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Study of purge angle effects on the desiccant wheel performance

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ABSTRACT

Desiccant cooling systems are spreading as a promising technology to reduce the energy consumption and environmental impact of conventional electric driven vapour compression systems for air conditioning purposes. Desiccant wheels (DWs) are the key component of the desiccant cooling systems which have received substantial attention. Desiccant Wheel if equipped with a purge section will show better performance, however in most cases purge section is not considered or a fixed purge angle is assumed. In this study, analysis of the purge angle effects on energy and dehumidification performances of DW is carried out and a novel optimal purge angle definition is introduced. A mathematical model is developed and validated in order to model the coupled heat and mass transfer processes in a DW. In addition, the effect of process and regeneration air velocities, regeneration air temperature, rotational speed, desiccant layer thickness, channel length (DW length) and channel hydraulic diameter on the purge angle are studied. The results showed that purge angle is a function of outlet air humidity profile, while the process air velocity as an operating parameter and channel length as a design parameter presented the most substantial effect on the profile. Furthermore, implementation of the optimal purge angle, improves the DW coefficient performance (DCOP) and results in desired conditions of outlet process air without the necessity of substantial increase in the DW size.

1. Introduction

In air conditioning systems interacting with vapour compression system (VCS), the reduction of supply air humidity ratio is achieved through cooling dehumidification, performed via cooling the air below its dew point temperature. The cooling dehumidification is an unfavourable process due to high electricity requirement and consistent CO_2 emissions to the atmosphere. Furthermore, cooling dehumidification may provide a low indoor air quality and thermal comfort, as temperature and humidity of supply air cannot be controlled separately. Desiccant cooling systems (DCS) is considered a feasible solution, where the latent and sensible loads are provided by the desiccant (liquid or solid) and a cooling unit such as direct/indirect evaporative cooler or cooling coil, respectively [1,2]. The main advantages of DCS are lower refrigerating capacity on cooling unit and possibility of using low temperature heat, i.e. wastes or renewable energy for regeneration of desiccant [3,4].

Solid desiccants are used in different technological arrangements and desiccant wheel (DW) is the widely applied configuration. In recent years, DWs have been examined extensively in both numerical and experimental studies. A number of researches have focused on DW modelling, parameter analysis, and its performance assessment as well as energy, exergy and dehumidification performance assessment [2,5–9]. The mathematical model was used to analyse the effect of different parameters of the DW such as temperature, humidity, pressure and rotational speed [10–12]. The effect of desiccant matrix properties on the performance of rotary dehumidifiers is also investigated by several researchers [13–15]. Although many studies have been conducted regarding DW operation parameters, few have considered purge air as a parameter.

The separation of process air stream at the exit of rotary dehumidifier into two streams results in purge (hot and relatively high humidity) and process (lower temperature and humidity ratio) air streams. Since the hot fraction of the air (purge air) is separated, the remaining process air stream has a lower temperature and humidity ratio (compared to the initial process stream) [16]. The purge air flow after exiting the DW can be mixed with the ambient air, then heated up in order to regenerate the DW. The purge sec-

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Nomenclature

a	channel height (m)
b	channel width (m)
c_p	specific heat at constant pressure ($J\,kg^{-1}\,K^{-1}$)
c_{pt}	specific heat of wet desiccant ($J\,kg^{-1}\,K^{-1}$)
d_e	hydraulic diameter (m)
D_G	combined ordinary and Knudson diffusivity ($m^2\,s^{-1}$)
D_S	surface diffusivity ($m^2\,s^{-1}$)
h_c	convective heat transfer coefficient ($W\,m^{-2}\,K^{-1}$)
h_{fg}	specific latent heat of vaporization ($J\,kg^{-1}$)
k	thermal conductivity ($W\,m^{-1}\,K^{-1}$)
K_y	mass transfer coefficient ($kg\,m^{-2}\,s^{-1}$)
L	channel length (m)
$\dot{m}$	mass flow rate ($kg\,s^{-1}$)
N	desiccant wheel rotational speed (revolutions per hour) (Rph)
p_0	ambient pressure (Pa)
q_{st}	isosteric heat of adsorption ($J\,kg^{-1}$)
qr	regeneration heat rate ($J\,s^{-1}$)
Q	air flow rate ($m^3\,h^{-1}$)
t	time (s)
T	temperature (K)
$\overline{T}_a$	average temperature (K)
u_a	air velocity (m/s)
W	desiccant water content ($kg\,kg^{-1}$)
y	radial coordinate
Y_a	air humidity ratio ($kg\,kg^{-1}$)
$\overline{Y}_a$	average humidity ratio ($kg\,kg^{-1}$)
Y_d	humidity ratio of air in equilibrium with desiccant ($kg\,kg^{-1}$)
Z	axial coordinate

Greek symbols

Δ	difference
Δ	desiccant layer thickness (m)
ε_t	mass fraction of sorbent
η	fraction of phase change energy entering into air
θ	desiccant wheel angle
ρ	density ($kg\,m^{-3}$)
ϕ_d	relative humidity of air in equilibrium with desiccant
Φ	wheel diameter (m)
Γ	ratio of channel height to its width
μ	viscosity ($kg\,s^{-1}\,m^{-1}$)

Subscripts

0	reference value
a	air
ad	air in equilibrium with desiccant
ads	adsorption section
d	desiccant
eff	effective purge angle
i	process section (i = p) or regeneration section (i = r)
l	liquid water
mixed	Mixture of ambient air and outlet purge air
opt	optimal purge angle
PI	process inlet
PO	process outlet
purge	purge section
RI	regeneration inlet
RO	Regeneration outlet
s	desiccant surface
v	water vapour
out	outlet

tion addresses two problems of DWs: carryover and high desiccant temperature in the process [17,18].

A recent study by Yadav and Yadav [19] investigated the purge sector for clockwise and anticlockwise rotation of desiccant wheel using a developed one dimensional (1-D) model of a DW. They studied the effect of different parameters as well as purge angle (of 5–20°) on inlet-outlet humidity ratio difference. The results of a previous study [14] demonstrated that using purge air as regeneration air of the DW performs better in terms of moisture removal, while causes an increase in temperature of the outlet process air.

The structure of enthalpy wheels (EWs) is similar to the DW, but the application is different. Enthalpy wheels with a purge section were also investigated by Ruan et al. [20] developing a 1-D transient heat and mass transfer model. The results indicated the necessity of an optimum wheel depth (length) and rotation speed to achieve maximum performance for EWs with purge air. Most of the researchers have considered fixed purge angle, except Golubovic et al. [16], who defined effective purge angle as a function of several DW operating conditions and investigated the performance of DW with and without heated purge. Heated "effective purge angle" showed overall positive effect on the performance of the rotary dehumidifier.

Recently, the application of DCS has been receiving more attention as an efficient method for controlling moisture content of the air. Therefore, strong research efforts are required to improve the performance of DW, which is the key component of DCS. The aim of this research is to analyse the DW purge angle, considering energy benefits and dehumidification performance. A new optimal purge angle definition is introduced as the core of this research which is compared to the conventional definition (effective purge). A two dimensional unsteady state modelling is developed and validated in order to model the coupled heat and mass transfer processes in a DW. The mathematical model is applied to analyse the effect of operating parameters, i.e. process and regeneration air velocities, regeneration air temperature, rotational speed and design parameters namely desiccant layer thickness, channel length (DW length) and channel hydraulic diameter, on the purge angle. Furthermore, the dehumidification and energy performance of the purge angle are investigated in detail. Results of this research can be insightful for DW and EW design and operation with higher performance in terms of dehumidification performance and energy consumption.

2. Methodology

2.1. Desiccant wheel modelling

DWs are rotors made of inert material coated with an adsorbent. The channels of the DW are designed as "honeycomb" that has several advantages, i.e. maximum superficial contact area, low pressure drops, low weight and high structural durability. The rotational speed is relatively low, typically in the range of 5–60 revolutions per hour (Rph) [12]. DWs are typically crossed by two air flows, including the process air and the regeneration air. The former is dehumidified to meet the latent loads and the latter is heated up to a suitable regeneration temperature, ensuring