
Available online 7 August 2014

Keywords:
Desiccant cooling
Solar
Simulation
System optimization

ABSTRACT

In this paper, a solar hybrid one-rotor two-stage desiccant cooling and heating system has been numerically analyzed. The system was made up of a one-rotor two-stage desiccant cooling unit, with design cooling capacity for 5 kW, and a solar collector array of 15 m^2. Performance model of the system was created in TRNSYS simulation studio. Firstly, base case performance models were programmed according to the configuration of the installed solar desiccant system and verified by the experimental data. Secondly, the year-round performance about the system was simulated. Finally, we optimized the parameters of the system, including the solar collector area, the ratio between fresh air and return air, and the heat exchanger efficiency. Numerical results agree with the experimental ones. The simulation results showed that about 60% of the humidity load can be totally handled by the one-rotor two-stage desiccant cooling unit, and about 40% of the heating load can be handled by solar energy.

1. Introduction

Continuous increase in indoor air quality requirements coupled with fears in energy shortage and global warming are the main challenges of building energy supply. As a renewable energy source, solar energy can facilitate ventilation as well as space heating and cooling in winter and summer. The solar driven desiccant cooling system is an environmentally-friendly air-conditioning technology. During solar desiccant cooling process, sensible and latent loads are processed independently leading to comfortable indoor environment. For this reason, the application of solar powered desiccant cooling system is becoming increasingly attractive.

In recent years, some researchers have investigated the solar desiccant cooling systems theoretically and experimentally. Studies done on a solar desiccant cooling by Bourdoukan et al. [1] found out that the overall efficiency of the solar installation was 0.55 with the thermodynamic coefficient of performance of 0.45 and a performance indicator of 4.5 based on the electrical consumption. Panaras et al. [2] conducted a theoretical and experimental study of a desiccant air-conditioning system. The study showed that the desiccant air-conditioning technology had the potential to satisfy actual cooling load. Their analysis further showed that operating the desiccant air-conditioning system at a minimum possible regeneration temperature combined with appropriate air flow rate enables exploitation of low temperature sources to achieve high COP levels. Mavroudaki et al. [3] conducted a study to investigate the potential of solar powered single-stage desiccant cooling in southern Europe. The study revealed that the system was feasible for use in parts of southern Europe. Davagere et al. [4] investigated the feasibility of solar desiccant air-conditioning system with different climates in four different cities through simulation. The simulation results showed that the system was capable of meeting the cooling demand. They further proposed that using different methods for supplying the thermal energy for desiccant

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http://dx.doi.org/10.1016/j.applthermaleng.2014.07.076
1359-4311/

Nomenclature

A	surface area (m^2)
c_p	heat capacity (J/(kg K))
d	diameter (m)
E	energy consumption (kW)
h	convective heat transfer coefficient (W/m^2 K)
I	solar radiation (W/m^2)
k	heat transfer coefficient (W/m^2 K)
m	mass flow rate (kg/s)
Q	heat transfer capacity (J)
T	temperature (°C)
t	time (s)
ε	efficiency of heat exchanger
λ	thermal conductivity (W/m K)
1, 2… 10	refers to the positions described in figure

Subscripts

1, 2, 3	refers to the running modes of the system
a	process air in the heat exchanger
Air	process air in the solar air collector
amb	ambient condition
ave	average air condition in the collector
c	convection heat transfer
fan	regeneration fan and process fan
HE	heat exchanger
in	inside of surface or inlet of process fluid
out	outside of surface or outlet of process fluid
Pre	process air
pump	pump used in cooling tower
r	radiation heat transfer
reg1	first-stage regeneration air
reg2	second-stage regeneration air
solar	solar gain from solar collectors
Tube	alumina tube in solar air collector
w	water

regeneration will minimize the auxiliary energy costs. Heidarinejad et al. [5] simulated a desiccant cooling system and applied the simulation to selected and important location in a multi-climate country like Iran. The simulation results showed that there is a significant increase in the share of thermal comfort obtained by desiccant cooling.

Unlike the aforementioned study, most of the effort was focused on the components, the heat regenerator, and more on the desiccant wheel simulation and optimization. Chung et al. [6] analyzed the effect of various kinds of design parameters on the performance of a desiccant cooling system using two different system configurations. They found out that the regenerative temperature had the greatest effect as compared to other parameters, with a contributing ratio of 23.9% and 31.9% for each system configuration. Sphaier et al. [7] investigated the impact of cycle component's characteristics on the overall system performance. The results showed that a 20–30% decrease in dehumidifier performance could lead to 30–50% reduction in the overall ventilation cycle performance. Dai et al. [8] conducted parameter analysis to improve rotary desiccant dehumidification using a mathematical model. It was demonstrated that the model was feasible and rapid in evaluating the performance of the rotary dehumidifier. Stabat et al. [9] developed a desiccant wheel behavioral model, which was in good agreement with experimental and manufacturer's data. Ahmed et al. [10] conducted an evaluation and optimization of a solar desiccant wheel performance using a numerical model. The effective air flow rate is between 1 and 5 kg/min with temperature between [60 °C, 90 °C] and wheel speed between [15 rev/h, 60 rev/h]. Chung et al. [11] simulated the desiccant wheel to evaluate the wheel performance by analyzing the moisture removal capacity through optimization of some operating and/or design parameters.

However, while a number of research works have been carried out on desiccant cooling system, the subject of desiccant cooling/heating system has received very little attention. In order to make the desiccant cooling/heating system operate throughout the year, it is necessary to study annual performance of the system. In this paper, we introduced a solar driven desiccant cooling and heating system, which adopts evacuated tube solar air collector and incorporates a developed one-rotor two-stage desiccant air-conditioning unit. A procedure is proposed for the simulation analysis of a solar driven desiccant cooling/heating system in TRNSYS simulation studio. The performance of the system is studied for both cooling during summer and heating during winter.

There are differences in research methodology and focus from previous researchers. Lihui has experimented with a one-rotor two-stage desiccant cooling/heating system driven by solar air collectors [12]. Ladong has done theoretical analysis of solar heating and humidification system with desiccant rotor [13]. This paper focuses on numerical analysis and parameter optimization of a solar hybrid one-rotor two-stage desiccant cooling and heating system.

In this paper, a solar hybrid one-rotor two-stage desiccant cooling and heating system has been numerically analyzed. The system mainly includes a desiccant cooling subsystem, solar heating subsystem and control devices. On the base of experimental investigation [12], a simulation model of the system is developed, using the TRNSYS computer simulation software package. A base case model was programmed in accordance with the configuration of the solar cooling/heating system installed in Shanghai. The year-round performance of the system was simulated after verification of the experimental data obtained from the test system. In addition, parameters of system were optimized considering the ratio between the fresh air and the return air, the collector area, and the efficiency of the cross-flow heat exchanger. Finally, we suggested the guidelines for design and operation of solar cooling/heating system.

2. System description

The solar driven one-rotary two-stage desiccant cooling/heating system was designed, installed, and operated in an office building at Shanghai Jiao Tong University (SJTU), east longitude 121° 25′ 34.13″, north latitude 31° 01′ 11.15″. Fig. 1 illustrates the schematic diagram of the installed system. The system consists of solar heating subsystem, and desiccant cooling/heating subsystem. It comprises three evaporative coolers (DEC), two air-to-air cross-flow heat exchangers (CHE) and one desiccant wheel (DW) coated with a composite desiccant. The conditioned space occupies an area of 23.2 m^2. The solar collector array area is 15 m^2, and the cooling capacity of the system is 5 kW. The honeycombed silica gel-LiCl composite desiccant wheels were used in this system. The main parameters of the system are listed in Table 1.