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Investigation of geometry effects of channels of a silica-gel desiccant wheel

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Abstract

Desiccant evaporative cooling systems are potential environment- friendly alternative to energy-intensive vapour compression chillers. They operate on an open heat-driven cycle consisting of a combination of a dehumidifier, a sensible heat exchanger and evaporative coolers. A desiccant wheel is the heart of the heat-driven cooling system and it uses a solid desiccant for dehumidification. The desiccant material is coated onto the supporting rotor structure. The matrix consists of multiple channels in the direction of the axis of the wheel rotation. The flow passage of the desiccant wheel is usually of sinusoidal shape. The performance of the whole cooling system largely depends on the dehumidification ability of the desiccant wheel and mathematical models are an effective tool to predict the heat and mass transfer behaviour of moisture transport in air dehumidification applications with rotary desiccant wheels. In this paper, a heat and mass transfer model incorporating both solid-side and gas-side resistances is presented and compared with experimental data. This model is used to investigate the effect of the geometry and shape of element channels on the transport process and the performance of the wheel.

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Keywords: Airconditioning; Desiccant; Desiccnat wheel; adsorption.

1. Introduction

Desiccant evaporative cooling systems are potential environment-friendly alternative to energy-intensive vapour compression chillers. They operate on an open heat-driven cycle consisting of a combination of a dehumidifier, a

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sensible heat exchanger and evaporative coolers. In this environmentally-friendly system, the dehumidification of air to a low humidity level is done using a desiccant wheel so that evaporative cooling or other cooling options can be employed effectively to reduce the air temperature.

A desiccant wheel is the heart of the heat-driven cooling system and it uses a solid desiccant for dehumidification. The desiccant material is coated onto the supporting rotor structure. The matrix consists of multiple channels in the direction of the axis of the wheel rotation. The wheel constantly rotates through two separate air streams, the supply air which is dried by the desiccant and hot regeneration air which reactivates the desiccant. The regeneration and supply air sides are separated by clapboard. The flow passage of the desiccant wheel is usually of sinusoidal shape.

The components of a desiccant dehumidifying cassette include a desiccant wheel with a matrix consisting of supporting material and desiccant material, clapboard, wheel case, driving motor and hot regeneration air stream as well as the supply air to be dehumidified. The desiccant wheel used for dehumidification is quite similar to those commonly employed in heat recovery, but it rotates at lower speeds (10-25 revolutions per hour (rph)) [1]. This rotational speed allows the desiccant to adsorb more moisture and minimizes the amount of heat carried over from the hot reactivation air into the supply air.

Nomenclature

Y_g	Humidity ratio of air inside the control volume 1 (kg/kg)	cp_g	Isobaric specific heat capacity of air (J/kg/K)
T_g	Temperature of air inside the control volume 1 (K)	cp_d	Specific heat capacity of desiccant (J/kg/K)
Y_d	Humidity ratio of air inside the control volume 2 (kg/kg)	c_t	Combined specific heat capacity (J/kg/K)
T_d	Temperature of air inside the control volume 2 (K)	α	Heat transfer coefficient (W/m^2K)
W_d	Water vapour content of desiccant (kg/kg)	u_g	Velocity of supply air and regeneration air (m/s)
ρ_g	Density of air (kg/m^3)	Da	Effective diffusion coefficient for ordinary and Knudsen diffusion
ρ_d	Density of desiccant (kg/m^3)	Ds	Surface diffusion coefficient
D_h	Hydraulic diameter (m)	q_a	Heat of adsorption (J/Kg)
Pi_n	Perimeter of the channel (m)	β	Mass transfer coefficient (kg/m^2K)
φ_d	Relative humidity of air in the control volume 2		

2. Model Development

The desiccant wheel can be considered as a set of identical axial channels coated with desiccant. The differential equations that represent these transport mechanisms will generally be set up to describe a single desiccant-coated flow channel, traversing through the respective supply and regeneration air streams in a 360° circular path [2]. Even though the heat and mass transfer within the wheel will be in all three dimensions, simplifications are needed to enable the analysis [3,4]. Consequently, the following assumptions are made. In order to investigate the significance of the two resistances categorised as gas-side and solid-side resistances, two different models, namely the gas-side resistance (GSR) model and the gas and solid-side resistance (GSSR), are developed

As the name indicates, a gas-side resistance (GSR) model of the desiccant wheel considers only the convective resistance in the bulk flow and so the resistances due to heat conduction and mass diffusion in the wheel are neglected [5-9].

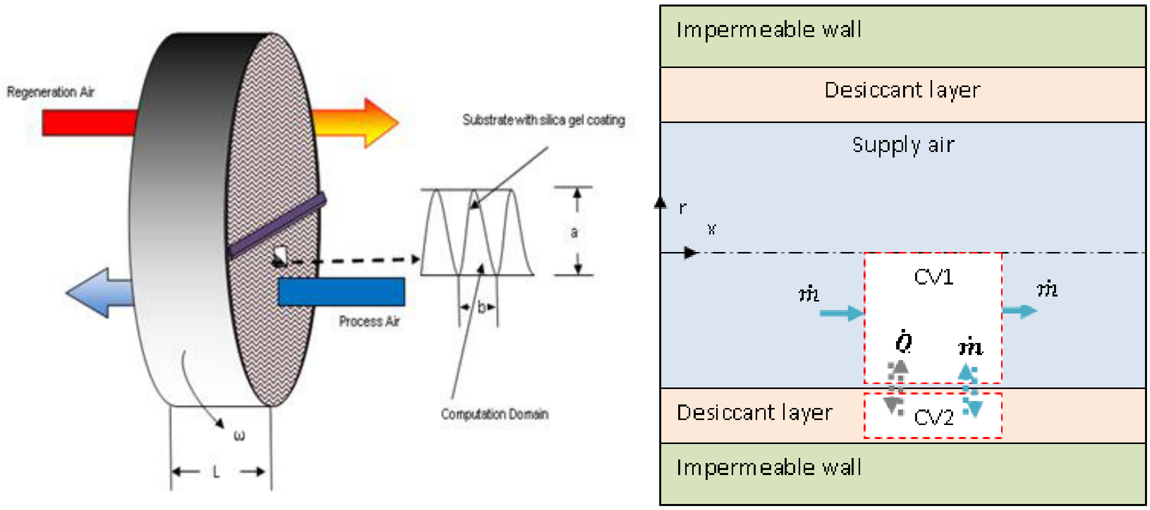

Fig. 1. Desiccnat wheel and Channel cross-section with control volume for modeling

The control volume is separated into two parts: one is the air passage and the other one is the desiccant layer. Figure 1 shows a desiccant wheel and the computation/domain of the model. The governing equations can be derived by using the principle of the conservation of mass and heat in these control volumes [10]. All these equations will have a mass/energy storage term, the rate of mass/energy variation term and source terms which will differ according to the resistances included and the dimensions of the heat and mass transfer considered.

Based on the above assumptions, the mass and energy conservation equations can be derived. Here Yg and Yd represent the humidity ratio in CV1 and CV2, and Tg and Td represent the temperature in these control volumes. Wd is the mass of water vapour adsorbed per unit mass of the desiccant and is called the uptake of water into the adsorbent.

With these assumptions, the mass and energy balance equations for the air and desiccant control volumes can be derived.

Mass balance in CV1:

$$\frac{1}{u_g} * \frac{\partial Y_g}{\partial t} + \frac{\partial Y_g}{\partial x} = \frac{4\,\beta}{u_g\,D_h}\left(Y_d - Y_g\right) \tag{1}$$

Energy balance in CV1:

$$\frac{1}{u_g} * \frac{\partial T_g}{\partial t} + \frac{\partial T_g}{\partial x} = \frac{4\alpha}{u_g\,D_h\,c_{pg}}(T_d - T_g) \tag{2}$$

Mass balance in CV2:

$$\rho_g \frac{\partial Y_d}{\partial t} + \rho_d \frac{\partial W_d}{\partial t} = \rho_g\, \mathrm{D_a} \frac{\partial^2 Y_d}{\partial t^2} + \rho_d\, \mathrm{D_s} \frac{\partial^2 W_d}{\partial t^2} + \frac{\beta \rho_g P_{in}}{A_d}(Y_g - Y_d\ ) \tag{3}$$

Energy balance in CV2:

$$\rho_d \ c_t \frac{\partial T_d}{\partial t} \ = \ \lambda_d \ \frac{\partial^2 T_d}{\partial x^2} + \ \frac{\alpha P_{in}}{A_d}(T_g - T_{d)} \ + \ \ q_a \rho_d \ \frac{\partial W_d}{\partial t} \quad (4)$$

Equations 1,2,3,4 and 4 will be the governing equations for the GSSR model. The governing equations have five unknown variables, Yg, Yd, Wd, Tg and Td. To solve these simultaneous equations, one of the variables has to be eliminated. This can be done using by relating the equilibrium humidity ratio of air, Yd, to the water content, Wd, and the temperature of the desiccant, Td. Therefore, an equilibrium isotherm relationship of silica gel can be used. Other auxiliary equations and boundary conditions are as specified in the earlier publication [6,10].

3. Results

The governing equations for the gas-side resistance (GSR) model and the gas and solid-side resistance (GSSR) model are solved using COMSOL Multiphysics which is finite element analysis, solver and simulation software for coupled partial differential equations. The following input data are used for the simulation. Since the supply air and regeneration sections are assumed to be equal, angles for both sections will be 180o and the ratio between the area of supply air section and regeneration air (SR ratio) is 0.5.

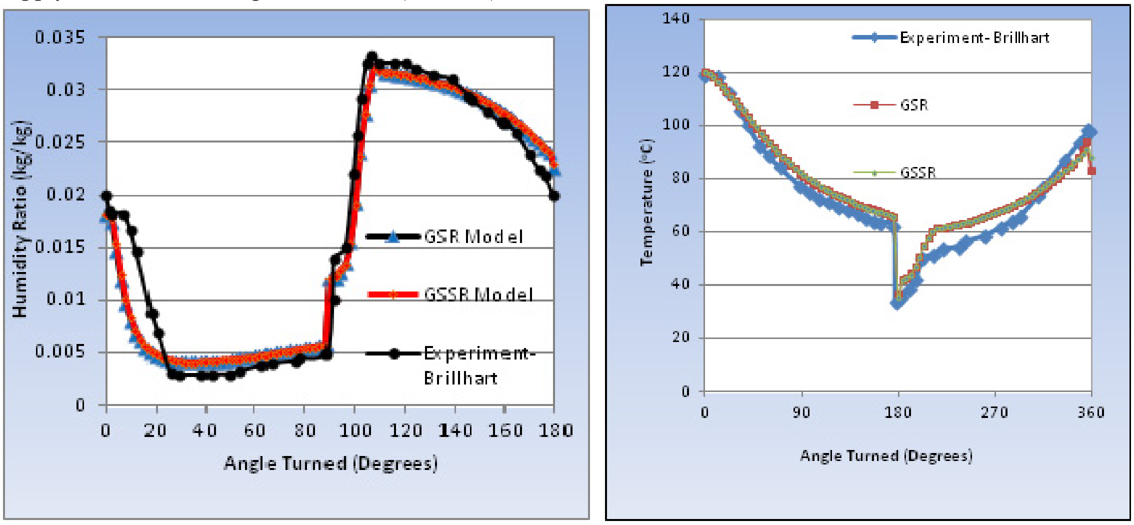

Fig. 2. Comparison of humidity ratio and Temperature with Brillhart's experimental results.

In Figure 2, the outlet humidity ratio and temperature results of the model are compared with Brillhart's experimental results [11]. It can be observed that the model has good agreement with the experimental outlet humidity ratio and temperature. As in the case of previous studies [12,13], the deviation of the humidity ratio curve from the experimental value may be attributed to greater experimental uncertainties at the beginning of the dehumidification period. The figures also demonstrate that, at the selected operating conditions, the effect of solid-side resistance is negligible.

4. Channel shape

The geometry and shape of element channels have significant impact on the transport process in a desiccant wheel and for better performance of the wheel [14]. There are a few studies conducted on the effect of channel shape on the performance of the wheel. Zhiming Gao conducted a study on the effect of channel shape, but the theoretical model ignores most of the solid-side resistances. Besides that, the method used for the determination of the Nusselt number was not based on laminar the flow. So, more investigation is needed to obtain detailed information on heat and mass transfer in ducts with different cross-sectional geometries. At present, most manufacturers of the desiccant wheels use sinusoidal channels. In this section, the mathematical model of desiccant wheel presented in the chapter 3 is used to predict the effect of passage shape and the geometrical size of the matrix on the performance of a desiccant wheel. The determination of heat transfer coefficients based on the hydraulic diameters generally give satisfactory results [15]. Figure 3 shows the channel shapes considered in this study. For flow through these kinds of channels, there will be different characteristics with regards to the hydraulic diameter and consequently the Nusselt number and friction factor [16].\

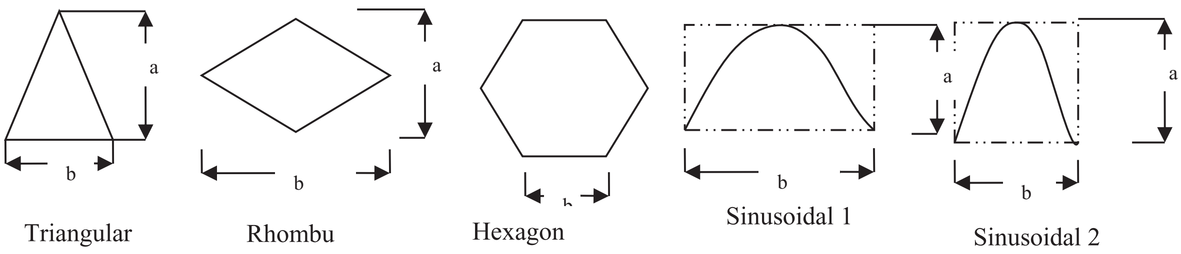

Fig. 3. Channel shapes.

Table 1 shows the different parameters and their calculations for various channels. In this study, for all channels, the area is kept equal and is assumed to be 3.89 mm2 which is areas of a typical sinusoidal channel of a desiccant wheel. So from this, the shape parameters are calculated. The hydraulic diameter is determined from area cross-section A and the perimeter P by using the following formula:

$$D_h = \frac{4A}{P} \tag{5}$$

Table 1. Details of Channel shapes considered

Channel Shape	Area	Area mm²	a mm	b mm	Perimeter mm	Dh mm
Sinusoidal 2	$A=2.a.b/\pi$	3.8977	1.7500	3.5000	8.5500	1.8235
Rectangular	A=a.b	3.8977	1.3960	2.7920	8.3760	1.8614
Rhombus	A=a.b/2	3.8977	2.2273	3.5000	8.2972	1.8791
Sinusoidal 1	$A=2.a.b/\pi$	3.8977	2.4749	2.4749	8.2296	1.8945
Square	$A=a^2$	3.8977	1.9743		7.8971	1.9743
Triangular	A=a.b	3.8977	1.1136	3.5000	7.6486	2.0384
Hexagonal	$A=a^2.3.sqtr(3)/2$	3.8977	1.2248		7.3491	2.1215
Circular	$A=\pi.a^2$	3.8977	1.1136		7.0000	2.2273

Fig. 4 shows the moisture removal obtained for channels with different shapes. It is clear from the figure that the channels with triangular, sinusoidal and rectangular cross-sections have better dehumidification performance than the other channels with hexagonal, circular, and square shapes. Among the top channels, the triangular channel is the best, followed by the sinusoidal channel with aspect ratio 2:1 and then the rectangular channel. This can be attributed to the combined effect of the change in the hydraulic diameter and in the Nusselt number for different channels. The top three shapes have a smaller hydraulic diameter and being smaller have higher velocities which results in higher heat transfer coefficients.

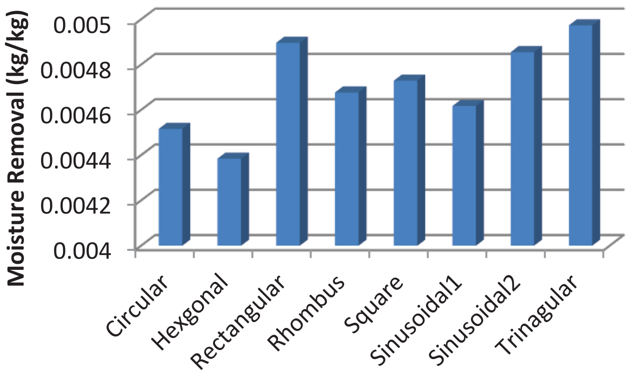

Fig. 4. Moisture removal for different channel shapes.

5. Conclusions

The numerical model of a counter flow desiccant wheel is developed and the results have been compared with published experimental data which showed close agreement. Using this model, different geometries of channels are investigated. The channels with triangular, sinusoidal and rectangular cross-sections have better dehumidification performance than the other channels with hexagonal, circular, and square shapes. Among the top channels, the triangular channel is the best, followed by the sinusoidal channel with aspect ratio 2:1 and then the rectangular channel. This can be attributed to the combined effect of the change in the hydraulic diameter and in the Nusselt number for different channels. The top three shapes have a smaller hydraulic diameter and being smaller have higher velocities which results in higher heat transfer coefficients.

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