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Comparative performance analysis of different solar desiccant dehumidification systems

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ABSTRACT

The transient performance of different configurations of solar desiccant cooling systems is analyzed and compared based on the concept of Finite Time Thermodynamics. The *TRNSYS* software is used to conduct the transient simulation, and the results are compared with the experimental data in literature. Solar desiccant cooling systems are studied in 3 different configurations, in which fresh air, conditioned air, and a mixture of fresh air and conditioned air enter the dehumidifier wheel, respectively. Also, the performance of desiccant cooling system is investigated in single-stage and double-stage configurations to consider the effect of the number of dehumidifier wheels. The coefficient of performance (COP) and exergy efficiency of different configurations are evaluated to determine the optimum arrangement. The highest COP is achieved for Dunckle configuration in ventilation mode and for Uçkan configuration in recirculation mode. The results indicate that the COP of single-stage systems is higher than double-stage in both recirculation and ventilation modes. The highest COP and exergy efficiency are achieved for Dunckle configuration in ventilation mode as 0.6 and 35%, respectively. Implementation of heat recovery system improves the performance of double-stage configuration more than the single-stage system. An economic analysis is performed to compare different configurations based on electrical energy saving and payback period. The result indicates that the Uckan and Dunckle configurations consume 50% lower electrical energy compared to air conditioning heat pumps with payback period of about 4 years.

1. Introduction

Solar assisted desiccant cooling system is an attractive and cost effective process for air conditioning application especially for hot and humid climates. This system is regarded as a promising alternative to conventional air-conditioning systems, because sensible and latent cooling loads are provided, independently. Several advantages have expanded the application of solar desiccant system during recent years, namely the growing technology, no use of chlorofluorocarbons, low electric power consumption, standard human comfort, energy saving and environmental protection [1]. These features have extended the application of this system to a wide-ranging area including hospitals, supermarkets, restaurants, theaters, schools and office buildings. The required thermal energy of this system can be obtained from solar systems, heat pumps, Organic Rankine cycles and any low grade heat source [1–4].

Two types of solid desiccants are usually utilized, namely rotary wheel desiccant wheel and fixed desiccant beds. Desiccant wheel has attracted more attention because it occupies less space, and it works uninterruptedly without any sensitivity to corrosion. Recent studies on rotary desiccants are mainly based on two main goals: development of advanced desiccant materials and identification of the most efficient system configurations.

Regarding advanced desiccant materials, several studies are focused on the thermal and adsorption properties of the desiccants to evaluate the effect of their physical and chemical characteristics [5–7]. Ge et al. [5,6] proposed a newly developed silica gel–haloid composite and a mathematical model for its adsorption performance. They performed a numerical investigation on two-stage rotary wheel desiccant, however, they did not present effectiveness parameters for the silica gel-haloid desiccant. A novel organic-inorganic hybrid desiccant material that combines high adsorption capability with good mechanical durability is introduced by Fu et al. [7].

Other studies are mainly related to development of efficient rotary desiccant systems. In this regard, several numerical and

Abbreviations: COP, coefficient of performance; AA, ambient air; AX, auxiliary heater; HX, heat exchanger; FM, flow mixer; SA, supply air; RA, return air; EA, exhaust air; FA, fresh air; PA, process air; REGA, regeneration air; RM, recirculation mode; DW, desiccant wheel; LPC, linear parabolic collector; RR, rotary recovery; EC, evaporative cooler; VM, ventilation mode; CPP, cost payback period.

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Nomenclatures

Variables

C_p	Specific heat (kJ kg^{-1} K^{-1})
ex	Specific exergy (kJ kg^{-1})
F1	Characteristic potentials
F2	Characteristic potentials
h	Specific enthalpy (kJ kg^{-1})
m	Flow rate (kg h^{-1})
Q	Heat transfer rate (kJ h^{-1})
T	Temperature (K)
s	Specific entropy (kJ kg^{-1} K^{-1})
w	Humidity ratio (kg kg^{-1}dry air)
R_a	Air gas constant (kJ kg^{-1} K^{-1})
W	Work rate (kJ kg^{-1})

subscripts

0	Dead state condition
a	Air stream
ambient	Ambient condition
c	Condenser
des	Destruction
e	Evaporator
eff	Efficiency
I	Inlet condition
cool	Cooling load
regen	Regeneration heat
space	Space condition
source	Source condition
R	Refrigerator
w	Water
rev	Reversible
C	Carnot system
s	Source
O	Outlet condition
v	Vapor

Greek letters

ε	Effectiveness

experimental simulation are conducted to identify the optimum working parameters and configurations of rotary desiccant systems. De Antonellis et al. [8] used one-dimensional gas side resistance model to investigate the performance of desiccant wheels at different working conditions and to optimize the dehumidification capacity and revolution speed. They revealed useful information regarding optimal configurations of desiccant wheel; however, their process model is simple and limited to specific assumptions. Paranas et al. [9] proposed a control strategy to maintain human comfort condition based on indoor temperature and humidity. They determined technical specifications of the desiccant air conditioning system equipment's and the control system; however, the proposed desiccant system is not enough flexible to highly variable working conditions. Sphaier et al. [10] concluded that the efficiency of heat recovery wheel and desiccant wheel have greater effect on the overall system performance than other components. Their conclusions are quite general and a detailed study is required to identify the effect of working parameters on the performance of the system. The effect of different design parameters on the performance of a desiccant cooling system is presented by Chung et al. [11]. They found that regenerative temperature is the most dominant parameter on efficiency and the cooling effect of the regenerative evaporative cooler determines the system performance.

An experimental study is reported by Ge et al. [12,13] on a two-stage rotary desiccant cooling system. Their study indicates that the COP of a one-rotor two-stage rotary desiccant cooling system is almost unity when the regeneration temperature is lower than 80 °C. The performance of their proposed system is not compared to other two-stage configurations including those with additional heat recovery. Heidarnejad et al. [14] investigated a two-stage indirect/direct evaporative cooling system in various climatic conditions experimentally. They found that utilization of two-stage configuration results in 60% power saving in comparison to mechanical vapor compression systems and about 55% higher water consumption rate than direct evaporative cooling systems.

Few experimental studies are conducted to evaluate the effect of different parameters on the performance of desiccant wheel systems. Panaras et al. [15] investigated the impact of regeneration temperature and air flow rate on the performance of the system in ventilation and recirculation modes. The results show that by increasing the regeneration temperature and inlet flow rate, the COP of system decreases, while at the same conditions the COP in recirculation mode is lower than that in ventilation mode.

Some novel desiccant cooling configurations have been developed and evaluated experimentally by Angrisani et al. [16]. The configuration proposed by Angrisani has about 20%–25% energy saving and 40%–50% reduction of equivalent CO_2 emissions. The initial operation and long-term performance of a novel desiccant based air conditioning system is reported by Hurdogan et al. [17]. They achieved almost 65% of the heating requirement of the system by utilizing a heat exchanger for pre-heating the regeneration air with exhaust air. The results of an experimental study by Uçkan et al. [18] on a desiccant based evaporative cooling system reveals that the system with fresh air stream meets 25% of total cooling load, and almost 34% and 75% of total heating and cooling demands can be supplied using regenerative heat exchangers, respectively. De Antonellis et al. [19] proposed useful correlations for the effect of different parameters on the effectiveness of a desiccant wheel based on experiments. La et al. [20–22] presented a new configuration that works based on indirect evaporative cooling instead of direct process in a two-stage configuration. They concluded that for subtropical climate, the COP of two-stage system with indirect evaporative cooler is higher than the single-stage system.

Numerous sensitivity analyses and thermodynamic studies are conducted to evaluate the efficiency of desiccant systems based on working parameters using the concepts of exergy and entransy. Exergy analysis is known as a proper tool to evaluate the sources of irreversibility in a desiccant cooling system configuration and the potentials for performance improvement. A thermodynamic study on a novel rotary desiccant cooling cycle is conducted by La et al. [22]. They concluded that utilization of integrated isothermal dehumidification and regenerative evaporative cooling process leads to more than three times higher exergy efficiency comparing with basic rotary desiccant cooling cycle and 20% lower regeneration temperature. Liu et al. [23] compared the performance of a one-stage and two-stage desiccant wheel systems from exergy point of view and with particular attention to the required heating source temperature. They concluded that the two-stage system has higher exergy efficiency due to lower exergy destruction in desiccant wheels. The study did not compare the economical and operational aspects.

Tu et al. [24,25] compared basic desiccant wheel system with irreversible and reversible processes using exergy concept. Their results revealed that multistage configuration and precooling system can reduce thermal exergy obtained by conditioned air. Gonçalves et al. [26] performed an exergy study on a desiccant cooling system to determine the performance improvement opportunities. They found that the overall energy and exergy efficiencies of the system are about 32.2% and 11.8%, respectively. Çarpinlioğlu