

MODELING AND SIMULATION OF HMT ON NATURAL GAS DEHYDRATION USING SOLID DESICCANTS

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Abstract: *Natural gas is the fastest growing primary energy source and its use is expected to almost double to 2020, providing a relatively more clean fuel for the worldwide energy demand. Some contaminants, such as water vapor, have to be removed before its use. Dehydration of natural gas is of extreme importance to avoid the formation of hydrates and other associated problems. Different dehydration methods exist; however the solid desiccant approach can dehydrate natural gas to levels of water vapor lower than other methods. This paper presents a simple formulation for simulating the dehydration of a wet methane stream flowing through a porous medium composed of hygroscopic particles. The model assumes small resistance to diffusion within particles and takes heat and mass transfer rates into account by employing constant transfer coefficients. The formulation was developed based in the traditional mass and energy conservation principles, considering a one-dimensional transient scenario. A dimensional analysis is also performed and relevant dimensionless groups are introduced. The set of dimensionless parameters are similar to effectiveness-NTU groupings, widely used in heat exchangers. Despite its simplicity, the proposed formulation presents a new contribution since similar analysis is apparently unavailable in the gas dehydration literature. Finally, in order to illustrate the effect of varying the dimensionless groups the formulation is solved using a combined finite-volumes/method-of-lines approach. The results example how the dimensionless parameters can influence the dehydration process.*

Keywords: *Natural Gas, Adsorption, Dehydration, Solid Desiccant, Dehumidification.*

1. NOMENCLATURE

A	area
c_p	constant pressure specific heat
h_h	convective heat transfer coefficient
h_m	convective mass transfer coefficient
i	specific enthalpy
j''	mass flux
L	cylinder height
m	mass
\dot{m}	mass flow rate
t	time
T	temperature
v_i	process gas flow velocity
v_b	bulk velocity
x	distance from the cylinder entrance
W	dry basis adsorbed water concentration
Y	dry basis vapor concentration

Greek Symbols

ρ	density
ϵ	total porosity
τ	periodical time

Subscripts

adv	advective
b	bed
δ	closed pore
e	effective or apparent
g	natural gas
in	inlet
i	process gas flow
l	adsorbed water (liquid phase)
max	maximum
min	minimum
op	operation
out	exit
p	particle
π	pore
s	solid phase or surface
v	water vapor

Superscripts

*	dimensionless quantity
\sim	dry basis

2. INTRODUCTION

From the standpoint of processing and conditioning of natural gas, it should be brought to water levels established by oil and natural gas standards in order to prevent the formation and deposition of solid hydrates (Carroll, 2009) that may in the long run reduce the useful diameter of pipes (Jassim *et al.*, 2010; Mokhatab *et al.*, 2007). Furthermore, it can block partly or wholly valves, corrosion formation (Obanijesu *et al.*, 2011) and reduce equipments life expectancy.

To prevent hydrate formation, different techniques may be used. Among them, there are processes more widespread such as liquid and solid desiccant for gas dehumidification.

Work made by Gandhidasan *et al.* (2001) performs a study on the use of solid desiccants based on silica gel regarding the effects in various parameters changes. Moreover, a study was developed on the efficiency, i.e. to estimate the energy required in the regeneration process. Recently, Nastaj and Ambrozek (2009) performed a theoretical analysis of the adsorptive drying process of gases in a cyclic temperature swing adsorption system with two fixed bed adsorption columns using silica gel as solid desiccant. The computer simulations results are used to study the effects of the inlet gas relative humidity on the breakthrough curves in the adsorption step and purge gas temperature on the breakthrough curves in the desorption step.

Apparently, a notable feature of previous works on dehydration of natural gas using solid desiccant is a few development compared to other methods of natural gas dehydration. In this context, this work presents a mathematical formulation for heat and mass transfer for desiccant dehydration of natural gas. The formulation herein presented is based on normalized dimensionless groups used in studies like those developed for heat and mass exchangers (Sphaier and Worek, 2009) and for storage of adsorbed natural gas (da Silva and Sphaier, 2010).

3. PROBLEM FORMULATION

In this section, the main formulations for the dehydration of natural gas using solid adsorbents are presented. The reservoir has only one entrance and one exit for the natural gas flow. Initially, the reservoir is empty and the pressure and temperature are equal to the surroundings. Then, as the natural gas with higher levels of water vapor flows into the reservoir the process of dehumidification begins.

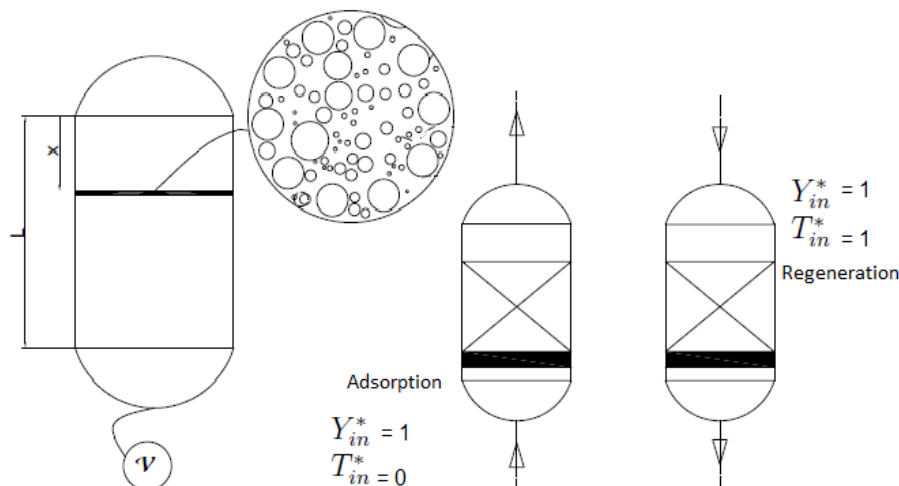


Figure 1. Volume, porous area view and dehydration cycle configuration

According to figure 1, two steps are done over dehydration cycle: adsorption and regeneration. The former intend to reduce the natural gas water vapor concentration and the latter is required to remove water of the solid desiccant providing the possibility of restarting the cycle.

The simplifying assumptions considered in the derivation of the current model are described such as: natural gas as water vapor and methane; incompressible flow; negligible pressure drop or loss; unidirectional flow; constant specific

heats; radiation effects are negligible due to the relatively low temperature differences; there is no chemical reaction nor any internal energy generation of any form; isotropic medium; no phase change besides that resulting from adsorption; and no heat losses to the environment.

3.1 Mass Balance

Since the mass of the solid portion and that of the natural gas are assumed invariable only a mass balance for water is required. Denoting \mathcal{V} as a portion of the vessel volume (that includes all volumes) and \mathcal{S} as its bounding surface, an integral mass balance is written as:

$$\frac{d}{dt} \int_{x_0}^{x_1} (\epsilon_b \rho_{v,i} + (1 - \epsilon_b) \epsilon_p \rho_{v,\pi} + \rho_l) \mathcal{A}_x dx = - (\mathbf{j}_{v,i}'' \cdot \hat{\mathbf{n}} \mathcal{A}_x)_{x=x_1} + (\mathbf{j}_{v,i}'' \cdot \hat{\mathbf{n}} \mathcal{A}_x)_{x=x_0} \quad (1)$$

where $\mathbf{j}_{v,i}'' = \rho_{v,i} \mathbf{v}_b = \epsilon_b \rho_{v,i} \mathbf{v}_i = \rho_g Y \mathbf{v}_b$ and $\mathcal{S} = \mathcal{A}_s / \mathcal{V}$

Finally, simplification yields:

$$\epsilon_b \frac{\partial Y}{\partial t} + (1 - \epsilon_b) \epsilon_p \frac{\partial Y_p}{\partial t} + \frac{\rho_b}{\rho_g} \frac{\partial W}{\partial t} + v_b \frac{\partial Y}{\partial x} = 0 \quad (2)$$

A general mass balance for the particles volume is given by:

$$\frac{d}{dt} \int_{x_0}^{x_1} (\rho_l + (1 - \epsilon_b) \epsilon_p \rho_{v,\pi}) \mathcal{A}_x dx = \int_{x_0}^{x_1} h_m \rho_g (Y - Y_p) \mathcal{S} \mathcal{A}_x dx \quad (3)$$

After simplifications, one can conclude that:

$$\frac{\rho_b}{\rho_g} \frac{\partial W}{\partial t} + (1 - \epsilon_b) \epsilon_p \frac{\partial Y_p}{\partial t} = h_m \mathcal{S} (Y - Y_p) \quad (4)$$

Subtracting equation (4) from (2) yields a mass balance for the process gas flow:

$$\epsilon_b \frac{\partial Y}{\partial t} + v_b \frac{\partial Y}{\partial x} = -h_m \mathcal{S} (Y - Y_p) \quad (5)$$

3.2 Energy Balance

Since pressure variations are assumed negligible, the following relations apply:

$$\begin{aligned} \frac{d}{dt} \int_{x_0}^{x_1} (\epsilon_b \rho_g (i_g + i_{v,i} Y) + (1 - \epsilon_b) \epsilon_p \rho_g (i_g + i_{v,\pi} Y_p) + i_l \rho_b W + i_s \rho_b) \mathcal{A}_x dx = \\ = - (\rho_g (i_{v,i} Y + i_g) (\mathbf{v}_b \cdot \hat{\mathbf{n}}) \mathcal{A}_x)_{x=x_1} + (\rho_g (i_{v,i} Y + i_g) (\mathbf{v}_b \cdot \hat{\mathbf{n}}) \mathcal{A}_x)_{x=x_0} \end{aligned} \quad (6)$$

Finally, simplification yields:

$$\epsilon_b \frac{\partial}{\partial t} (i_g + i_{v,i} Y) + (1 - \epsilon_b) \epsilon_p \frac{\partial}{\partial t} (i_g + i_{v,\pi} Y_p) + \frac{\rho_b}{\rho_g} \frac{\partial}{\partial t} (i_l W) + \frac{\rho_b}{\rho_g} \frac{\partial i_s}{\partial t} + v_b \frac{\partial}{\partial x} (i_{v,i} Y + i_g) = 0 \quad (7)$$

The energy balance for the particles is more simple, because there is only vapor diffusion and it is given by:

$$\begin{aligned} \frac{d}{dt} \int_{x_0}^{x_1} ((1 - \epsilon_b) \epsilon_p (i_g \rho_g + i_{v,\pi} \rho_{v,\pi}) + i_l \rho_l + i_s \rho_b) \mathcal{A}_x dx = \\ = \int_{x_0}^{x_1} (i_{v,f} h_m \rho_g (Y - Y_p) + h_h (T - T_p)) \mathcal{S} \mathcal{A}_x dx \end{aligned} \quad (8)$$

Lastly, simplification yields:

$$(1 - \epsilon_b)\epsilon_p \frac{\partial}{\partial t}(i_g + i_{v,\pi} Y_p) + \frac{\rho_b}{\rho_g} \frac{\partial}{\partial t}(i_l W) + \frac{\rho_b}{\rho_g} \frac{\partial i_s}{\partial t} = \left(i_{v,f} h_m (Y - Y_p) + \frac{h_h}{\rho_g} (T - T_p) \right) S \quad (9)$$

Subtracting equation (9) from (7) yields a energy balance for the process gas flow:

$$\epsilon_b \frac{\partial}{\partial t}(i_g + i_{v,i} Y) + v_b \frac{\partial}{\partial x}(i_g + i_{v,i} Y) = - \left(i_{v,f} h_m (Y - Y_p) + \frac{h_h}{\rho_g} (T - T_p) \right) S \quad (10)$$

3.3 Simplified Energy Balances in Terms of Temperatures

Defining dry-basis specific heats, an effective (apparent) density and introducing the heats of sorption, respectively as:

$$\rho_g \tilde{c} = \rho_g (c_{p_g} + Y c_{p_v}) \quad (11)$$

$$\rho_e \tilde{c}_e = \rho_b (c_s + c_l W) + \rho_g (c_{p_g} + Y_p c_{p_v}) (1 - \epsilon_b) \epsilon_p \quad (12)$$

$$\rho_e = \rho_b + (1 + \epsilon_b) \epsilon_p \rho_g \quad (13)$$

$$i_{sor}^p = i_{v,\pi} - i_l, \quad i_{sor}^i = i_{v,i} - i_{v,\pi}, \quad i_{sor} = i_{sor}^p + i_{sor}^i = i_{v,i} - i_l \quad (14)$$

Using the definitions of specific heats for perfect gases and incompressible substances, expanding equations (9) and (10), using and multiplying the mass conservation equations (4) and (5) by $i_{v,\pi}$ and $i_{v,i}$, for particles and process gas flow equations, respectively, yields:

$$\frac{\rho_e}{\rho_g} \tilde{c}_e \frac{\partial T_p}{\partial t} = \left(\varphi i_{sor}^i h_m (Y - Y_p) + \frac{h_h}{\rho_g} (T - T_p) \right) S + \frac{\rho_b}{\rho_g} i_{sor}^p \frac{\partial W}{\partial t} \quad (15)$$

$$\tilde{c} \left(\epsilon_b \frac{\partial T}{\partial t} + v_b \frac{\partial T}{\partial x} \right) = \left((1 - \varphi) i_{sor}^i h_m (Y - Y_p) - \frac{h_h}{\rho_g} (T - T_p) \right) S \quad (16)$$

where φ is the fraction of i_{sor}^i that contributes directly to heating (or cooling) the process gas flow; conversely, $1 - \varphi$ is the fraction of i_{sor}^i that contributes directly to heating (or cooling) the adsorbent particles.

4. NORMALIZATION

4.1 Dimensionless groups

The first dimensionless groups are the dimensionless dependent and independent variables involved in the studied problem:

$$T_p^* = \frac{(T_p - T_{ref})}{\Delta T}, \quad T^* = \frac{(T - T_{ref})}{\Delta T}, \quad Y_p^* = \frac{Y_p}{Y_{max}}, \quad Y^* = \frac{Y}{Y_{max}}, \quad W^* = \frac{W}{W_{max}} \quad (17)$$

$$t^* = \frac{t}{\tau}, \quad x^* = \frac{x}{L} \quad (18)$$

where $\Delta T = T_{max} - T_{min}$ and $T_{ref} = T_{min}$.

The next groups are the dimensionless parameters, such as the dimensionless dwell time (residence period), volumetric and heat capacities ratios, dimensionless numbers of transfer units, dimensionless concentration of water in the adsorbent, dimensionless heat of adsorption and heat capacity ratios, expressed respectively as:

$$\tau_{res} = \frac{L}{v_b} \epsilon_b, \quad \tau_{res}^* = \frac{\tau_{res}}{\tau}, \quad V_r = \frac{V}{\tau}, \quad V = v_b \mathcal{A}_x, \quad C_r = \frac{c_b \rho_b L \mathcal{A}_x}{\tau} \quad (19)$$

$$C = \rho_g v_b A_x c_{pg}, \quad V_r^* = \frac{V_r}{V}, \quad C_r^* = \frac{C_r}{C}, \quad \mathcal{X}_i = \frac{\tilde{c}}{c_{pg}}, \quad \mathcal{X}_p = \frac{\rho_e \tilde{c}_e}{\rho_b c_b}, \quad N_{tu}^h = \frac{h_h A_s}{C} \quad (20)$$

$$N_{tu}^m = \frac{h_m A_s}{V}, \quad \Omega = \frac{\rho_b}{\rho_g} \frac{W_{\max}}{Y_{\max}}, \quad i_{sor}^{p*} = i_{sor}^p \frac{\rho_g Y_{\max}}{\rho_b c_b \Delta T}, \quad i_{sor}^{i*} = i_{sor}^i \frac{\rho_g Y_{\max}}{\rho_b c_b \Delta T} \quad (21)$$

4.2 Dimensionless governing equations

For the mass balance of the particles, the dimensionless equation yields:

$$\Omega V_r^* \frac{\partial W^*}{\partial t^*} + (1 - \epsilon_b) \epsilon_p V_r^* \frac{\partial Y_p^*}{\partial t^*} = N_{tu}^m (Y^* - Y_p^*) \quad (22)$$

For the mass balance of the process gas flow, the dimensionless equation is written as:

$$\tau_{res}^* \frac{\partial Y^*}{\partial t^*} + \frac{\partial Y^*}{\partial x^*} = N_{tu}^m (Y_p^* - Y^*) \quad (23)$$

For the energy balance for the particles, the dimensionless equation is given by:

$$\mathcal{X}_p \frac{\partial T_p^*}{\partial t^*} = \varphi \frac{N_{tu}^m}{V_r^*} i_{sor}^{i*} (Y^* - Y_p^*) + \frac{N_{tu}^h}{C_r^*} (T^* - T_p^*) + \Omega i_{sor}^{p*} \frac{\partial W^*}{\partial t^*} \quad (24)$$

For the energy balance of the process gas flow, the dimensionless equation results:

$$\mathcal{X}_i \left(\tau_{res}^* \frac{\partial T^*}{\partial t^*} + \frac{\partial T^*}{\partial x^*} \right) = (\varphi - 1) N_{tu}^m \frac{C_r^*}{V_r^*} i_{sor}^{i*} (Y_p^* - Y^*) + N_{tu}^h (T_p^* - T^*) \quad (25)$$

4.3 Performance Assessment

The performance of the dehydration process is assessed by the dehydration effectiveness (η_m) and it has been employed for assessing the performance of desiccant wheels (Nóbrega and Brum, 2011; Niu and Zhang, 2002). The formulation comprises a measure of the level of dehydration of the gas stream with the ideal parameter $Y_{out,min}^* = 0$:

$$\eta_m = \frac{(Y_{in}^* - Y_{out}^*)}{(Y_{in}^* - Y_{out,min}^*)} \quad (26)$$

5. RESULTS AND DISCUSSION

To solve the equations, it was used the Finite Volume Method (Patankar, 1980) with a uniformly spaced mesh following the methodology presented in Sphaier and Worek (2009), and the entire implementation was done in the *Mathematica* system (Wolfram, 2003). To express the relationship between the quantity adsorbed W , humidity and temperature of gas in equilibrium with this phase, we used the following adsorption isotherm:

$$W^* (T_p^*, Y_p^*) = \frac{1}{1 - r + r/\phi}, \quad \phi = \phi(T_p, Y_p) = \frac{Y_p}{r_M^{v,g} + Y_p} \frac{p_{op}}{p_{vs}(T_p)}, \quad r_M^{v,g} = \frac{M_v}{M_g} \quad (27)$$

where ϕ is the relative humidity of natural gas presented in references (ASHRAE, 2005), r is the separation factor of the adsorption isotherm (Basmadjian, 1997) and $r_M^{v,g}$ is the relation between vapor and dry natural gas molecular masses (Friend *et al.*, 1989; Kohl and Nielsen, 1997).

The density of the gas was calculated assuming pure methane gas with ideal gas behavior. Table 1 presents the numerical data (Çengel and Boles, 1998) used in the simulations assuming silica gel as solid dehydration medium (Hubard, 1954).

Table 1. Values Used in the Numerical Solution

Parameters	Symbols	Values
Minimum Temperature (K)	T_{min}	300
Specific Mass of Methane (kg/m ³)	ρ_g	$5.512 \cdot 10^{-6} P_{op}$
Specific Heat of Methane (J/kg·K)	c_{p_g}	2253.7
Specific Heat of Adsorbent (J/kg·K)	c_b, c_s	921
Specific Heat of Liquid Water (J/kg·K)	c_l	4180
Specific Heat of Water Vapor (J/kg·K)	c_{p_v}	1872.3
Maximum Concentration of Water on Adsorbent (kg/kg)	W_{max}	0.45
Molecular Mass of Methane (kg/kmol)	M_g	16.043
Molecular Mass of Water (kg/kmol)	M_v	18.015
Methane Gas Constant (J/kg·K)	R_g	518.35
Particle Porosity	ϵ_p	0.366
Bed Porosity	ϵ_b	0.3
Maximum Concentration of Vapor (g/kg)	Y_{max}	32.1
Adsorption Heat (J/kg H ₂ O)	i_{sor}	2.7×10^6
Heat Capacity Ratio	C_r^*	10^{-1}
Volumetric Capacity Ratio	V_r^*	$570^{-1} C_r^*$
Dimensionless Period of Residence	τ_{res}^*	$0.3 V_r^*$
Dimensionless Concentration of Water in Adsorbent	Ω	19557
Dimensionless Heat of Adsorption	i_{sor}^{i*}	0

The dimensionless inlet values, Y_{in}^* and T_{in}^* , can assume different values for each process, but for the studied cases it was assumed $Y_{in}^* = 1$ and $T_{in}^* = 0$ at adsorption process and $Y_{in}^* = 1$ and $T_{in}^* = 1$ at regeneration process, as observed in figure 1. For the adsorption processes, the inlet condition describes that the fluid is totally saturated with water and the temperature is the minimum established. For the regeneration process, the absolute humidity of the gas is the same as the adsorption process inlet, however the temperature is the maximum stipulated.

For the first studied case with separation factor $r = 0.1$ and maximum temperature $T_{max} = 400$ K as shown in figure 2, the dehydration effectiveness (η_m) increases with pressure (p) and number of transfer unit (N_{tu}^h). Nearly by $N_{tu}^h = 4$, it is observed a non increasing behavior of η_m , so one can considered it as a best point operation. At some pressure value there is not significant η_m increase, as result the pressure can be limited to an operation value with minimum waste of compression power.

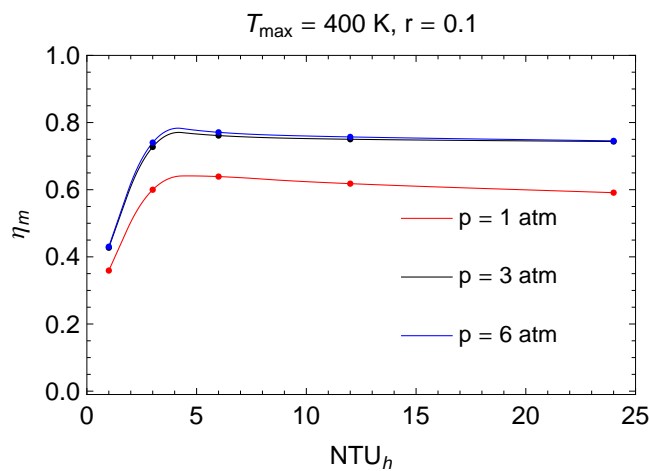


Figure 2. Variation of η_m with respect to N_{tu}^h for $r = 0.1$

In figure 3 with separation factor $r = 1$ and $T_{max} = 400$ K, the η_m also increases with p and N_{tu}^h . About $N_{tu}^h = 4$,

it is observed a non increasing behavior of η_m , so one can considered it as a good region of operation. At some pressure value there is not significant η_m increase, as result the pressure can be limited to an operation value with minimum waste of compression power. Relatively to the case shown in figure 3, it is identified a better η_m response to higher pressures, thus a solid desiccant with $r = 1$ is foremost to operate.

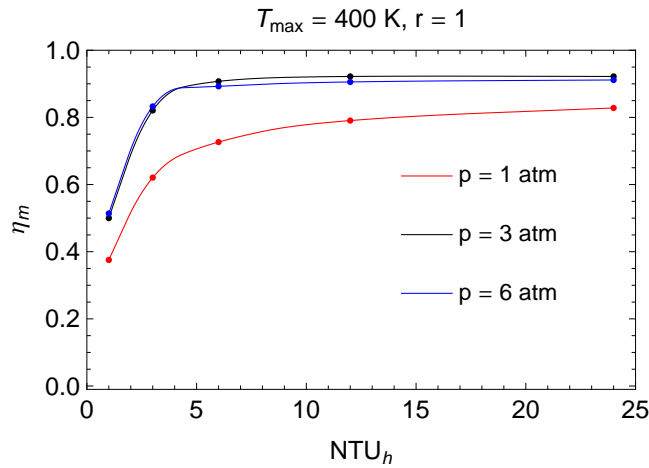


Figure 3. Variation of η_m with respect to N_{tu}^h for $r = 1$

For the last case as shown in figure 4 with separation factor $r = 10$ and $T_{max} = 400 \text{ K}$, it is noted one more time that the η_m increases with p and N_{tu}^h . About $N_{tu}^h = 5$, it is observed a constante behavior of η_m , so one can considered it as a good operation parameter. In this case, the pressure variation has more significance than the last two cases, however for lower pressures the η_m is not relatively fine.

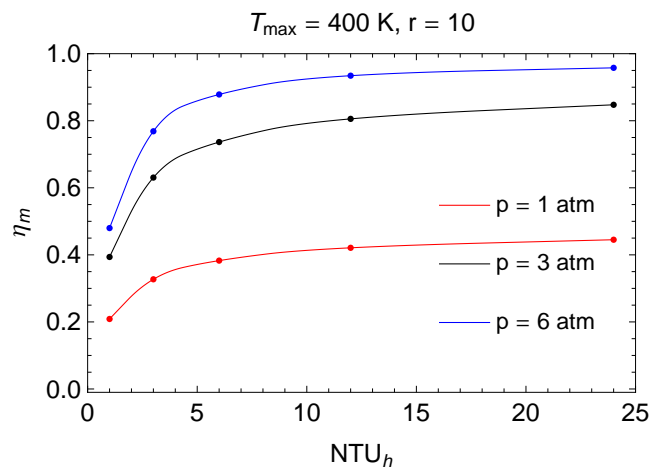


Figure 4. Variation of η_m with respect to N_{tu}^h for $r = 10$

6. CONCLUSIONS

This study presented a simple mathematical model for simulating the process of natural gas dehydration using solid desiccants. A system of one-dimensional governing equations for heat and mass transfer within the adsorbent material were obtained. Dimensionless groups associated to this problem were presented and the formulation was normalized using these groups. A numerical solution of the problem was implemented using the Finite Volumes Method combined with the Method of Lines. Then, simulation results were carried-out to illustrate the effect of varying the operation pressure on the dehydration effectiveness. The results show that for the simulated conditions, bigger pressures results in better

dehydration effectiveness. For most studied cases, there are better regions to operate such as between $N_{tu}^h = 4$ and $N_{tu}^h = 5$. For higher operation pressures, it is better to use solid desiccants with higher r to obtain greater η_m , however for lower pressures, it is recommended to use lower r to gain greater η_m . In spite of the relevance of this study, the results are still preliminary and future research should definitely be conducted.

7. ACKNOWLEDGEMENTS

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8. REFERENCES

- ASHRAE, 2005. *ASHRAE Handbook Fundamentals*. American Society of Heating, Refrigerating and Air-conditioning Engineers, Atlanta, GA.
- Basmadjian, D., 1997. *The Little Adsorption Book: A Practical Guide for Engineers and Scientists*. CRC Press.
- Carroll, J.J., 2009. *Natural Gas Hydrates A Guide for Engineers*. Gas Liquid Engineering, Ltd., 2nd edition.
- da Silva, M.J.M. and Sphaier, L.A., 2010. "Dimensionless lumped formulation for performance assesment of adsorbed natural gas storage". *Applied Energy*, Vol. 87, No. 5, pp. 1572–1580.
- Çengel, Y.A. and Boles, M.A., 1998. *Thermodynamics: An Engineering Approach*. WCB/McGraw-Hill, Hightstown, NJ, 3rd edition.
- Friend, D.G., Ely, J.F. and Ingham, H., 1989. "Thermophysical properties of methane". *Journal of Physical and Chemical*, Vol. 18(2), pp. 583–638.
- Gandhidasan, P., Al-Farayedhi, A.A. and Al-Mubarak, A.A., 2001. "Dehydration of natural gas using solid desiccants". *Energy*, Vol. 26, pp. 855–868.
- Hubard, S.S., 1954. "Equilibrium data for silica gel and water vapor". *Industrial and Engineering Chemistry*, Vol. 46, No. 2, pp. 356–358.
- Jassim, E., Abdi, M.A. and Muzychka, Y., 2010. "A new approach to investigate hydrate deposition in gas-dominated flowlines". *Journal of Natural Gas Science and Engineering*, Vol. 2, pp. 163–177.
- Kohl, A. and Nielsen, R., 1997. *Gas Purification*. Gulf Publishing Company, 5th edition.
- Mokhatab, S., Wilkens, R.J. and Leontaritis, K.J., 2007. "A review of strategies for solving gas-hydrate problems in subsea pipelines". *Energy Source*, Vol. 29, pp. 39–45.
- Nastaj, J. and Ambrozek, B., 2009. "Modeling of drying of gases using solid desiccants". *Drying Technology*, Vol. 27, pp. 1344–1352.
- Nóbrega, C.E.L. and Brum, N.C.L., 2011. "A graphical procedure for desiccant cooling cycle design". *Energy*, Vol. 36, pp. 1564–1570.
- Niu, J.L. and Zhang, L.Z., 2002. "Effects of wall thickness on the heat and moisture transfers in desiccant wheels for air dehumidification and enthalpy recovery". *Int. Comm. Heat Mass Transfer*, Vol. 29(2), pp. 255–268.
- Obanijesu, E.O., Akindeju, M.K., Vishnu, P. and Tade, M.O., 2011. "Modelling the natural gas pipeline internal corrosion rate resulting from hydrate formation". *21st European Symposium on Computer Aided Process Engineering - ESCAPE 21*, pp. 1161–1164.
- Patankar, S.V., 1980. *Numerical Heat Transfer and Fluid Flow*. Hemisphere.
- Sphaier, L.A. and Worek, W.M., 2009. "Parametric analysis of heat and mass transfer regenerators using a generalized effectiveness-NTU method". *International Journal of Heat and Mass Transfer*, Vol. 52, pp. 2265–2272.
- Wolfram, S., 2003. *The Mathematica Book*. Wolfram Media/Cambridge University Press, New York/Champaign, IL, 5th edition.

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