Dehumidification Analysis of Rotary Solid Desiccant Wheel System for different Surface Materials

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Abstract. In recent decades, desiccant dehumidification has been given much interest in the air conditioning industry area. Compared to the conventional vapour compression air conditioning system, desiccant dehumidification has various advantages, including separate humidity and temperature control. In this paper, the analysis of the Rotary Solid Desiccant Wheel System has been performed. Here, we have studied three diffusion coefficients: Ordinary, Knudsen and Surface diffusion coefficients for Rotary Solid Desiccant Wheel System. Also, the analysis has been performed for three different solid desiccant materials: Silica Gel, Molecular Sieve and Activated Alumina to incorporate and to study the effect of pore size on moisture transport and to examine the impact of Tortuosity factor on moisture transport phenomenon. This analysis can correctly select the best desiccant material suitable for the desiccant dehumidification industry.

1. Introduction
Desiccants are unique materials that exhibit an excellent capability to adsorb water vapour upon contact with moist air at average temperatures. However, desiccants utilized for space conditioning must be able to hold significant quantity of water. Desiccant dehumidification cooling does not involve cooling to the dew point. It can adsorb moisture at almost any level of humidity. The air has to be cooled to a dew point in a conventional air conditioning system for dehumidification. In some cases, humid air is overcooled to achieve low humidity, which decreases energy efficiency. Industrial solid desiccant ingredients can hold up water to more than half of their weight. Silica gel, molecular sieve and activated alumina are the most general marketable solid desiccants in use. The desiccants having porous materials with tiny microscopic pores and large surface area are called solid desiccants. The porous characteristic of desiccants is the indication that desiccants have a remarkable ability to hold water vapour. Desiccants undergo large numbers of adsorption/desorption cycles over their lifetime. Adsorption and desorption are heat and mass transfer processes between humid air and desiccant [1].

At present, much experimental and simulation research has been done in the desiccant constructed dehumidification industry. Chant (1991) [2] studied solid side resistance differently. They solved the diffusion coefficient equation for moisture passage in the solid side, assuming a parabolic concentration profile (PCP) inside the constituent part. Based on the PCP model, developed a heat and mass transfer model used for desiccant wheel with moist laminar airflow. The experimental data matched with simulation results. Dai et al. (2001) [3] obtained wave analysis to evaluate rotary
desiccants' performance using a psychrometric chart. According to wave, the shape was proposed to improve dehumidification performance and specific essential parameters, i.e., heat capacity, rotation speed, adsorption heat, desiccant matrix thickness, regeneration temperature and desiccant isothermal shape were deliberated in information using a Psychrometric chart. Niu and Zhang (2002) [4] established a two dimensional transient heat and mass transfer model designed for the desiccant wheel, allowing for heat conduction and diffusion in axial and thickness side. They analyzed the optimum rotary speed of the desiccant wheel affected by the passage wall thickness for two main utilizations, i.e. dehumidification of air and recovery enthalpy. Zhang et al. (2003) [5] established a one dimensional attached heat and mass transfer model that is predictable for usage in designing and manufacturing a honeycombed desiccant wheel rotary type. They found a humped curve about air humidity ratio alongside air channel in the process of regeneration side. The bulge of air specific humidity moves from duct entry to duct leaving and gradually increases till bulge reaches duct leaving the side in the regeneration process. Ge et al. (2008) [6] studied that investigators have made a mathematically model to the attached heat and mass transfer process inside desiccant wheel. They described in their research paper the fundamental principle of heat and mass transfer mechanism and technique of model formation of desiccant wheels.

Here, we have studied three diffusion coefficients, i.e. Ordinary, Knudsen and Surface diffusion coefficient for Rotary Solid Desiccant Wheel System having three altered solid desiccant materials, such as Silica Gel, Molecular Sieve and Activated Alumina. Thus, we studied effect of pore size on moisture transport and examined the impact of the Tortuosity factor on the moisture transport phenomenon. The proper selection of the best desiccant material as per the suitable application in the desiccant dehumidification industry can be attained through this analysis.

2. Experimental Arrangement

![Figure 1. Plan diagram of a rotary desiccant wheel](image)

Experiments have been performed on the rotary desiccant wheel by measuring dry bulb temperature and relative humidity with the help of a digital Thermo hygrometer. A detailed plan diagram of rotary desiccant wheel is presented in figure 1. Line diagram of experimental arrangement is displayed in figure 2.
2.1. **Assessing device and Instruments**

Here Relative humidity and dry bulb temperature (DBT) of air are measured with help of a Thermo hygrometer. An anemometer measures air velocity. Table 1 shows the assessing device and instruments used.

| Equipment          | Range          | Accuracy        |
|--------------------|----------------|-----------------|
| Thermo Hygrometer  | -10 to +60°C   | ±0.5°C          |
|                    | 0 to 100 %RH   | ±2.5%           |

3. **Methodology**

Mass transfer around material particles and moist air contains external convection and internal diffusion. Mass transfer is complicated inside the solid particle due to the desiccants of porous nature. In porous solids, three diffusion mechanisms can occur, i.e. i) Ordinary diffusion ii) Knudsen diffusion iii) surface diffusion [7]. The relations for diffusions coefficients are shown in equations (1-3).
3.1 Ordinary diffusion coefficient

The ordinary diffusion coefficient can be deliberated by Niu et al. [4]:

\[ D_0 = 1.758 \times 10^{-4} \frac{T_a^{1.685}}{P_{atm}} \]  

(1)

3.2 Knudsen Diffusion coefficient

In desiccant pores Knudsen diffusion occurs. It depends on a parameter that cannot be neglected, i.e., pore diameter. Knudsen diffusion can be deliberated by Niu et al. [4]:

\[ D_K = 97\tau \left( \frac{T_a}{M} \right)^{0.5} \]  

(2)

3.3 Surface Diffusion coefficient

The surface diffusivity can be deliberated by following equation given by Niu et al. [4]:

\[ D_s = \frac{1}{\zeta} \times 1.6 \times 10^{-6} e^{-0.974 \times 10^{-2} \frac{q_{atm}}{T_a}} \]  

(3)

Where \( \zeta \) is tortuosity factor that accounts for increase in diffusion length due to tortuous path of real pores.

4. Results and Discussion

4.1 Diffusion Coefficients Analysis for Silica Gel as a Desiccant Material

Table 2 shows the observation table for mass transfer analysis at \( P_{atm} = 1 \) bar

| \( T_1 \) (°C) | \( RH_1 \) (%) | \( T_2 \) (°C) | \( RH_2 \) (%) | \( T_3 \) (°C) | \( RH_3 \) (%) | \( T_4 \) (°C) | \( RH_4 \) (%) |
|---------------|--------------|---------------|--------------|---------------|--------------|---------------|--------------|
| 27.1          | 74           | 30            | 45           | 26.3          | 63           | 44.5          | 12           |
| 28.1          | 67           | 30.4          | 45           | 26.2          | 62           | 45.1          | 12           |
| 30.5          | 57           | 32.5          | 45           | 26.3          | 63           | 46.2          | 11           |
| 32.2          | 50           | 34.6          | 45           | 26.6          | 63           | 47.5          | 11           |
| 33.2          | 49           | 35.5          | 45           | 26.7          | 61           | 48.2          | 11.2         |
| 33.7          | 44           | 35.8          | 40           | 26.9          | 61           | 49.4          | 10.5         |
| 34.1          | 45           | 34.7          | 41           | 27.1          | 59           | 50.5          | 9.8          |
| 34.8          | 46           | 35.1          | 42           | 27.1          | 58           | 51.8          | 9.6          |
Figure 3. Variation of Diffusion coefficients with process air inlet temperatures

Figure 4. Variation of Diffusion coefficients with regeneration air inlet temperatures
4.2. Knudsen diffusion coefficient Analysis for Silica gel, Molecular sieve and Activated alumina

| Desiccants       | Avg. pore diameter (nm) |
|------------------|-------------------------|
| Silica gel       | 2-5                     |
| Molecular sieve  | 0.4                     |
| Activated Alumina| 4.5                     |

Figure 5. Variation of Knudsen diffusion coefficient for Silica gel, Molecular sieve and Activated alumina with process air inlet temperatures

Figure 6. Variation of Knudsen diffusion coefficient for Silica gel, Molecular sieve and Activated alumina with regeneration air inlet temperatures
4.3. **Surface diffusion coefficient Analysis for Silica gel, Molecular sieve and Activated alumina**

| Desiccants         | Tortuosity factor |
|--------------------|------------------|
| Silica gel         | 2.5              |
| Molecular sieve    | 6                |
| Activated Alumina  | 0.7              |

Figure 7. Variation of Surface diffusion coefficient for Silica gel, Molecular sieve and Activated alumina with process air inlet temperatures

Figure 8. Variation of Surface diffusion coefficient for Silica gel, Molecular sieve and Activated alumina with regeneration air inlet temperatures
Figures 3 and 4 shows that all three diffusion coefficients, i.e. Ordinary diffusion, Knudsen diffusion & Surface diffusion offer a steep increment with temperature. However, they are increasing with air inlet temperatures at the process and regeneration sectors. Also, figures 3 and 4 show that for the exact temperature of the air at process and regeneration sector \(D_{\text{Surface}}<D_{\text{Knudsen}}<D_{\text{Ordinary}}\). Thus, the mass transfer analysis of silica gel shows that the surface diffusion coefficient is the most dominant moisture transport mechanism for the rotary desiccant wheel system. The smaller the diffusion coefficient, greater the effectiveness of rotary desiccant wheel system [8]. Figures 5 and 6 shows the Knudsen diffusion coefficient variation for Silica gel, Molecular sieve and Activated alumina with air inlet temperatures at process and regeneration sectors. It shows that as the air temperature rises at the process and regeneration sectors, the Knudsen diffusion coefficient value increases for all three desiccant materials, confirming the increase in moist air's diffusivity with desiccant. As pore radius increases, the Knudsen diffusion coefficient increases. Since the pore radius of Silica gel is the largest among the three desiccant materials, it has the highest value of the Knudsen diffusion coefficient. Figures 7 and 8 shows variation of Surface diffusion coefficient for Silica gel, Molecular sieves and Activated alumina with air inlet temperatures at process and regeneration sectors. It shows that as the air temperature rises at process and regeneration sectors, the Surface diffusion coefficient value increases, which confirm the increase in diffusivity of moist air with desiccant (but very steep variation). As the Tortuosity factor increases, the Surface diffusion coefficient decreases. Since the Tortuosity factor of Activated alumina has the most negligible value of 0.7, it has the highest value of Surface diffusion coefficient [9].

5. Conclusions

The main aim of this paper was to study three diffusion coefficients, i.e. Ordinary, Knudsen and Surface diffusion coefficient for Rotary Solid Desiccant Wheel System having three different solid desiccant materials, i.e. Silica Gel, Molecular Sieve and Activated Alumina. The effect of pore size on moisture transport and the impact of the Tortuosity factor on the moisture transport phenomenon were examined. Thus it was concluded:

- In a nutshell, this complete moisture transfer process between desiccant material and moist air can be understood as smaller the diffusion coefficient more will be effectiveness of rotary desiccant wheel system.
- Surface Diffusion is dominant mechanism of moisture transport for rotary desiccant wheel system.
- Considering the effect of pore size, Silica gel is the best desiccant material amongst all three materials.
- Considering the effect of the Tortuosity factor, Activated Alumina is the best choice for desiccant dehumidification compared to Silica gel and molecular sieve.
Nomenclature

\( D_0 \) Ordinary diffusion coefficient (m\(^2\)/s)
\( D_K \) Knudsen diffusion coefficient (m\(^2\)/s)
\( D_s \) Surface Diffusion coefficient (m\(^2\)/s)
\( T_a \) Air Temperature (°C)
\( T_1 \) process air inlet temperature
\( T_2 \) process air outlet temperature
\( T_4 \) regeneration air inlet temperature
\( T_3 \) regeneration air outlet temperature
\( RH_1 \) process air inlet relative humidity
\( RH_2 \) process air outlet relative humidity
\( RH_4 \) regeneration air inlet relative humidity
\( RH_5 \) regeneration air outlet relative humidity
\( q_{st} \) Adsorption heat of regular density of the material

Greek symbols:
\( \zeta \) tortuosity factor

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