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Simulation of Adsorption Process in a Rotary Solid Desiccant Wheel

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Abstract. Solid desiccant air dehumidifier system is widely being used to supply dry air for many industrial processes. As humid atmospheric air flows through the system, the water vapor in the air is adsorbed by the desiccant material, resulting in dry air leaving the system. The performance of the system is usually determined through experimental work. However, this practice is often complex to carry as it requires precise measuring instruments, time consuming and it can be labor intensive too. A numerical solution has become a preferred choice to determine the performance of the system. The goal of this work is to determine the moisture removal capacity (MRC), thermal effectiveness (ε_{th}) and dehumidification effectiveness (ε_{DW}) of a solid desiccant wheel of an air dehumidifier system by a validated numerical method. A representative two-dimensional model of the air channel was developed and meshed using triangular elements. Flow simulations were carried out under a transient condition. The numerical model was validated by comparing the simulation results at the outlet of the air channel with similar results of experimental data obtained from the literature. The relative errors were found to be about 1.05% for air temperature and 8% for air humidity, indicating that the numerical model has a good capability of estimating the desiccant material performance. It was also found that the MRC, ε_{DW} and ε_{th} are about 22 g/s, 76% and 43% respectively.

INTRODUCTION

Solid desiccant air dehumidifier (SDD) are widely used in many industries such as in Heating, Ventilation, Air-Conditioning (HVAC) system, foods, pharmaceutical, and battery production. It supplies dry and warm air required by the processes. When used in the HVAC system, the air dehumidifier offers a better humidity control, more efficient latent load removal, and lower electricity cost compare to conventional system. An important component in the SDD system is the rotary solid desiccant wheel (RSDW). It is essentially specially constructed air flow channels the surfaces of which are coated with the desired solid desiccant material. Engineers and researchers are usually interested to find out the air temperature and air humidity at the outlet of the system. In addition, it is important to know the dehumidification and thermal effectiveness of the system. Traditionally, these are accomplished through experimental works. However, this practice is often complex to be carried out due to the requirement of precise measuring instruments, time consuming and labor intensive. Plus, the heater unit required to produce a high temperature regeneration air consumes a considerable electrical energy input.

Many researchers have been working on the parametric study on the RSDW performance criteria by experiments and numerical modelling. Fu *et al.* [1,2] studied the effect of material properties on heat and mass transfer in honeycomb

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Nomenclature

A	Cross-sectional area of air channel (m^2)
C	Constant in adsorption curve
c_p	Specific heat (kJ/kg.K)
D_v	Diffusivity (m^2/s)
D_h	Hydraulic diameter of air channel (m)
f	Desiccant content
h	Convective heat transfer coefficient (kW/m^2.K)
k	Convective mass transfer coefficient (m/s)
k_m	Internal mass transfer coefficient based on moisture content difference (1/s)
k_d	Thermal conductivity of desiccant (kW/m.K)
Nu	Nusselt number
q_{st}	Adsorption heat (kJ/kg)
Sh	Sherwood number
t	Time (s)
T	Temperature (K)
w_{max}	Maximum water uptake of desiccant (kg/kg)
x	Axial coordinate (m)
y	Height coordinate (m)

Greek letters

φ	Relative humidity
ε_{DW}	Dehumidification effectiveness
ε_{th}	Thermal effectiveness
ε	Porosity
ρ	Density
ω	Moisture content

Subscript

a	Air
d	Desiccant
ds	Desiccant channel
eq	Equilibrium
max	Maximum

-type adsorbent wheels for total heat recovery while Zhang *et al.* [3] on RSDW using two-dimensional (2D) air channel model. Cheng *et al.* [4] suggested that the alternative way to experimental work is by using a numerical modelling approach. This approach is less complex, much cheaper, less time consuming and less labor intensive. For simplification, many researchers used a single channel model to represent the airflow through the desiccant wheel [3,4]. Yadav *et al.* [5] stated it may because of geometric similarity and to avoid prohibitive computation costs, it is reasonable to represent the multiple channels in the desiccant wheel by a single channel. The numerical approach can avoid all the drawbacks that occur in experimental work as suggested by Cheng *et al.* [4]. In addition, a parametric study can be carried out for improving the performance of such system. Kamsah *et al.* [9] has studied the effects of regeneration air inlet temperature and process air outlet velocity on the thermal effectiveness, dehumidification efficiency and MRC of a desiccant wheel system. They found that both thermal effectiveness and dehumidification efficiency decrease with the increase in the regeneration air inlet temperature. Therefore, it is significant to perform a numerical solution to replace the experiment method and the model can be simplified using 2D geometry. The objective of this study is to determine the moisture removal capacity (MRC), thermal effectiveness and dehumidification effectiveness of a solid desiccant wheel made of silica gel B material. A numerical method was used to develop a 2D model of a single air channel that represents a flow path of the process air through the solid desiccant material. Flow simulations were carried out under a transient condition to predict the average temperature and humidity of process air at the outlet of the channel. The numerical simulation steps include creating the 2D geometry of the air channel, meshing the domain, setting up the boundary and initial conditions and finally specifying the solver settings. The model was validated by comparing the numerical simulation results with experimental data obtained from the literature.

ROTARY DESICCANT WHEEL

Figure 1 illustrates a schematic diagram of a solid desiccant wheel of an air dehumidifier system. It consists of a desiccant material constructed in a form of a wheel that rotates at a low speed, an air heater and a drive motor. The wheel comprises of a process air section and a regeneration air section. The humid process (ambient) air flows through the process air section during which the moisture content of the air will be adsorbed by the desiccant material. The temperature of this air rises slightly since the adsorption process releases heat energy. As a result, the process air leaves the desiccant wheel with lower humidity and slightly higher temperature. On the other hand, a hot regeneration air flows through the regeneration section of the wheel, usually in an opposite direction to the process air. As it happens, the water vapor that is sitting on the desiccant material surface is absorbed by the hot air. This absorption process also involves heat transfer and as a result, the regeneration air exits the wheel with higher humidity and slightly lower temperature. The regeneration section of the desiccant wheel becomes dry and ready for the new process air to flow pass through it. Since the desiccant wheel is rotating slowly, the above sequences of processes continue [6].

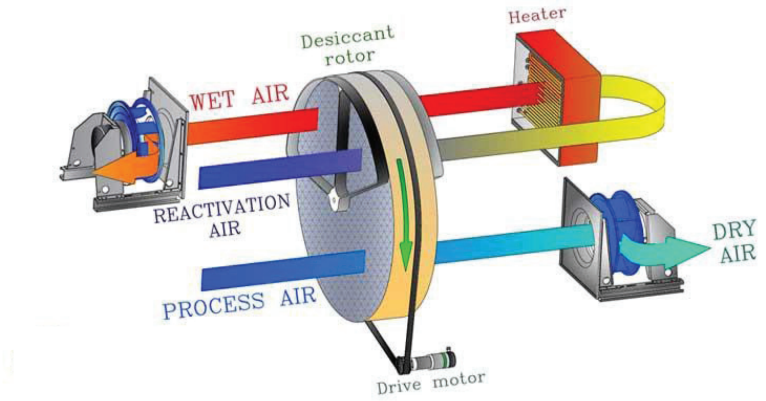


FIGURE 1. A schematic diagram of a solid desiccant wheel air dehumidifier system [7]

MODEL OF ADSORPTION PROCESS

The mathematical model of the adsorption process in a 2D air channel geometry was reported by Zhang *et al.* [3]. The governing equations comprise of mass and energy conversation equations which are,

$$\frac{\partial}{\partial t}(\omega_a) + u\,\nabla \cdot (\omega_a) = \frac{4k}{D_h}(\omega_{ds} - \omega_a) \tag{1}$$

$$\rho_a c_{pa}\frac{\partial}{\partial t}(T_a) + u\rho_a c_{pa}\nabla \cdot (T_a) = \frac{4h}{D_h}(T_{ds} - T_a) \tag{2}$$

The second term of Eqn. (1) represents the convection-diffusion process while the term on the right-hand side represents the water vapor transfer to the adsorbent layer. The second term of Eqn. (2) describes a convective heat transfer due to fluid flow while the term on the right side represents the heat transfer to adsorbent layer. The convective heat and mass transfer coefficient denoted as *h* and *k* respectively are calculated using Eqn. (3a) and Eqn. (3b) respectively.

$$h = \frac{Nu\,k_a}{D_h} \tag{3a}$$

$$k = \frac{Sh\,D_{va}}{D_h} \tag{3b}$$

The value of *Nu* and *Sh* for sinusoidal channel shape are 2.2 and 2.05 respectively [3]. The mass conversation and energy balance in the solid desiccant are given by the following Eqns. (4) and (5)

$$(1-\varepsilon)\rho_d\frac{\partial}{\partial t}(\omega_d) + \rho_d\nabla \cdot (-D_{vs}\nabla\omega_d) = -\rho_d k_m(\omega_{eq} - \omega_d) \tag{4}$$

$$\rho_d c_d\frac{\partial}{\partial t}(T_d) + \nabla \cdot (-k_d\nabla T_d) = q_{st}\rho_d k_m(\omega_{eq} - \omega_d) \tag{5}$$

The second term of Eqn. (4) describes the mass diffusion process that occurs in the solid desiccant. The right-hand term of the equation represents the mass adsorption rate. In Eqn. (5) the second term describes the heat conduction that occurs in the solid desiccant material and the term on the right side represents the rate of adsorption heat. The equilibrium water uptake in the desiccant material, ω_{eq} and the relative humidity, φ at atmospheric condition are given by Eqn. (6).

$$\omega_{eq} = \frac{f\omega_{max}}{(1-C+\frac{C}{\varphi})} \tag{6a}$$

$$\varphi = \omega_d(10^{-6}e^{5295/T_d}) \tag{6b}$$

The boundary conditions at the inlet of the air channel are given by Eqns. (7a) and (7b) while the initial conditions at time $t = 0$ are given by Eqns. (7c) and (7d), as follows:

$$T_a|_{x=0} = T_{a,inlet}, \tag{7a}$$

$$\omega_a|_{x=0} = \omega_{a,inlet}, \tag{7b}$$

$$T_a|_{t=0} = T_{a,ambient}, \tag{7c}$$

$$\omega_a|_{t=0} = \omega_{a,ambient} \tag{7d}$$

NUMERICAL SIMULATION METHODOLOGY

Figure 2 shows the simplified geometry of the single air channel in the desiccant material. The dimension of channel length, L is 100 mm, the channel height, h is 1.8mm and desiccant thickness, t is 0.15mm. The driving force for the adsorption process is the humidity gradient between the flowing air and the desiccant material. The adsorption process releases heat because the moisture in the air condenses to become water vapor that would fall on the surface of the desiccant material. This condensation process releases heat energy. The numerical simulation of air flow through this channel and the adsorption process was assumed to be in transient condition. The diffusion of water vapor through the solid desiccant material was not considered in the simulation. The desiccant material chosen in this study is silica gel B, a similar material used by Zhang *et. al.* [3]. The important properties of this material are listed in Table 1. Radiation effects and body forces were also neglected to simplify the numerical simulation process. The specific heat and thermal conductivity of desiccant materials were assumed constant. The channel wall was considered adiabatic.

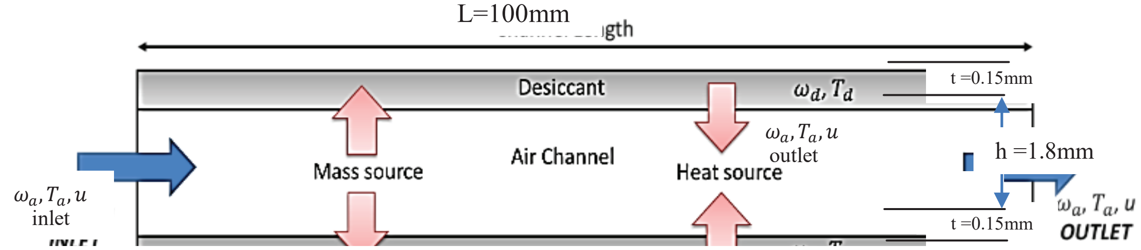
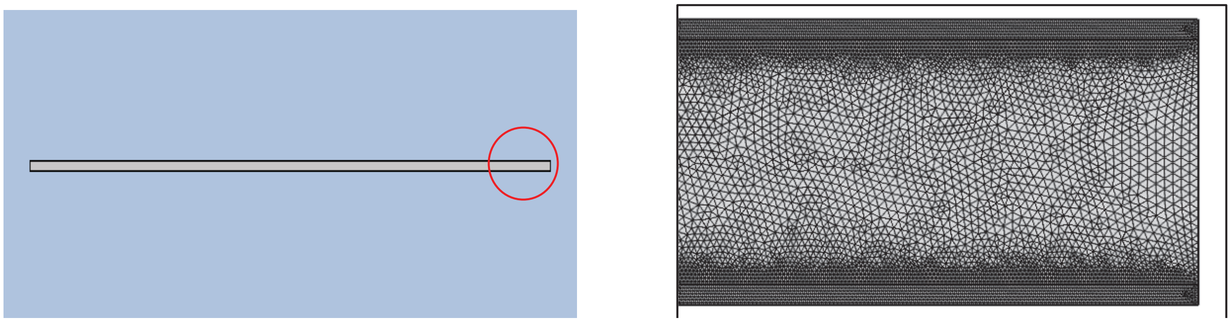


FIGURE 2. Representative 2D model of a single air channel for the desiccant material

In Fig. 3(a), a 2D geometry which represents the air and desiccant channels was constructed and meshed using a Multiphysics software. Some parameters and variables are defined in the software. Three physics model were chosen to solve the equation which are, transport concentrated species, heat transfer in fluid and convection-diffusion equation. The rectangular shape geometry was discretized using triangular elements. The meshing at desiccant channel was refined as shown in Fig. 3(b). A PARDISO solver has been chosen as a solution method. Since the governing equations are nonlinear and coupled to one another the solution process involves iterations wherein the entire set of governing equations is solved repeatedly until the solution converges. A segregated step method was used to solve each of the physics model. The numerical software was used to carry out flow simulation in a transient mode. The time step chosen was 1 second for a total time step of 300.

Validation of Numerical Model

The numerical model was validated by comparing the time-variation of moisture and air temperature at the outlet of the channel with the experimental results of Zhang *et al.* [3]. For this purpose, the dimensions of the air channel, the boundary conditions and the properties of the desiccant material were made the same as those described by Zhang *et al.* [3]. The input parameters for the numerical simulation and the inlet conditions of the process air are shown in Table 1 and Table 2, respectively. The cross-section of the air channel is honeycomb (sinusoidal) and the desiccant material was silica gel B. Zhang's experiment was done in alternate manner between the process and regeneration air cycle. Each cycle took 300 seconds to complete. However, in this study numerical flow simulation was only done for the adsorption process. Therefore, the results comparison with Zhang *et al.* [3] might not give a very good agreement. Also, the regeneration air temperature could affect the properties of the process air temperature at the outlet section of the desiccant wheel, as described by Kamar *et al*. [8]. However, because of the simplification made, the effects of regeneration air temperature on the properties of the process air at the channel exit was not considered in this study. A complete cycle of the simulation would comprise of three processes namely adsorption, regeneration and a combined. The results of the adsorption simulation are used as the initial conditions for the regeneration process simulation. The outlet air temperature and humidity at the outlet of the air channel are utilized as the boundary conditions for the third cycle, i.e. the combined process simulation. Obviously, the outcomes of the complete simulation will be different than those obtained from the simulation carried out in this work.



(a) (b)

FIGURE 3. (a) A 2D numerical model of the air channel and (b) meshing of the air channel (a close-up view of the circled section of the air channel)

TABLE 1: Input parameters for the numerical flow simulation

	Specifications		Specification		Specifications
Channel length, L (m)	0.1	c_d(kJ kg^{-1} K)	0.921	ε	0.5
Channel shape passage	Sinusoidal	k_d(k Wm^{-1} K)	1.98×10^{-4}	C	1.1
Channel height, h (mm)	1.8	ρ_d(kg/m^3)	790	f	0.8
q_{st}(kJ/kg)	2362	ω_{max} (kg/kg)	0.4	k_m(1/s)	0.32

TABLE 2: Inlet conditions of process air

Operating Parameters	Specification
Process air inlet moisture content, $\omega_{a,inlet}$(g/kg dry air)	23.25
Process air inlet velocity, u (m/s)	1
Process air inlet temperature, $T_{a,\text{ inlet}}$ (K)	303

Performance of the Desiccant Wheel System

This study is aimed to evaluate the performance of the solid desiccant wheel system namely its moisture removal capacity (MRC), dehumidification effectiveness, and thermal effectiveness. The MRC is given by

$$MRC = \rho_a uA(\omega_{a,inlet} - \omega_{a,out}) \tag{8}$$

The dehumidification effectiveness, ε_{DW} and thermal effectiveness, ε_{th} of the desiccant wheel are respectively given by,

$$\varepsilon_{DW} = \frac{\omega_{a,inlet}-\omega_{a,out}}{\omega_{a,inlet}-\omega_{a,outideal}} \tag{9}$$

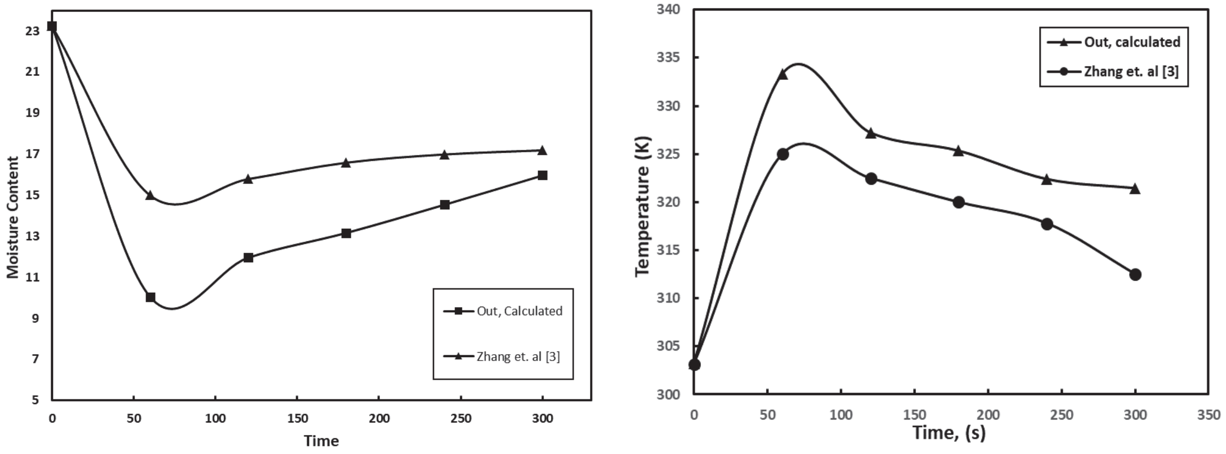
$$\varepsilon_{th} = \frac{T_{a,out}-T_{a,inlet}}{T_{reg}-T_{a,inlet}} \tag{10}$$

RESULTS AND DISCUSSIONS

Temperature and Moisture Variation at Outlet Section

Figure 4 shows the variation of moisture and process air temperature with time, at the outlet section of the air channel model (x = 100 mm). The calculated values are the average of temperature and moisture content along the vertical line in the y-direction. As seen in Fig. 4(a) the moisture content of the process air decreases sharply from about 23.25 g/kg of dry air to 10 g/kg of dry air within 60 seconds. The moisture content then constantly increases until it finally reached 15g/kg of humidity with further increase in the time, up to 300 seconds. The reason is desiccant has reached its equilibrium situation where its capability to adsorb the water vapor become slower after a certain time. This finding is compared with the results of Zhang *et al.* [3]. It can be observed that the moisture variation obtained from the numerical simulation follows a pretty similar trend as that of Zhang *et al.* [3]. However, the numerical results show slightly lower value of moisture content. The largest difference occurs at the time of 60 seconds, which is about 5 g/kg or dry air. This difference may be because the effects of regeneration air (for desorption process) was not being considered in this simulation. The regeneration air would remove the water vapor that is adhered on the desiccant, so the desiccant still could adsorb more water vapor at the process air.

It is also seen in Figure 4(b) that temperature of the process air increases sharply from 300 K to 333 K within the same period of 60 seconds. The air temperature then falls a little and eventually become decreasing with time, at about 323 K. Since the adsorption process releases heat, the air temperature will gradually increase. A comparison with the result reported by Zhang *et al.* [3] shows that the result of numerical simulation follows a more or less similar trend. However, the numerical results are a lot higher than the values reported by Zhang *et al.* [3]. The maximum difference of about 20 K occurs after a period of 300 seconds. It was found that the relative errors between the numerical results and the published values are about 1.05% for temperature and 8% for humidity, respectively. In summary, the numerical results show a good agreement with the published experimental data [3].

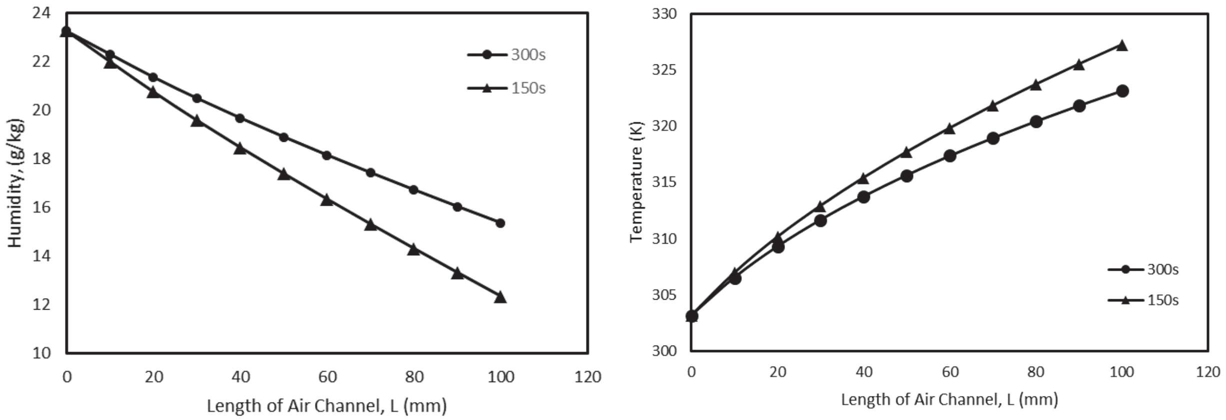


(a) (b)

FIGURE 4. Variation of (a) moisture content and (b) process air temperature with time, at the outlet section of the air channel model. Comparisons with similar results obtained by Zhang *et al.* [3] are also shown in both figures.

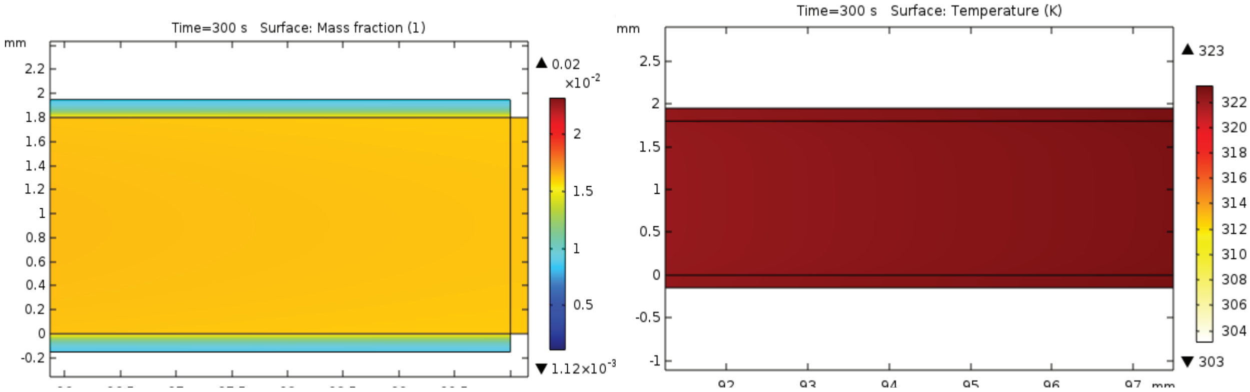
Temperature and Humidity Variation along Channel Length

Figure 5 show the variation of moisture content and air temperature along the center line of the air channel length at simulation times of 150 seconds and 300 seconds, respectively. It can be seen from Fig. 5 that the air temperature increasing uniformly as it flows through the channel while the moisture content of the air decreases uniformly along the channel length, for both times. For the first 20 mm length of the channel, there appear to be slightly small changes in the air temperature and moisture content, for both the times. This could be because the desiccant material along that length has reached its maximum ability to attract water vapor compared to other locations. The temperature distribution at time t = 150 seconds is slightly higher1 than that at time t = 300 seconds, along the rest of the channel length. This is because at time t = 150 seconds, the desiccant material still has higher ability to adsorb water vapor compare to at time t = 300 seconds. Accordingly, more heat is released at this time resulting in higher air temperature. Figure 6 shows the contour plots of humidity and air temperature along the section near the end of the channel when t = 300 seconds. As seen from the figures there are moisture and temperature gradient in the x- and y-direction. The symmetrical feature of the contour plots about the centerline of the channel can also be observed from the figures. The moisture in the air close to the desiccant channel is lower because of the adsorption process that took place there. In contrast, the air temperature is higher close to the desiccant channel because of the heat released by the process.



(a) (b)

FIGURE 5. Variation of (a) moisture content and (b) air temperature along the channel length at time t = 150 s and t = 300 s



(a) (b)

FIGURE 6. Contour plot of (a) humidity and (b) air temperature near the outlet end of the air channel model

Performance of the Solid Desiccant Wheel

The ability of the desiccant material to remove water vapor (moisture) from the process air is measured by its moisture removal capacity (MRC), given by Eqn. (8). In addition, thermal and dehumidification effectiveness are also used to assess the ability of the desiccant wheel system to heat up the process air and to remove water vapor from the air. These are given by Eqs. (9) and (10), respectively. The MRC was calculated based on the parameters given in Table 1 and Table 2, and using the value of $\omega_{out,ideal}$ = 12.5 g/kg dry air which was taken from psychrometric chart for $\omega_{out,ideal}$ while A = 2.29 mm^2, ρ_a = 1.1614 kg/m^3 are from the literature [3]. The value of $\omega_{\mathrm{a,out}}$ was taken as the average value of air humidity at the outlet which is 15.06 g/kg dry air of the air channel obtained from the numerical simulation. The same values of air humidity were employed to compute the dehumidification effectiveness using Eqn. (9). The thermal effectiveness was calculated based on data given in the same tables together with inlet regeneration air temperature of T_{reg} = 343 K which was based on Zhang *et al.* [3]. The values of the performance criteria found are MRC = 22 g/s, ε_{DW} = 76%, and ε_{th} = 43%. These values however represent the performance of the desiccant wheel during the adsorption process only since the simulation involving the regeneration or desorption process was not considered in the present study.

CONCLUSIONS

Numerical method was used to carry out transient simulation of moisture adsorption process in a single air channel of a solid desiccant material. The objective was to determine the moisture removal capacity (MRC), dehumidification and thermal effectiveness of the desiccant material during a desorption process. The numerical model was validated by comparing the variation of air humidity and air temperature at channel outlet with similar data from the literature. The relative errors for the air temperature and air humidity were found to be 1.05% and 8%, respectively. It was also found that the MRC, dehumidification and thermal effectiveness of the desiccant material are 22 g/s, 76% and 43%, respectively.

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