Equilibrium Moisture Effects in Silica Gel Adsorption/Desorption

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ABSTRACT

This research involves a numerical analysis focused on examining how the initial moisture content and equilibrium moisture content affect a Regular Density (RD) silica gel-packed bed, in terms of the composite mass and heat transfer dynamics during the adsorption and desorption processes. The detailed interaction between the air and the desiccant material is thoroughly represented through the development of the governing drying kinetics, mass conservation, and energy conservation equations, thereby establishing a solid mathematical foundation to clarify these essential processes. All numerical simulations are meticulously executed using the Finite Volume Element method, allowing for a detailed analysis of the mass and heat transfer phenomena within the RD silica gel-packed bed. The utilization of this advanced computational technique enables a deeper understanding of the complex interactions between the moisture content and transfer process efficiency in the desiccant system. This research culminates in the development of correlations that serve as predictive tools. An accurate estimation is facilitated by both the removal/addition of humidity from/to the air and the maximum enthalpy released/absorbed by the RD silica gel medium throughout the adsorption and desorption phases. These correlations, rooted in the equilibrium and initial moisture content of the RD silica gel medium, provide valuable insights into optimizing the performance and efficiency of desiccant systems in various operating conditions. There are intricate relationships between moisture content and transfer processes. This study contributes to advancing the understanding of desiccant systems, paving the way for more efficient and sustainable air treatment technologies.

Keywords-numerical simulation; air conditioning; absorption; desorption; equilibrium moisture content; regular density silica gel; heat and mass transfer

I. INTRODUCTION

During the sorption carried out between the air and desiccant medium, the amount of mass and heat transfer [1, 2] are significantly influenced by the variation of operating conditions, such as the desiccant equilibrium and initial moisture content, desiccant medium porosity, particle radius, inlet air, temperature, air velocity, etc. The accurate quantification of the desiccant equilibrium and initial moisture influence helps in the correct design of an efficient dehumidification system. Some interesting research works dealing with the impact of operating conditions on mass and heat transfer are pointed out in the literature. Authors in [3] experimentally investigated the influence of the rotational speed on the desiccant wheel performance in terms of the dehumidification coefficient of performance, performance dehumidification effectiveness, and sensible energy ratio. Furthermore, the effects of the inlet temperature and inlet humidity of the process air, temperature of the regeneration air, and ratio of the process air to regeneration air mass flow rates, on the desiccant wheel optimal rotational velocity are examined. This permits the optimization of the desiccant wheel dehumidification performance. The results show that the desiccant wheel's optimal rotational velocity varies from 5 to 10 revolutions per hour, depending on the operating conditions. Moreover, it is observed that the sensible energy ratio increases monotonically with the desiccant wheel rotational velocity.

Authors in [4] relied on published experimental results of an investigation on the global performance of a desiccant wheel for various inlet states of process and regeneration air flows and various desiccant wheel rotational speeds. They studied a new pair of independent effectiveness parameters and derived certain correlations for their estimation. The results demonstrate that these correlations are in good agreement with the experimental data. Authors in [5] explored the effect of the atmospheric pressure, varying with the altitude, on the heat and mass transfer in the desiccant wheel. The process and regeneration of air inlet temperature, water vapor content, and mass air flow rate are assumed constant. The results display that the decrease of the atmospheric pressure reduces the heat and mass transfer. This phenomenon becomes more pronounced with higher air flow rates and shorter channel wheels. Additionally, correction correlations are developed to accurately estimate the heat and mass transfer in a desiccant wheel operating under non-standard atmospheric pressure conditions. This research work aims to precisely quantify the effect of the desiccant equilibrium and initial moisture content on the two major characteristics of mass and heat transfer. The maximum removed/added quantity of humidity from/to the process/regeneration air and the maximum enthalpy released/absorbed by desiccant material during the adsorption/desorption mode are also investigated.

II. PROBLEM STATEMENT

Figure 1 provides a detailed schematic representation of a solar desiccant air conditioning system based on the Pennington cycle. This innovative system is designed to manage two distinct air loads effectively. The latent load is associated with the air moisture and the sensible load is associated with the air temperature regulation. In this system, the latent load is primarily addressed within a specialized desiccant dehumidification compartment, which may feature technologies, such as packed bed systems or desiccant wheels. These components play a crucial role in extracting moisture from the air stream, contributing significantly to the overall dehumidification process. Conversely, the sensible load is predominantly managed within the heat exchanger section, which may incorporate technologies, like thermal wheels or conventional heat exchangers. These elements focus on regulating the air temperature to ensure optimal comfort levels within the conditioned space. This research article places particular emphasis on the dehumidification compartment of the system, where the supply air destined for the conditioned space undergoes the crucial dehumidification process. Furthermore, this compartment undergoes a regeneration process facilitated by low-grade energy air. The heating of this regeneration air, as it circulates back from the conditioned space, is efficiently powered by solar energy through a sophisticated system comprising solar collectors, a storage tank, and a solar heat exchanger. The system integrates direct evaporative coolers to effectively modulate both the latent and sensible loads of the air, contributing to enhanced energy efficiency and overall performance. This comprehensive approach to air conditioning underscores the system's ability to leverage solar energy for sustainable and efficient operation, aligning with the contemporary trends in environmentally friendly HVAC solutions.

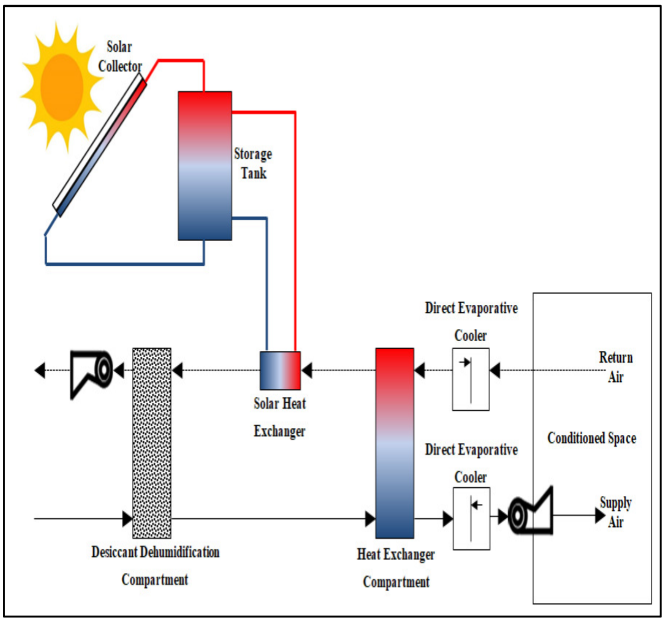

Fig. 1. Desiccant air conditioning system.

A. *Silica Gel Packed Bed*

The considered dehumidification compartment is a multi-packed bed dehumidifier [8]. Packed beds have a square cross-section Sb = 2.5×10^{-3} m^2, a height Hb = 0.2 m, and are filled with RD silica gel as a desiccant medium.

B. *Heat and Mass Transfer*

The heat and mass transfer phenomena within the desiccant medium are intricately governed by a series of fundamental principles encapsulated in drying kinetics, mass conservation, and energy conservation equations. These equations serve for understanding and quantifying the complex interplay of physical processes that define the behavior of moisture within the desiccant material. Mass conservation equations provide a comprehensive framework for tracking the movement of moisture within the desiccant media while ensuring that the total amount of moisture entering and leaving the system is accurately accounted for, maintaining the balance of mass within the system. These equations allow for a complete understanding of how moisture is distributed and exchanged throughout the desiccation and desorption stages.

C. *Drying Kinetic Equation*

The drying kinetic equation of the desiccant medium is expressed as [9]:

$$\frac{\partial q}{\partial t} = \frac{15 D_e}{r_p^2}(q_\infty - q) \quad (1)$$

The effective diffusivity coefficient of the desiccant medium is expressed as [10]:

$$D_e = \frac{D_0}{\tau_s}\exp(-0.947.\frac{H_{ads}.10^{-3}}{T}) \quad (2)$$

Mass conservation equation:

The mass transfer within the desiccant medium is governed by the mass conservation equation [8, 11]:

$$\varepsilon\rho_a\frac{\partial\omega}{\partial t} + \rho_a V\frac{\partial\omega}{\partial x} = \rho_a D_e(\frac{\partial^2\omega}{\partial x^2}) - (1-\varepsilon)\rho_s\frac{\partial q}{\partial t} \quad (3)$$

Energy conservation equation:

The energy transfer within the desiccant medium is governed by the energy conservation equation [8, 11]:

$$(\varepsilon\rho_a(C_{pa} + \omega C_{pv}) + (1-\varepsilon)\rho_s(C_{ps} + qC_{pw}))\frac{\partial T}{\partial t} + \rho_a(C_{pa} + \omega C_{pv})V\frac{\partial T}{\partial x} = \rho_s H_{ads}(1-\varepsilon)\frac{\partial q}{\partial t} + (\varepsilon\lambda_a + (1-\varepsilon)\lambda_s)\frac{\partial^2 T}{\partial x^2} \quad (4)$$

III. RESULTS AND DISCUSSION

A. *Influence of the Equilibrium Moisture Content on the Mass and Heat Transfer during the Adsorption Mode*

The influence of the desiccant equilibrium moisture content q∞ on the moisture removal and enthalpy release at the outlet of the bed (x = 0.2 m) is numerically investigated under the following operating conditions: bed porosity ε=0.6, particle radius r_p = 1 mm, inlet air temperature T_{inlet} air =35°C, air velocity V= 2 m/s, desiccant equilibrium moisture content q_∞=0.25, and 0.34 kg (H_2O)/kg dry silica gel. All numerical simulations are carried out using the Finite Volume Element method. Figure 2 depicts the variation of the maximum amount of the removed moisture from the supply air during the adsorption mode when the desiccant equilibrium moisture content varies.

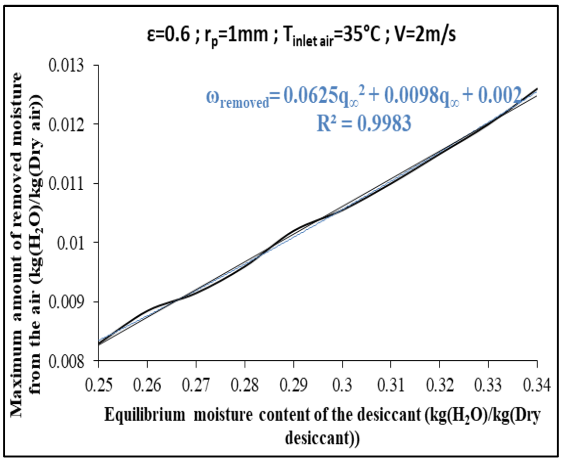

Fig. 2. Maximum amount of the removed moisture from the air, during the adsorption mode, in function of the equilibrium moisture content of the desiccant.

The maximum amount of removed moisture, during the adsorption mode, in function of the desiccant equilibrium moisture content, presents a polynomial evolution governed by the following correlation, with a coefficient of determination R^2 = 0.9983:

$$\omega_{removed} = \omega_{initial} - \omega_{min} = 0.0625 \times q_\infty^2 + 0.0098 \times q_\infty + 0.002 \quad (5)$$

Figure 3 depicts the variation of the maximum amount of enthalpy released by the desiccant medium, during the adsorption mode, when the desiccant equilibrium moisture content varies.

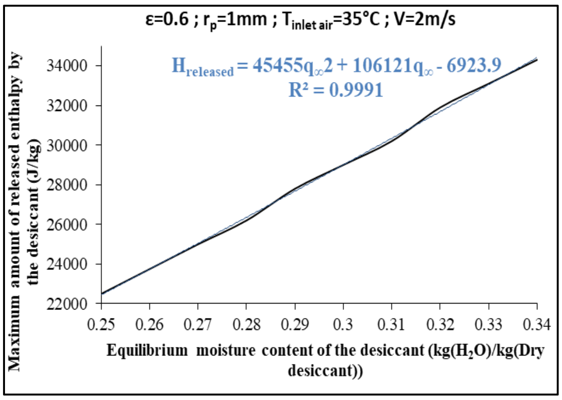

Fig. 3. Maximum amount of the released enthalpy by the desiccant, during the adsorption mode, in function of the equilibrium moisture content of the desiccant.

With a coefficient of determination of R^2=0.9991, the maximum quantity of released enthalpy during the adsorption mode exhibits a polynomial evolution as a function of the desiccant equilibrium moisture content and is guided by the following correlation, which highlights the precise relationship between the desiccant's equilibrium moisture content and the enthalpy released during adsorption. The polynomial evolution points to a complicated but predictable interaction between the energy changes that take place throughout the adsorption process and the moisture content of the desiccant. The remarkably high R^2 value of 0.9991 stresses the correctness and dependability of this relationship showing an almost perfect fit between the observed data and the expected correlation, making it possible to accurately anticipate enthalpy release based on desiccant moisture content. This finding has significant implications for the optimization of adsorption-based systems, rendering the construction of more effective and efficient systems easier.

$$H_{released} = H_{max} = 45455 \times q_\infty^2 + 106121 \times q_\infty - 6923.9 \quad (6)$$

The numerical results reveal that both heat and mass transfer evolutions present increasing tendencies during the adsorption mode. This is expected since the increase of the desiccant equilibrium moisture content enhances the mass transfer rate between the air and the desiccant medium. The amount of exothermic Van Der Walls bonds formation during adsorption is augmented. The amount of energy released during adsorption is enhanced. Equations (5) and (6) allow the prediction of the maximum amount of the removed moisture from the supply air and the maximum amount of released enthalpy by the desiccant medium, given the desiccant equilibrium moisture content.

B. Influence of the Initial Moisture Content on the Mass and Heat Transfer during the Desorption Mode

The influence of the desiccant initial moisture content qi on the moisture removal and enthalpy release at the outlet of the bed (x = 0.2 m), is numerically investigated under the following operating conditions: bed porosity $\varepsilon = 0.6$, particle radius $r_p = 1$ mm, inlet air temperature T_{inlet} air =70°C, air velocity V= 2 m/s, desiccant initial moisture content $q_i = 0.25$, and 0.34 kg (H_2O)/kg dry silica gel. All numerical simulations are carried out deploying the Finite Volume Element method. Figure 4 depicts the variation of the maximum amount of added moisture to the regeneration air, during the desorption mode, when the desiccant initial moisture content varies. In Figure 4, the comprehensive illustration provided highlights the dynamic relationship between the maximum amount of moisture added to the regeneration air and the variability in the desiccant initial moisture content throughout the desorption phase. The plotted data show how alterations in the desiccant's initial moisture levels directly influence the quantity of moisture introduced into the regeneration air stream. As the desiccant's initial moisture content fluctuates, a discernible trend in the maximum amount of added moisture is revealed, offering valuable insights into the intricate interplay between these variables. This visualization serves as a pivotal tool in understanding the nuanced dynamics of the desorption process, shedding light on the impact of the initial conditions on the moisture transfer mechanisms at play. Based on Figure 4, essential information regarding the optimal management of the moisture levels in the regeneration air can be extracted, strengthening the efficiency and efficacy of the desorption processes within the desiccant systems.

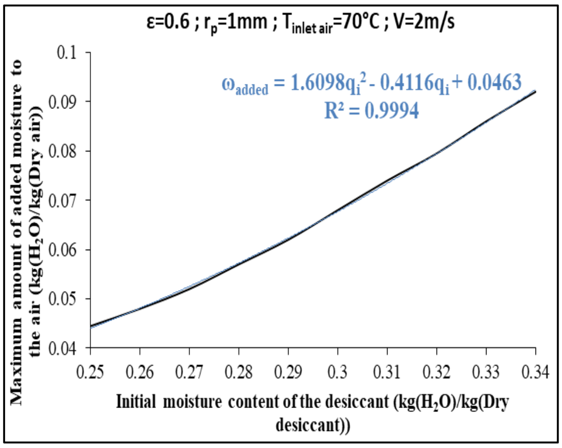

Fig. 4. Maximum amount of the added moisture to the air, during the desorption mode, in function of the initial moisture content of the desiccant.

The maximum amount of added moisture, during the desorption mode, in function of the desiccant initial moisture content, presents a polynomial evolution governed by the following correlation, with a coefficient of determination $R^2 = 0.9994$:

$$\omega_{added} = \omega initial_{max} = 1.6098 \times q_i^2 - 0.4116 \times q_i + 0.046 \quad (7)$$

Figure 5 depicts the variation of the maximum amount of enthalpy absorbed by the desiccant medium, during the desorption mode, when the desiccant initial moisture content varies.

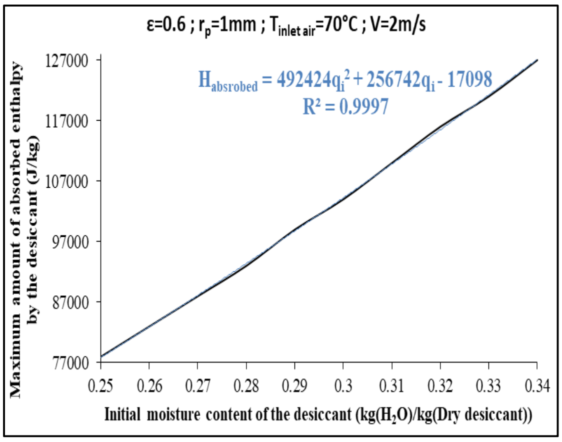

Fig. 5. Maximum amount of the absorbed enthalpy by the desiccant, during the desorption mode, in function of the initial moisture content of the desiccant.

The maximum amount of absorbed enthalpy, during desorption mode, in function of the desiccant initial moisture content, presents a polynomial evolution, governed by (8) with a coefficient of determination $R^2 = 0.9997$:

$$H_{absorbed} = -H_{min} = 49242 \times q_i^2 + 256742 \times q_i - 17098 \quad (8)$$

The numerical results indicate that both the heat and mass transfer evolutions present increasing tendencies during the desorption mode. The observed rise in heat and mass transfer tendencies during the desorption phase, as exhibited by the numerical data, underscores a critical relationship between the desiccant's initial moisture levels and the efficiency of these processes. With a higher moisture content at the outset, the desiccant facilitates a swifter exchange of mass between the air and the desiccant medium. Consequently, this heightened initial moisture content prompts an escalation in the breaking of endothermic Van der Waals bonds during desorption. This enhanced bond disruption demands a greater input of energy, resulting in a notable amplification of energy absorption throughout the desorption process. A direct correlation between initial conditions, mass transfer rates, and the overall energy dynamics at play is observed. Equations (7) and (8) allow an easy prediction for the maximum amount of added moisture to the regeneration air and the maximum amount of absorbed enthalpy by the desiccant medium, given the desiccant initial moisture content.

IV. CONCLUSIONS

The present study performed an investigation into the effects of the desiccant equilibrium and initial moisture content, with mass and heat transfer interactions, within the air-desiccant medium, providing a comprehensive understanding of these essential processes. Notably, the identification of second-order polynomial trends governing mass and heat transfer variations underscores the structured nature of these phenomena. The precise assessment of the maximum moisture extraction from the desiccant during the adsorption mode is linked to the equilibrium moisture content through a well-defined correlation. The crucial role of moisture management in optimizing desiccant performance is emphasized. Future research works may focus on more comprehensive studies of the transient dynamics associated with the mass and heat transfer mechanisms. The system's behavior under dynamic operating conditions is aimed to be better understood. Insights into enhancing the transfer efficiency and overall system performance could be provided through the exploration of innovative desiccant materials and configurations. Additionally, developing advanced predictive models that account for multi-parameter interactions and real-time data could aid in designing more adaptable and energy-efficient desiccant systems. Incorporating intelligent control strategies and automation techniques could further optimize system operation, improving sustainability and performance. The influence of the desiccant equilibrium and initial moisture content on mass and heat transfer between the air and the desiccant medium was rigorously quantified. It is evidenced that the mass and heat transfer variations have second-order polynomial tendencies. The maximum amount of the removed moisture from the desiccant during the adsorption mode is evaluated, given the equilibrium moisture content, using:

$$\omega_{\text{removed}} = 0.069 \times q_\infty^2 + 0.005 \times q_\infty + 0.002$$

The maximum amount of the released enthalpy during the adsorption mode is evaluated, given the equilibrium moisture content, using:

$$H_{\text{released}} = 10654 \times q_\infty^2 + 72243 \times q_\infty - 2266$$

The maximum amount of the added humidity during the desorption mode is evaluated, given the initial moisture content, using:

$$\omega_{\text{added}} = 1.569 \times q_i^2 - 0.391 \times q_i + 0.044$$

The maximum amount of the absorbed enthalpy during desorption mode is evaluated, given the initial moisture content, using:

$$H_{\text{absorbed}} = 55976 \times q_i^2 + 22121 \times q_i - 12552$$

These correlations will be useful in designing an efficient dehumidification system properly.

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NOMENCLATURE

C_{pa}: Air-specific heat (kJ/kgK)

C_{ps}: Silica gel specific heat (kJ/kgK)

C_{pv}: Water vapor specific heat (kJ/kgK)

C_{pw}: Water-specific heat (kJ/kgK)

D_0: Surface diffusion coefficient (m^2/s)

De: Effective diffusivity (m^2/s)

H_{ads}: Heat of adsorption (kJ/kg(water))

q: Silica gel moisture content (kg (H_2O)/kg (dry silica gel)

q_∞: Equilibrium moisture content (kg (H_2O)/kg (dry silica gel)

r_p: Silica gel radius particle (mm)

T: Air temperature (K)

ε: Medium porosity

λ_a: Air thermal conductivity (W/mK)

λ_s: Silica gel thermal conductivity (W/mK)

ρ_a: Air density (kg/m^3)

ρ_s: Silica gel density (kg/m^3)

τ_s: Tortuosity factor for intraparticule surface diffusion

ω: Air humidity ratio (kg (H_2O)/kg (dry air)

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