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Numerical Analysis of Silica Gel Bed Used In Desiccant Air Cooler and Dehumidifier

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ABSTRACT
Large commercial buildings, such as supermarkets or restaurants, require large capacity air conditioning units to control not only the indoor temperature but also the moisture that may be generated by people, cooking, and other processes. The desiccant dehumidification units used in these air conditioning units are generally equipped with silica gel packed bed. The nature of dehumidification by silica gel is quite complex and transient. The transient nature of the bed is due to the fact that as time passes the moisture content of the silica gel particles increases which leads to a lesser adsorption rate and thus the outlet conditions of the air starts changing with each elapsed moment.

In this paper, a two dimensional mathematical model to predict the dehumidification trend of a fixed solid desiccant bed filled with silica gel is presented. Partial differential equations and algebraic equations concerning water content balance and energy conservation for flowing air and solid desiccant were used to describe the complicated heat and mass transfer occurring in moisture adsorption.
Keywords: - Dessicant, Silica Gel Bed, Silica Gel Particle.

I. Introduction

The sorption dehumidification of air by solid desiccants could represent an interesting alternative to traditional dehumidification processes by air cooling below the dew point which involves both cooling and heating capacity. Chemical dehumidification by solid desiccants allows consistent humidity reduction and its energy cost, due to desiccant regeneration, can be significantly reduced by proper heat recovery. This process is also useful in reducing airborne microbial contamination.

Desiccants are hygroscopic substances that exhibit such a strong affinity for moisture that they can draw water vapor directly from the surrounding air. Solid desiccant like silica gel to dehumidify air, due to the difference in the partial pressure of water vapor on the surface of the desiccant and the atmosphere.

They attract moisture until they reach equilibrium with the surrounding air. Chemical dehumidification by solid desiccants allows consistent humidity reduction and its energy cost, due to desiccant regeneration.

II. Problem Definition

Adsorption of moisture by silica gel bed is quite complex due to its inherent transient nature. The present mathematical model of silica gel particle bed represents the overall heat and mass transfer from the air stream to the silica-gel particle bed. The transient nature of the beds, is due to the fact that as time passes the moisture content of the silica gel particles increases which leads to a lesser adsorption rate and thus the outlet conditions of the air starts changing with each elapsed moment.

To know the exact outlet condition of the air after passing through the desiccant bed and the variation of different inlet conditions with time and length of the bed are studied.

III. Methodology

3.1 Mathematical Modeling of Silica Gel Bed: -

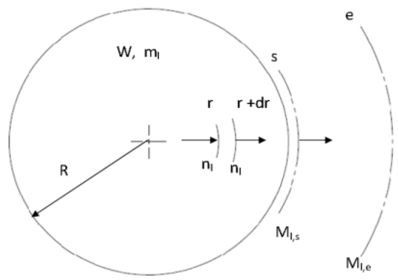
The entire mathematical modelling is done in two parts

1. Mathematical modelling of a single silica gel particle: Based on mass diffusion principles.
2. Mathematical modelling of silica gel bed: Based on mass and energy conservation principles.

3.2 Mathematical modeling of a single silica gel particle:

In a silica gel particle water vapour gets adsorbed by diffusion process. Since of the pores of silica gel are generally less than 100 Å, thus the ordinary diffusion can be ignored in usual silica gel applications.

Considering a spherical particle of silica gel with initial gel water content Wo = f(r), and a uniform temperature which is suddenly exposed to humid air with water vapor mass fraction m_{le}



The governing equation for water conservation:

$$\frac{\partial W}{\partial t} = \frac{1}{r^2}\frac{\partial}{\partial r}\left[r^2 D \frac{\partial W}{\partial r}\right],$$

Where

$$D = D_{s,eff} + D_{k,eff}\frac{g'(W)}{\rho_p}.$$

3.3 Modeling of silica gel packed particle beds

Fig 1:- Cad model of the desiccant bed.

Differential equations governing the transient response of a packed bed of desiccant particles are derived by applying mass conservation principle, boundary conditions, Gas-phase energy conservation equation,

$$A\rho_b c_b \frac{\partial T_s}{\partial t} = p[h_c(T_e - T_s) - H_{ads}K_G(m_{l,s} - m_{l,e})]$$

Assuming initial conditions as

$$T_s(z, t = 0) = T_o,\ T_e(z = 0, t) = T_{in}$$

and $m_{l,e}(z = 0, t) = m_{l,i}$.

Average water content of a particle was obtained by

$$W_{avg} = \frac{\int_0^R 4\pi r^2 W \rho_p dr}{\frac{4}{3}\pi R^3 \rho_p}$$

The six governing equations with their i**nitial and boundary condition** are solved for six unknowns:-

1. $$\frac{\partial W}{\partial t^*} = \frac{1}{r^{*2}}\frac{\partial}{\partial r^*}\left(D^* r^{*2}\frac{\partial W}{\partial r^*}\right)$$

2. $$\frac{\partial \dot{m}_{l,e}}{\partial z^*} = N_{tu}(m_{l,s} - m_{l,e})(1 - m_{l,e})$$

3. $$\frac{\partial T_e}{\partial z^*} = -N_{tu}\left[\frac{h_c}{K_G} + c_{pl}(m_{l,s} - m_{l,e})\right](T_e - T_s)$$

4. $$c_b\frac{\partial T_s}{\partial t^*} = \frac{1}{DAR}\left[\frac{h_c}{G_a}(T_e - T_s) - H_{ads} \times 1.7 \times Re^{-.42}(m_{l,s} - m_{l,e})\right]$$

5. $$W_{avg} = \frac{\int_0^R 4\pi r^2 W \rho_p dr}{\frac{4}{3}\pi R^3 \rho_p}$$

6. $$m_{ls} = \frac{.622RH \times P_{sat}(T_s)}{P_{total} - .378RH \times P_{sat}(T_s)}$$

Discretizing equation using implicit method for nodes between i=2 to N-1, we get

$$-W_{N-1}^{\ n+1} + W_N^{\ n+1} = \frac{-\Delta r^*}{\beta}(m_{l,s} - m_{l,e})$$

So, a (N) = -1, b (N) =1, c (N) =0, and

$$d(N) = \frac{-\Delta r^*}{\beta}(m_{l,s} - m_{l,e}).$$

On Discretizing the boundary condition at the node i=1 using forward differencing We get

$$-W_1^{\ n+1} + W_2^{\ n+1} = 0,$$

So, a (1) =0, b (1) =-1, c (1) =1, d (1) =0

The equations obtained after Discretizing forms a tri-diagonal matrix which is then solved by Thomas algorithm. The other differential equations which are first order equations are solved using *Runge Kutta method*.

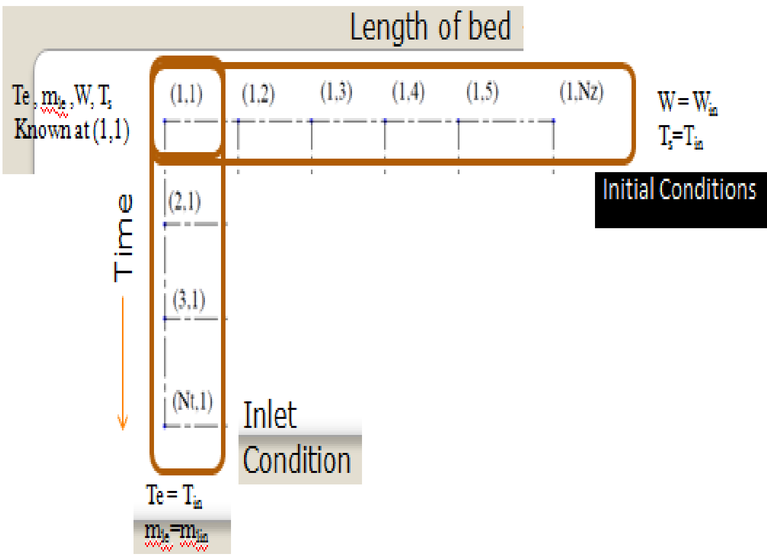


Fig 2:- Tri-diagonal matrix solved by Thomas algorithm

Hence after solving we get:-

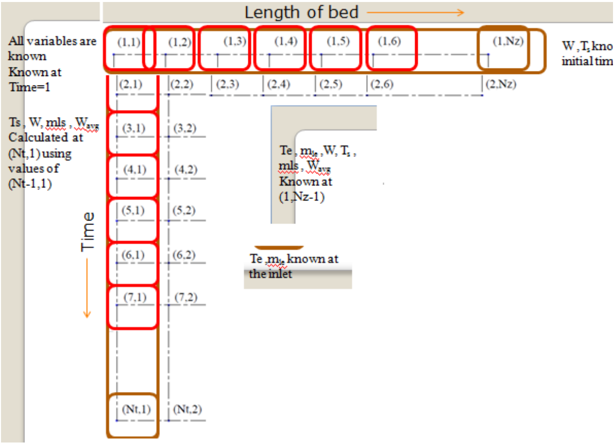


Fig 3:- Applying Runge Kutta Method

Solving in the similar way and Calculating for other points for (2,3),(2,4). . . . . (2 ,Nz) we to get a time marching solution till time = Nt.Hence **All variables are known for all time intervals** .

IV. CALCULATING EFFECT OF FOURIER MASS TRANSFER NUMBER (FO_M) ON PENETRATION OF WATER INSIDE SILICA GEL.

It is seen that higher Fo_m causes higher penetration of water inside the particle.

$Fo_m = D \times t / R^2$ Where,

D=Total Diffusivity (m^2/s), t=time(s), R= Radius of Particle (m), which can be interpreted as Increase in Diffusivity, increases penetration in spherical particle.

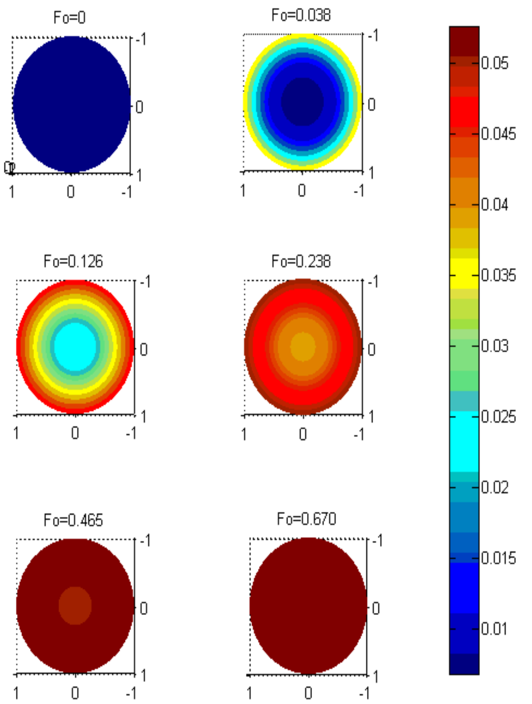


Fig 4:- Effect of Fourier mass transfer number on penetration of water inside silica gel.

This can be interpreted as

1. Increase in Diffusivity, increases penetration in spherical particle.
2. With increase in time, water penetrates deeper into the particle
3. With increase in radius, the penetration of water decreases.

4.1 Variation of W_{avg}, T_s, T_e, m_{ls}, m_{le} at with z* and t* values for a particle with R=1.94 mm

A. Variation of W_{avg} with z* and t*

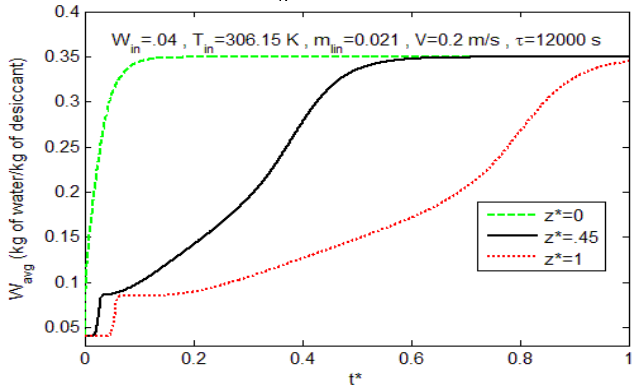


Fig 5:- Variation of W_{avg} with z* and t*

The following observations can be made for a particle at z*=0.45:-

1) W_{avg} is constant till t*=0.02.
2) It increases steeply till t* reaches .03
3) Then W_{avg} increases slowly till saturation is achieved

B. Variation of m_{ls} and m_{le} with z* & t*

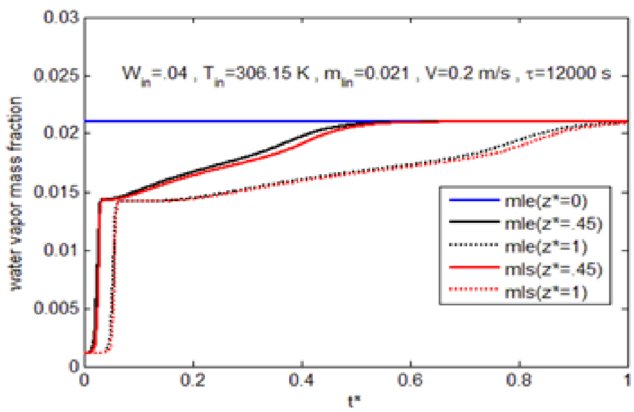


Fig 6:- Variation of m_{ls} and m_{le} with z* & t*

The following observations can be made for a particle at z*=0.45

1) Decreases to a very low value as soon as it enters the bed.
2) Remains constant for a while, then increases rapidly
3) Later it increases slowly before coming to the saturation limit.

C. Variation of T_s and T_e with z* and t*

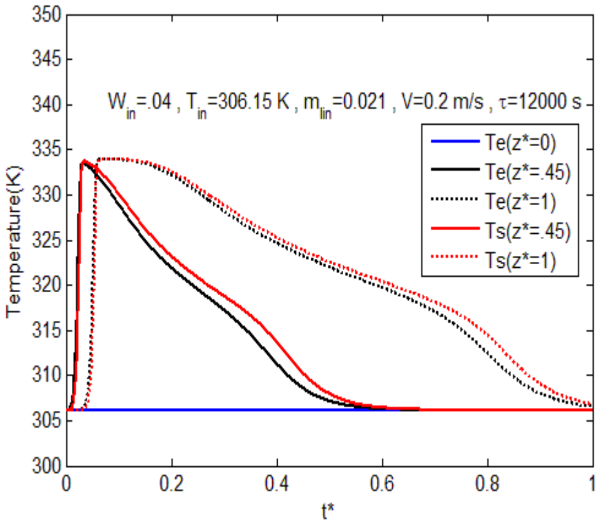


Fig 7:- Variation of T_s and T_e with z* and t*

The following observations can be made:

1) Ts increases first and then decreases because of the lower value of Hads han the convective heat transfer to the surrounding air.

2) Since Te is dependent on Ts. So, it has the same characteristic like Ts.

D. Variation of Wavg, Te, and mle with t* at z*=1 for three different inlet velocities of air

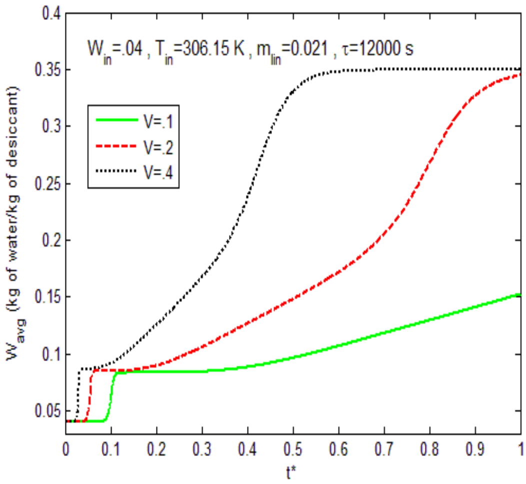


Fig 8:- Variation of Wavg, Te, and mle with t* at z*=1 for three different inlet velocities of air

It is seen that:

1. Maximum water content in desiccant bed is independent on velocity of air.
2. Rate of saturation is high for higher velocities (mass flow rate).

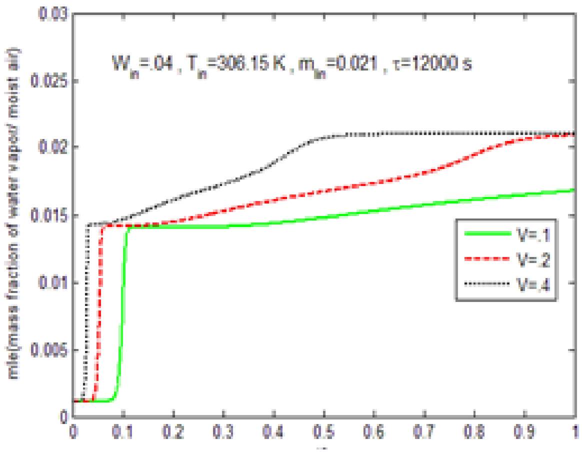


Fig 9:- Mass fraction of water vapour at different velocities of air.

It is seen that:

- Low inlet velocities provides lower mass fraction of air at the outlet for a longer time.
- The graph seems to be scaled along x axis with a factor equal to their speed ratios.

E. Variation of Wavg, Te, and mle with t* at z*=1 for three different inlet temperatures of air

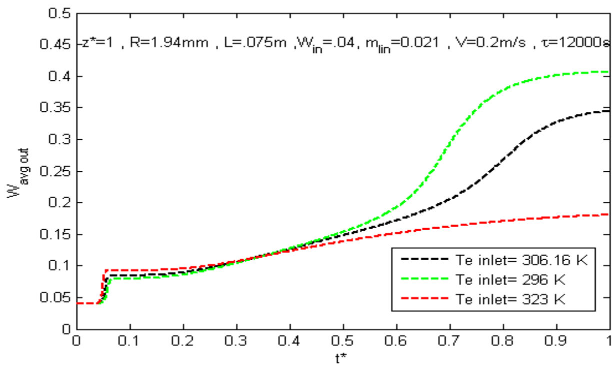


Fig 10:- Variation of Wavg, Te, and mle with t* at z*=1 for three different inlet temperatures of air

- It is seen that:
  - Maximum water content in desiccant bed is dependent on the temperature of inlet air.
  - Lower temperatures of inlet air increases the water holding capacity.
  - Saturation time required for saturating the bed for air at lower inlet temperature is lower.

F. Variation of Wavg and Te with t* at z*=1 for three different inlet water mass fraction of air

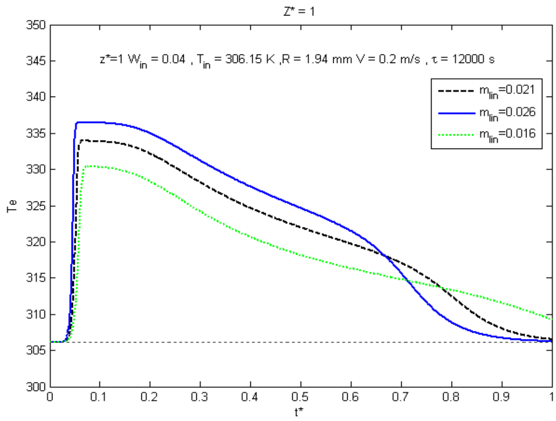


Fig 11:- Variation of Wavg and Te with t* at z*=1 for three different inlet water mass fraction of air

It is seen that:

- Temperature of air at outlet for higher water mass fraction of inlet air is higher for most values of t*.
- Higher water concentration in inlet air causes desiccant to saturate at a faster speed.

V. CONCLUSION

In this paper, a two dimensional Mathematical model to predict the dehumidification trend of a fixed solid desiccant bed filled with silica gel is presented. The comparison of silica gel particle of two different radiuses reveals that smaller desiccant particles have more affinity towards water; hence can be used where faster dehumidification is required and it is not exposed to atmosphere frequently, whereas larger particles will be more inert to atmospheric humidity and slow in dehumidification.

In desiccant beds, where reactivation is quickly possible, smaller particles will be preferable, but where the bed is required to run for longer period, larger particles will have advantage. Summarizing we get

1. Penetration of water inside silica gel particle depends on Fourier mass transfer number. larger particles more time required for saturation.
2. Maximum water content in the silica gel particle becomes equal at the saturation throughout the bed and is found to be 0.3492 kg water/kg desiccant when Ts=306.15K, Te=306.15K, mle=.021kg water/kg humid air. Requires about 3hrs for the particle at z*=1 to reach 90% of saturation.
3. The adsorption rate in silica gel particle is more when its temperature at surface (Ts) is low.
4. The water vapor mass fraction of air at outlet is very low for smaller t*, which then rises suddenly to a higher value and gradually to inlet condition on saturation.
5. The maximum water content that can be stored in silica gel depends on temperature of inlet air. Lower temperature results in higher water content and vice versa.
6. Smaller silica gel particles are suitable for making desiccant bed where good quality dehumidified air is required over a longer period.

REFERENCES

Journal Article:-

[1] Clark J.E, and H. Buchberg (1981) , 'Design and Testing of Thin Adiabatic Desiccant Beds for Solar Air Conditioning Applications', Journal of Solar Energy Engineering, pp 89-91.

[2] H. Pahlavanzadeh and A. Zamzamian (2006),'A Mathematical Model for a Fixed Desiccant Bed Dehumidifier', Iranian Journal of Science & Technology, Vol 30.

[3] Rosen J. B. (1952), 'Kinetics of a Fixed Bed System for Solid Diffusioninto Spherical Particles' Journal of Physical Chemistry, Vol 20, pp 387-393

Thesis:-

[4] Kamal A. Abou Khamis,(2000)'Analysis and Design of Desiccant Cooling Systems'M.S. Thesis, oungstown State University, Ohio, U.S.A.

[5] Nienberg J. W. (1977), 'Modeling of Desiccant Performance for Solar Desiccant Evaporative Cooling Systems' M.S. Thesis,School of Engineering and Applied Science, University of California, Los Angeles.

[6] Pesaran A.A. (1980),'Air Humidification in Packed Silica Gel Beds,'M.S. Thesis, School of Engineering and Applied Science,University of California, Los Angeles.

Books:-

[7] Cengel, Yunus A. and Boles, (1994) 'Thermodynamics An Engineering Approach' Second Edition, McGraw Hill Inc, New York.

[8] Lewis G. Harriman III, (1990),'The Dehumidification Handbook' Second Edition, Munters Corporation, U.S.A

[9] Edwards, D. K., V. E. Denny, and A. F. Mills (1979), 'Transfer Processes' (2nd ed.), Hemisphere/McGraw-Hill Book Company, Inc., New York.