



HEAT AND MASS TRANSFER FORMULATION AND PARAMETERS VARIATION ANALYSIS FOR SOLID DESICCANT DEHYDRATION OF NATURAL GAS

Jorge Duarte Benth

Leandro Alcoforado Sphaier

Laboratório de Mecânica Teórica e Aplicada, Programa de Pós-Graduação em Engenharia Mecânica, Departamento de Engenharia Mecânica, Universidade Federal Fluminense

Rua Passo da Pátria 156, bloco E, sala 216, Niterói, RJ, 24210-240, Brazil

benth@vm.uff.br

lasphaier@id.uff.br

Abstract. *Natural gas production or transmission has an inherent problem such as the formation of hydrates due to water vapor presence, which can lead to safety hazards to production and transportation systems and to substantial economic risks. Eliminating water vapor can overcome hydrate related issues. For that, the solid desiccant approach can bring natural gas to levels of water vapor lower than other existing methods. It is carried out a formulation for simulating the dehydration of a wet methane stream flowing through different porous mediums composed of hygroscopic substances. Resistance to diffusion within particles is neglected and the model takes heat and mass transfer rates into account by employing constant transfer coefficients. The formulation was developed based on 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 literature. In order to illustrate the effects of varying the dimensionless groups, the formulation is solved using a combined finite-volumes/method-of-lines approach. The transient solutions are analyzed for different operation conditions and different dimensionless parameter values. The results example how the dimensionless parameters can influence the dehydration process.*

Keywords: *Natural Gas, Dehydration, Solid Desiccant, Hydrate, Dehumidification*

1. INTRODUCTION

Safety hazards to production and transportation systems and huge economic risks are provided when water vapor in natural gas (NG) production or transmission may form solid compounds, corrosion and other damages for pipes and equipments. 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. There is a large amount of examples to NG utilization such as vehicular natural gas, fuel for gas turbine, gas lift on oil production, among others.

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. Farag *et al.* (2011) performed a study of natural gas dehydration using 3A molecular sieve as solid desiccant material. This work aims to experimentally simulate an actual existing plant by means of water vapor concentration and gas flow rate variation. Netusil and Dittl (2011) carried out a comparison for three different widely applied methods for natural gas dehydration: absorption, adsorption and condensation.

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 have 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](#)).

2. 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.

According to Fig. 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.

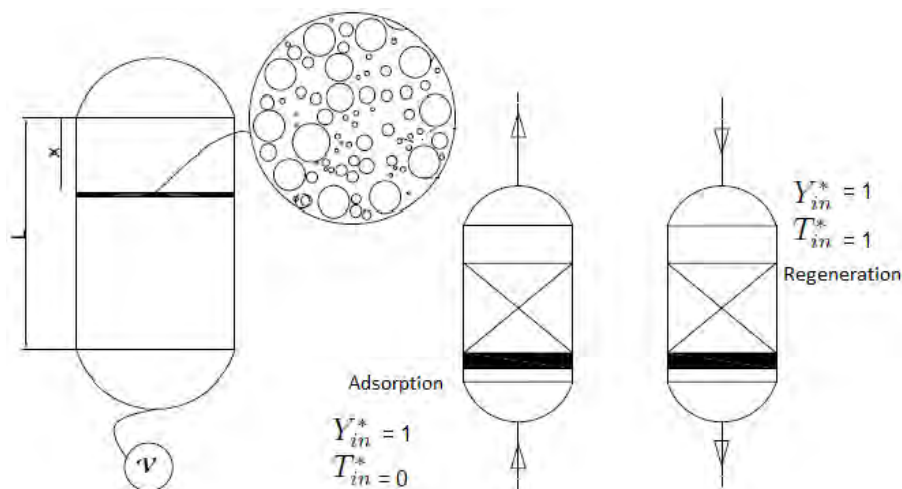


Figure 1. Volume, porous area view and dehydration cycle configuration

2.1 Simplifying Assumptions

The simplifying assumptions considered for this model are followed described: dilute vapor concentration in gas phase (moist gas); velocities are unaffected by variations in concentration; natural gas as water vapor and methane; incompressible flow (Mach number - $Ma < 0.3$); 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; micro-pore diffusion is fast such that this resistance is negligible; the influence of body forces (such as gravity) is negligible; the pores can be modeled as cylindrical and the porosity is homogeneous; the inlet fluid properties as well as the flow rate is uniform; reversible adsorption; ideal gas mixture; flow occurs in process gas flow, while diffusion may occur within particles; no phase change besides that resulting from adsorption; and no heat losses to the environment.

2.2 Mass Balance

Since the masses of solid portion and natural gas are assumed invariable, only a mass balance for water is required. An integral mass balance is written as:

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

denoting \mathcal{V} as the vessel volume and \mathcal{S} as its bounding surface, t means time, ϵ_b is bed porosity, $\rho_{v,i}$ stands for process gas flow density, ϵ_p denotes adsorbent porosity, $\rho_{v,\pi}$ means adsorbent density, ρ_l is adsorbed water density, $\mathbf{j}_{v,i}''$ denotes mass flux for the process gas flow, \mathcal{A} means perpendicular area, \mathbf{v}_b is the bulk velocity, \mathbf{v}_i is the process gas flow velocity, $\hat{\mathbf{n}}$ means normal vector, ρ_g means the natural gas density, Y is the dry basis vapor concentration, Y_p is the dry basis particle concentration and W stands for dry basis adsorbed water concentration. Also, one can define $\mathbf{j}_{v,i}'' = \rho_g Y \mathbf{v}_b$, $\rho_l = \rho_b W$ and $Y_p = \rho_{v,\pi} / \rho_g$.

Finally, assuming x as the variable for the distance from the cylinder entrance, mathematical manipulation and simplifications yield:

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

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

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

denoting h_m as the convective mass transfer coefficient, \mathcal{A}_s is the surface area and \mathcal{S} as particle specific surface area, respectively. As well, one can determine $\mathcal{S} = \mathcal{A}_s / \mathcal{V} = \mathcal{A}_x^{-1} d\mathcal{A}_s / dx$.

After simplifications, one can conclude that:

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

Subtracting Eq. 4 from Eq. 2 yields a mass balance for the process gas flow, such as:

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

2.3 Energy Balance

For the dehydration process, the energy balance can be define as:

$$\frac{dU}{dt} + \frac{dK}{dt} = \dot{Q} + \dot{W}_v + \dot{W}_n + \dot{W}_t + \dot{U}_{adv} + \dot{K}_{adv} \quad (6)$$

where U is internal energy, \dot{W}_n means the flux work and \dot{U}_{adv} stands for advective internal energy rate.

Since there is no heat or friction losses ($\dot{Q} \approx 0$ and $\dot{W}_t \approx 0$) and potential, kinetics and pressure variations are negligible ($dK/dt - \dot{K}_{adv} - \dot{W}_v \approx 0$), Eq. 6 can be expressed as:

$$\begin{aligned} \frac{d}{dt} \int_{\mathcal{V}} (\epsilon_b (i_g \rho_g + i_{v,i} \rho_{v,i}) + (1 - \epsilon_b) \epsilon_p (i_g \rho_g + i_{v,\pi} \rho_{v,\pi}) + i_l \rho_l + i_s \rho_b) d\mathcal{V} = \\ = - \int_{\mathcal{S}} (i_{v,i} \mathbf{j}_{v,i}'' + i_g \mathbf{j}_g'') \cdot \hat{\mathbf{n}} d\mathcal{A} \quad (7) \end{aligned}$$

denoting i_g as the dehydrated natural gas enthalpy, $i_{v,i}$ is the process gas flow enthalpy, $i_{v,\pi}$ is the particle enthalpy, i_l means the liquid phase enthalpy, i_s stands for adsorbent enthalpy and \mathbf{j}_g'' is the gas mass flux defined as $\mathbf{j}_g'' = \rho_g \mathbf{v}_b$.

Finally, simplification yields:

$$\begin{aligned} \epsilon_b \frac{\partial}{\partial t} (i_g + i_{v,i} Y) + (1 - \epsilon_b) \epsilon_p \frac{\partial}{\partial t} (i_g + i_{v,\pi} Y_p) + \frac{\rho_b}{\rho_g} \frac{\partial}{\partial t} (i_l W) + \\ + \frac{\rho_b}{\rho_g} \frac{\partial i_s}{\partial t} + v_b \frac{\partial}{\partial x} (i_{v,i} Y + i_g) = 0 \end{aligned} \quad (8)$$

Energy balance for the particles is given by:

$$\frac{dU}{dt} = \dot{Q} + \dot{I} \quad (9)$$

where \dot{I} is the enthalpy rate and \dot{Q} means the heat rate.

Mathematical manipulation results for Eq. 9 such as:

$$\begin{aligned} \frac{d}{dt} \int_V ((1 - \epsilon_b) \epsilon_p (i_g \rho_g + i_{v,\pi} \rho_{v,\pi}) + i_l \rho_l + i_s \rho_b) dV = \\ = \int_S i_{v,f} h_m \rho_g (Y - Y_p) dA + \int_S h_h (T - T_p) dA \end{aligned} \quad (10)$$

denoting $i_{v,f}$ as vapor film enthalpy, h_h is the convective heat transfer coefficient, T means process gas flow temperature and T_p is the particle temperature.

Finally, simplification yields:

$$\begin{aligned} (1 - \epsilon_b) \epsilon_p \frac{\partial}{\partial t} (i_g + i_{v,\pi} Y_p) + \frac{\rho_b}{\rho_g} \frac{\partial}{\partial t} (i_l W) + \frac{\rho_b}{\rho_g} \frac{\partial i_s}{\partial t} = \\ = \left(i_{v,f} h_m (Y - Y_p) + \frac{h_h}{\rho_g} (T - T_p) \right) S \end{aligned} \quad (11)$$

Subtracting Eq. 11 from Eq. 8 yields an energy balance for the process gas flow:

$$\begin{aligned} \epsilon_b \frac{\partial}{\partial t} (i_g + i_{v,i} Y) + v_b \frac{\partial}{\partial x} (i_g + i_{v,i} Y) = \\ = - \left(i_{v,f} h_m (Y - Y_p) + \frac{h_h}{\rho_g} (T - T_p) \right) S \end{aligned} \quad (12)$$

2.4 Simplified Energy Balances in Terms of Temperatures

Expanding Eq. 11 and Eq. 12, using and multiplying the mass conservation Eq. 4 and Eq. 5 by $i_{v,\pi}$ and $i_{v,i}$, for particles and process gas flow equations respectively yield:

$$\begin{aligned} (1 - \epsilon_b) \epsilon_p \left(\frac{\partial i_g}{\partial t} + Y_p \frac{\partial i_{v,\pi}}{\partial t} \right) + \frac{\rho_b}{\rho_g} \left(W \frac{\partial i_l}{\partial t} + (i_l - i_{v,\pi}) \frac{\partial W}{\partial t} + \frac{\partial i_s}{\partial t} \right) = \\ = \left((i_{v,f} - i_{v,\pi}) h_m (Y - Y_p) + \frac{h_h}{\rho_g} (T - T_p) \right) S \end{aligned} \quad (13)$$

$$\begin{aligned} \epsilon_b \left(\frac{\partial i_g}{\partial t} + Y \frac{\partial i_{v,i}}{\partial t} \right) + v_b \left(\frac{\partial i_g}{\partial x} + Y \frac{\partial i_{v,i}}{\partial x} \right) = \\ = \left((i_{v,f} - i_{v,i}) h_m (Y - Y_p) + \frac{h_h}{\rho_g} (T - T_p) \right) S \end{aligned} \quad (14)$$

Using the definitions of specific heats for perfect gases and incompressible substances, assuming the following dry basis specific heats: $\tilde{c} = c_{p_g} + Y c_{p_v}$ and $\rho_e \tilde{c}_e = \rho_b (c_s + c_l W) + \rho_g (c_{p_g} + Y_p c_{p_v}) (1 - \epsilon_b) \epsilon_p$ and substituting in Eq. 13

and Eq. 14, one can obtain:

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

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

where ρ_e is an effective or apparent density defined as $\rho_e = \rho_b + (1 + \epsilon_b) \epsilon_p \rho_g$. For the specific heats: \tilde{c} and \tilde{c}_e stand for the dry basis specific heat for the natural gas flow and effective solid (considering all volumes and adsorbed water); c_s , c_l , c_{p_g} and c_{p_v} are the constant pressure specific heat for solid adsorbent, liquid phase, natural gas and vapor, respectively; .

Introducing the heats of sorption for particle and process gas flow, respectively as $i_{sor}^p = i_{v,\pi} - i_l$ and $i_{sor}^i = i_{v,i} - i_{v,\pi}$. The remaining parameter 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. In other words:

$$\varphi = \frac{i_{v,f} - i_{v,\pi}}{i_{v,i} - i_{v,\pi}}, \quad 1 - \varphi = \frac{i_{v,i} - i_{v,f}}{i_{v,i} - i_{v,\pi}} \quad (17)$$

3. NORMALIZATION

3.1 Dimensionless groups

First dimensionless groups are the dependent and independent variables involved in the studied problem, such as:

$$T_p^* = \frac{(T_p - T_{ref})}{\Delta T}, \quad T^* = \frac{(T - T_{ref})}{\Delta T}, \quad Y_p^* = \frac{Y_p}{Y_{max}}, \quad Y^* = \frac{Y}{Y_{max}} \quad (18)$$

$$W^* = \frac{W}{W_{max}}, \quad t^* = \frac{t}{\tau}, \quad x^* = \frac{x}{L} \quad (19)$$

where Y_{max} is the maximum process gas flow dry basis concentration, W_{max} is the maximum adsorbent concentration, L is the cylinder height, τ is the operation time, ΔT is given by the subtraction between maximum and minimum temperatures as $\Delta T = T_{max} - T_{min}$ and the reference temperature is adopted as the minimum one, such as $T_{ref} = T_{min}$.

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 and dimensionless heat of sorption, expressed respectively as:

$$\tau_{res}^* = \frac{\tau_{res}}{\tau}, \quad V_r^* = \frac{V_r}{V}, \quad C_r^* = \frac{C_r}{C} \quad (20)$$

$$\mathcal{X}_i = \frac{\tilde{c}}{c_{p_g}}, \quad \mathcal{X}_p = \frac{\rho_e \tilde{c}_e}{\rho_b c_b} \quad (21)$$

$$N_{tu}^h = \frac{h_h \mathcal{A}_s}{C}, \quad N_{tu}^m = \frac{h_m \mathcal{A}_s}{V} \quad (22)$$

$$\Omega = \frac{\rho_b}{\rho_g} \frac{W_{max}}{Y_{max}} \quad (23)$$

$$i_{sor}^{p*} = i_{sor}^p \frac{\rho_g Y_{max}}{\rho_b c_b \Delta T}, \quad i_{sor}^{i*} = i_{sor}^i \frac{\rho_g Y_{max}}{\rho_b c_b \Delta T} \quad (24)$$

recognizing that the residence period, the volumetric capacities for cylinder and natural gas, the heat capacities for cylinder

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and natural gas are respectively defined as:

$$\tau_{res} = \frac{L}{v_b} \epsilon_b, \quad V_r = \frac{\mathcal{V}}{\tau}, \quad V = v_b \mathcal{A} \quad (25)$$

$$C_r = \frac{c_b \rho_b L A_x}{\tau}, \quad C = \rho_g v_b A_x c_{p_g} \quad (26)$$

3.2 Dimensionless governing equations

For the particle mass balance Eq. 4, the dimensionless equation yields:

$$\Omega V_r^* \frac{\partial W^*}{\partial t^*} + (1 - \epsilon_b) \epsilon_p V_r^* \frac{\partial Y_p^*}{\partial t^*} = N_{tu}^m (Y^* - Y_p^*) \quad (27)$$

For the process gas flow mass balance Eq. 5, the dimensionless equation is written as:

$$\tau_{res}^* \frac{\partial Y^*}{\partial t^*} + \frac{\partial Y^*}{\partial x^*} = N_{tu}^m (Y_p^* - Y^*) \quad (28)$$

For the particle energy balance Eq. 15, the dimensionless equation is given by:

$$\chi_p \frac{\partial T_p^*}{\partial t^*} = \varphi \frac{N_{tu}^m}{V_r^*} i_{sor}^{i*} (Y^* - Y_p^*) + \frac{N_{tu}^h}{C_r^*} (T^* - T_p^*) + \Omega i_{sor}^{p*} \frac{\partial W^*}{\partial t^*} \quad (29)$$

For the process gas flow energy balance Eq. 16, the dimensionless equation results:

$$\chi_i \left(\tau_{res}^* \frac{\partial T^*}{\partial t^*} + \frac{\partial T^*}{\partial x^*} \right) = (\varphi - 1) N_{tu}^m \frac{C_r^*}{V_r^*} i_{sor}^{i*} (Y_p^* - Y^*) + N_{tu}^h (T_p^* - T^*) \quad (30)$$

4. PERFORMANCE ASSESSMENT

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

$$\eta_m = \frac{Y_{in}^* - Y_{out}^*}{Y_{in}^* - Y_{out,min}^*} = 1 - \frac{Y_{out}^*}{Y_{in}^*} \quad (31)$$

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:

$$W^* (T_p^*, Y_p^*) = \frac{1}{1 - r + r/\phi} \quad (32)$$

$$\phi = \phi(T_p, Y_p) = \frac{Y_p}{r_M^{v,g} + Y_p} \frac{p_{op}}{p_{vs}(T_p)} \quad (33)$$

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

The density of the gas was calculated assuming pure methane with ideal gas behavior. Table 1 presents the numerical data used in the simulations, all of which were taken from references (Çengel and Boles, 1998; Van-Wylen *et al.*, 2009)

assuming silica gel as solid dehydration medium (Hubard, 1954).

Table 1. Values Used in the Numerical Solution

Parameters	Symbols	Values
Maximum Temperature (K)	T_{\max}	400
Minimum Temperature (K)	T_{\min}	300
Methane Density (kg/m ³)	ρ_g	$5.512 \cdot 10^{-6} p$
Methane Specific Heat (J/kg·K)	c_{p_g}	2253.7
Adsorbent Specific Heat (J/kg·K)	c_b, c_s	921
Liquid Water Phase Specific Heat (J/kg·K)	c_l	4180
Water Vapor Specific Heat (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
Heat of Sorption (J/kg H ₂ O)	i_{sor}	2.7×10^6
Volumetric Capacity Ratios	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
Inlet Initial Dimensionless Concentration (Adsorption)	Y_{in}^*	1
Inlet Initial Dimensionless Temperature (Adsorption)	T_{in}^*	0
Inlet Initial Dimensionless Concentration (Regeneration)	Y_{in}^*	1
Inlet Initial Dimensionless Temperature (Regeneration)	T_{in}^*	1

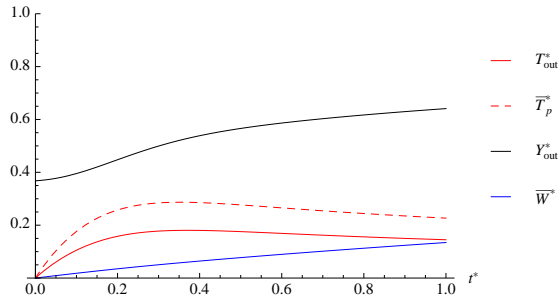
The dimensionless inlet values, Y_{in}^* and T_{in}^* , can assume different values for each process, but for studied case it was assumed $Y_{in}^* = 1$ and $T_{in}^* = 0$ for adsorption process; and $Y_{in}^* = 1$ and $T_{in}^* = 1$ for regeneration process, as observed in Fig. 1. For the adsorption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

The set of steps set out in Fig. 2 adopted for the Heat Capacity Rate the value of $C_r^* = 0.1$ and was determined for several values of Heat Number of Transfer Unit (N_{tu}^h). Thus, the adsorption process expresses important caveats, such as the dimensionless outlet temperature of the natural gas flow (T_{out}^*) shows an increase at the beginning of the process and, after passing a peak, it decreases even between values lower than the dimensionless inlet temperature of the gas. The heating occurs because the water adsorption phenomenon of water by the solid desiccant.

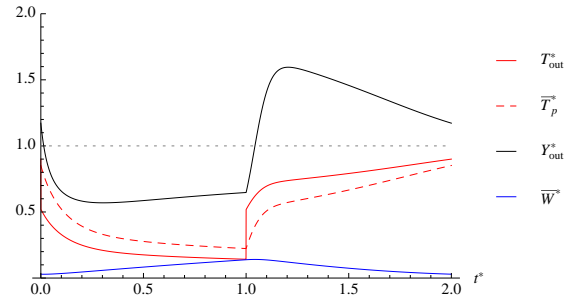
Still on the Fig. 2, the dimensionless outlet temperature of the particle (T_p^*) exhibits behavior similar to that established for the dimensionless outlet temperature of the process gas flow (T_{out}^*). The dimensionless concentration for the process gas flow (Y_{out}^*) behaves softer according to N_{tu}^h increases. And, generally, grows with the increasing dimensionless time (t^*), i.e. it leaves the desiccant material with a greater quantity of water. This can be proven by the fact that the dimensionless concentration of the desiccant (W^*) also increase as time passes, thus leading it to saturation. Also, note that the peaks related to temperatures become more pronounced when N_{tu}^h increases, because it is facilitating the heat exchange between the process gas flow and the solid adsorbent.

Now for the Dehydration Effectiveness (η_m) as observed on Fig. 3 with separation factor $r = 10$, it is noted that the η_m increases with p and N_{tu}^h . About $N_{tu}^h = 5$, it is observed an uniform behavior of η_m , so one can considered it as a good operation parameter. In this case, the pressure variation has more significance and higher pressures would be more recommended to accomplish higher dehydration effectiveness.

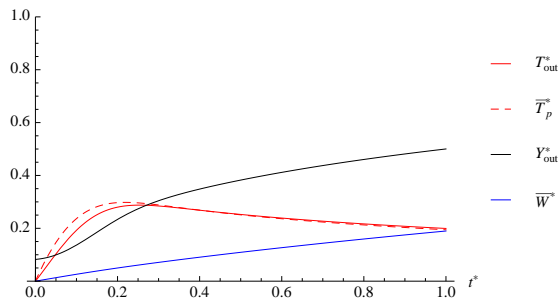
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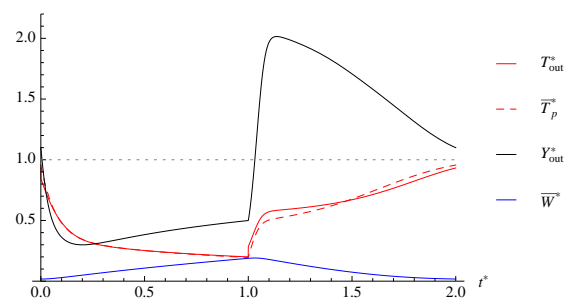
(a) Concentration and Temperature for First Cycle Adsorption, $N_{tu}^h = 1$ and $C_r^* = 0.1$.



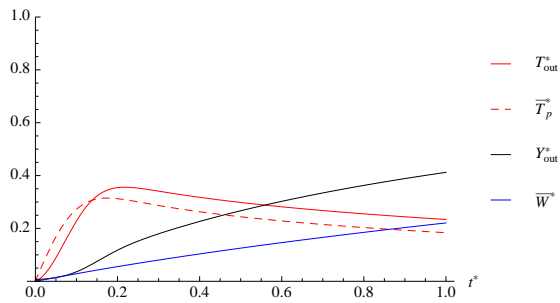
(b) Concentration and Temperature for Full Cycle, $N_{tu}^h = 1$ and $C_r^* = 0.1$.



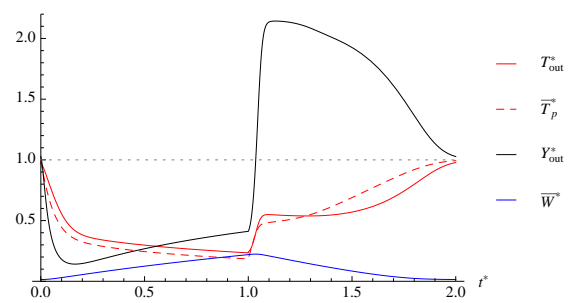
(c) Concentration and Temperature for First Cycle Adsorption, $N_{tu}^h = 2.5$ and $C_r^* = 0.1$.



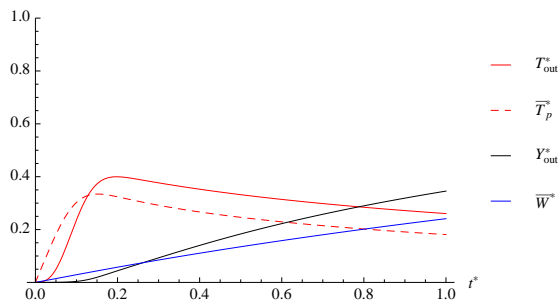
(d) Concentration and Temperature for Full Cycle, $N_{tu}^h = 2.5$ and $C_r^* = 0.1$.



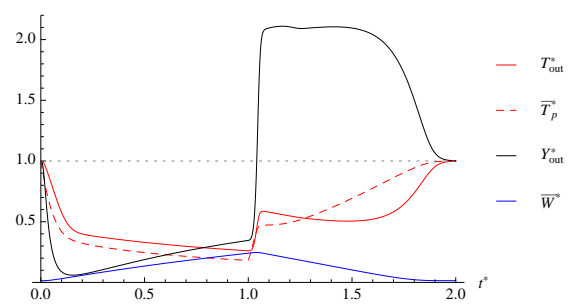
(e) Concentration and Temperature for First Cycle Adsorption, $N_{tu}^h = 5$ and $C_r^* = 0.1$.



(f) Concentration and Temperature for Full Cycle, $N_{tu}^h = 5$ and $C_r^* = 0.1$.



(g) Concentration and Temperature for First Cycle Adsorption, $N_{tu}^h = 10$ and $C_r^* = 0.1$.



(h) Concentration and Temperature for Full Cycle, $N_{tu}^h = 10$ and $C_r^* = 0.1$.

Figure 2. Average Temperature and Concentration for $C_r^* = 0.1$.

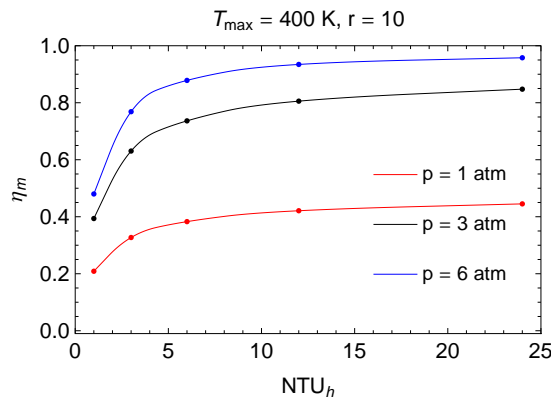


Figure 3. Variation of η_m with respect to N_{tu}^h for $r = 10$

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 for the temperature and concentration behaviors; and to illustrate the effect of varying the operation pressure on the dehydration effectiveness.

The results show that for the simulated conditions: better responses can be obtained with higher Heat Number of Transfer Unit (N_{tu}^h), like smaller time needed for the regeneration process and higher removed water mass. Bigger pressures results in better Dehydration Effectiveness (η_m). Also, there are better regions to operate such as between $N_{tu}^h = 4$ and $N_{tu}^h = 5$. Finally, it would be better recommended to operate using 6 bar pressure, in order to assess higher dehydration effectiveness.

In spite of the relevance of this study, the results are still preliminary and future research should definitely be conducted.

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