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The effects of operational conditions of the desiccant wheel on the performance of desiccant cooling cycles

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ABSTRACT

A desiccant cooling model is developed and applied to the ventilation, recirculation, makeup, and mix modes of the operating system. The mathematical model is based on the transient coupled heat and mass transfer and is used to predict the performance of the system under various design and operational conditions. The numerical results are validated using experimental measurements. The effects of the regeneration temperature and rotational speed of the desiccant wheel on the COP and output cycle temperature are investigated. The results show the availability of an optimum regeneration temperature and rotational speed in which the output cycle temperature has a minimum value. The optimum regeneration temperature and rotational speed are detected and shown on the Psychrometric charts. Calculating these values has a significant effect on the energy use of these cycles.

1. Introduction

Recently, evaporative and desiccant cooling technology systems are increasingly being developed as an alternative to the conventional vapor-compression systems. Desiccant cooling systems are heat driven cooling units. The basic component in the operation of the system is the use of a desiccant wheel in which air is dehumidified. Then, the resulting air is cooled in a heat exchanger and is further cooled by an evaporative cooler. Afterwards, the resulting cooled air is directed into the room. A heat supply is needed in the system to regenerate the desiccant. Renewable energy such as solar and geothermal heat as well as waste heat from any conventional fossil fuels can be used because a low grade heat, at a temperature of about 60–95 °C is needed.

The major advantages of desiccant cooling are:

- CFCs free; thus, the system is environmentally friendly.
- The system causes much electrical power savings, mainly in places where the thermal energy sources are easily found.
- Construction and maintenance are simple.

Because of these advantages, much effort is devoted in the research and application of desiccant cooling components, especially desiccant wheels [1–9]. Also, there are studies concentrated on the potential use of desiccant cooling systems in various locations in the USA and Europe [10–12]. Zhang and Niu [13] indicated that a chilled-ceiling combined with desiccant cooling could save up to 40% of primary energy consumption when compared to a conventional constant air volume system. Sand and Fischer [14] have shown that by designing a combined vapor-compression/active desiccant system in which the desiccant component is positioned after a conventional cooling coil, the dehumidification effectiveness of the desiccant is significantly enhanced. Dai et al. [15] conducted a comparative study of a standalone vapor-compression system (VCS), the desiccant associated VCS, and the desiccant and evaporative cooling associated VCS. They found an increase of the cooling load production by 38.8–76% and an increase of COP by 20–30%. Mazzei et al. [16] compared the operating costs of the desiccant and traditional systems using a computer simulation tool and predicted operating cost savings of about 35% and a reduction of thermal power up to 52%. Casas and Schmitz [17] showed that combining the desiccant technology, radiant floor cooling, borehole heat exchangers and CHP, resulted in considerable energy saving in comparison to conventional cooling systems. With this hybrid system, the energy demand is shifted from electrical to thermal energy and makes it possible to use waste heat for air conditioning in the summer. The energy consumption decreases by 70% or 30% if an electrical chiller would be used. Panaras et al. [18] estimated the achievable working range of an all-desiccant air conditioning system under specific comfort requirements. Vitte et al. [19] proposed a control strategy to improve the performance of hybrid desiccant evaporative cooling systems while satisfying thermal comfort. This strategy can be performed by calculating the differential of

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Nomenclature

A_{duct}	Cross-sectional area of desiccant wheel element (m^2)
C	Constant in sorption curve
C_p	Specific heat ($kJ\,kg^{-1}\,K^{-1}$)
COP	Coefficient of performance
D_{AK}	Ordinary diffusion coefficient ($m^2\,s^{-1}$)
D_{AO}	Knudsen diffusion coefficient ($m^2\,s^{-1}$)
D_h	Hydrodynamic diameter of a duct (m)
D_s	Surface diffusivity ($m^2\,s^{-1}$)
f	Fraction of desiccant in the wheel material
F	Constant in Eq. (6)
h	Convective heat transfer coefficient ($W\,m^{-2}\,K^{-1}$)
h_m	Convective mass transfer coefficient ($kg\,m^2\,s^{-1}$)
k	Thermal conductivity ($W\,m^{-1}\,K^{-1}$)
L	Length of duct (m)
Le	Lewis number
$\dot{m}$	Mass flow rate of air stream ($kg\,s^{-1}$)
N	Rotational speed (rpm)
P	Pressure (Pa)
P_{duct}	Duct perimeter (m)
Q_{sor}	Adsorption heat ($kJ\,kg^{-1}$)
R	Wheel radius (m)
T	Temperature (°C)
u	Velocity of air stream ($m\,s^{-1}$)
W	Water uptake in desiccant ($kg_{water}/kg_{dry\,desiccant}$)

Greek letters

α	Angle (rad)
α_0	Dehumidification angle (rad)
τ	Tortuosity factor
θ	Dimensionless angle (rad/2π)
ε	Effectiveness
ε_t	Total porosity
ϕ	Relative humidity
δ	Half thickness of duct (m)
ω	Humidity ratio ($kg_{moisture}/kg_{dry\,air}$)
ρ	Density ($kg\,m^{-3}$)

Subscripts

a	Dry air
d	Desiccant
DB	Dry bulb
WB	Wet bulb
EC	Evaporative cooler
eff	Effective
eq	Equilibrium content
g	Gas
HR	Heat recovery
max	Maximum value
min	Minimum value
out	Outlet
p	Process
R	Regeneration
v	Vapor
vs	Saturation vapor

enthalpy between outdoor and indoor air conditions. Heidarinejad et al. modeled a desiccant cooling system and applied it to the selected and important locations in a multi-climate country like Iran [20]. Pasdar Shahri et al. thermodynamically modeled desiccant cooling cycles for a specific wheel and investigated the effect of outdoor conditions on the performance of the cycles [21]. It was shown that these cycles are capable of providing thermal comfort in a wide range of outdoor conditions.

Most of the previous research did not consider a general mathematical model for desiccant cooling cycles, especially in mix and makeup mode. Also, the influences of the desiccant wheel operational conditions on the performance of the cycles and achieved output air temperature have not been fully investigated. This paper aims to analyze the influence of the important operation parameters of the desiccant wheel on the performance of the cooling systems. In addition, the results are presented in form of charts, which make the design procedure easier.

2. Principles of desiccant cooling cycles

As shown in Fig. 1, two air streams, process (state points 1–4) and regeneration (state points 5–9), are involved in the desiccant cooling process. Both air streams are mixed in a proper ratio of return and ambient air. As the processed air flows through the desiccant wheel, moisture is removed from the air stream. The desiccant wheel is restored to its dry state by exposure to the heated regeneration air stream as it rotates. Due to both the heat transfer in the regeneration side of the rotating desiccant wheel and the latent heat effect, the process air stream is heated during the dehumidification process. To reduce the energy consumption associated with the post-cooling, the processed air leaving the desiccant wheel is cooled via heat recovery. By heat recovery, heat is transferred from the processed air stream to the regeneration air. Consequently, the relatively cool incoming regeneration air is preheated, which reduces the energy needed to heat the wheel. In many systems, a direct evaporative cooler is also incorporated on the regeneration side, upstream of the heat recovery (Fig. 1). When the evaporative cooling unit is activated, the incoming regeneration air is cooled to a temperature at or near the wet bulb temperature depending on its effectiveness before entering the heat recovery. This improves the cooling performance. Furthermore, an evaporative cooler is used in the process air stream, which prepares cooled air for indoor comfort.

Four cycles are investigated in this study, namely ventilation, recirculation, makeup and mix mode. In the ventilation cycle, only return air is used in the regeneration air stream and ambient air is used in the process air. In the recirculation cycle, only return air is used in the process air and ambient air is used in the regeneration air. The makeup mode uses ambient air in both process and regeneration and no return air is used. Finally, in the mix mode a percent of return air is used in both the process and regeneration air stream.

3. Governing equations

3.1. Desiccant wheel

All types of cycles use a typical configuration of a desiccant wheel that rotates slowly and continuously between two counter flow processes. Generally, the wheel contains parallel small channels and desiccant material, typically with sinusoidal or hexagonal cross-sections (Fig. 2a and b). The process air flows through the channels and the desiccant material adsorbs moisture from the air. As the desiccant material picks up moisture, it becomes saturated and its surface vapor pressure rises. Then as the wheel rotates into the regeneration side, the hot regeneration air heats the desiccant, so the surface vapor pressure increases allowing the desiccant to release its moisture into the regeneration air. A schematic view of one channel in the desiccant wheel is presented in Fig. 2c.

To simulate a desiccant wheel the following assumptions are made: