BİR ADSORBENT YATAKTA ISOBARİK ADSORPSİYON PROSESİ İÇİN YEREL ISIL DENGE VE SABİT BASINÇ KABULUNUN DOĞRULANMASI

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Özet: Bu çalışmanın amacı, adsorbent yatakta ısı ve kütle transferini analiz etmek için kullanılan yerel ısıl denge ve sabit basınç yaklaşımı varsayımların geçerliliğini araştırmaktır. İçerisinde silika jel partikülleri içeren bir yatak ile su kabı olan bir deney düzeneği tasarlanmış ve adsorpsiyon sürecinde yatağın içinde farklı yerlerde yerel sıcaklık ve basınç ölçülmüştür. Ayrıca, sabit basınç yaklaşımı ve yerel ısıl denge varsayımlara dayalı ısı ve kütle transferi denklemleri çözülmüştür. Sayısal sonuçlar, ilgili deneysel sonuçlarla karşılaştırılmış ve aralarında oldukça iyi bir uyum tespit edilmiştir. Gerçekleştirilen karşılaştırmaya dayanarak, incelenen yatak için iki önemli sonuç şu şekildedir: a) katı madde ve su buharı arasında yerel ısıl denge bulunmaktadır, b) bir yatak içinde parçacıklar arası kütle transferi direnci ihmal edilebilir düzeyde olup konsantrasyonunun ve sıcaklığın belirlenmesi için sabit basınç yaklaşımı geçerlidir. Ayrıca, bu çalışmada sunulan deneysel sonuçlar diğer araştırmacıların sayısal çalışmalarının geçerliliğini doğtulamak için değerli veriler sağlayacaktır.
Anahtar Kelimeler: Adsorpsiyon, ısı ve kütle transferi, yerel ısıl denge, sabit basınç yaklaşımı.

VALIDATION OF LOCAL THERMAL EQUILIBRIUM AND UNIFORM PRESSURE ASSUMPTIONS FOR AN ISOBARIC ADSORPTION PROCESS IN AN ADSORBENT BED

Abstract: The aim of the present study is to investigate the validation of the local thermal equilibrium and uniform pressure approach assumptions employed for analyzing heat and mass transfer in the adsorbent beds. An experimental setup consists of an adsorbent bed filled with silica gel particles and a water vessel was designed and constructed such way to measure the local temperature and pressure in different locations inside the bed during the adsorption process. Moreover, the heat and mass transfer equations based on uniform pressure approach and local thermal equilibrium assumptions were solved. The numerical results were compared with the corresponding experimental results and excellent agreement between them was observed. Based on the performed comparisons, two significant remarks for the studied bed were concluded, a) a local thermal equilibrium between solid and water vapor exists, b) the interparticle mass transfer resistance in the bed is negligible and the uniform pressure approach for determination of concentration and temperature distributions inside the bed can be used. Furthermore, the presented experimental results in this study provide valuable data for validation of computational studies for other researchers.
Keywords: Adsorption, heat and mass transfer, local thermal equilibrium, uniform pressure approach.

NOMENCLATURE

A   constant for Eqs. (8) and (9) , [min]
C_p specific heat of adsorbent, [J/Kg K]
D_{eff} effective diffusivity, [m²/s]
D_o reference diffusivity, [m²/s]
P   pressure, [kPa]
R   radial direction, m, gas constant, [J/molK]
r_p radius of adsorbent granule, [m]
T   temperature, [K]
t   time, [sec.]
W local adsorbate concentration, [kg_l/ kg_s]
$\overline{W}$ average adsorbate concentration, [kg_l/ kg_s]
z   axial direction

Greek symbols

ρ   density, [kg/m³]
ΔH_{ads} heat of adsorption, [J/kg]
φ porosity
ξ a dependent variable
λ   thermal conductivity, [W/mK]
τ time [min]

Subscriptions

bottom   bottom part Teflon sheet
min-os   min. temp. of bed outer surface
init   initial
eff   effective

v	vapor
l	adsorbate
s	adsorbent
sat	saturation
t	at time t
upper	upper part Teflon sheet
∞	equilibrium

INTRODUCTION

The attention of researchers on analyzing heat and mass transfer in adsorbent beds increases in recent years due to wide applications of adsorption processes in industry such as gas separation, storage of gases (hydrogen, CO_2 etc), thermal energy storage and adsorption chillers. A fixed adsorbent bed can be open or closed type. In the open type adsorbent bed, the adsorption process occurs under atmosphere pressure while high or low pressure exists in a closed type adsorbent bed. Many theoretical and numerical studies performed on analyzing heat and mass transfer in both types of adsorbent beds. In some studies, the assumption of local thermal equilibrium was used and consequently the heat transfer in adsorbent bed is represented by a single energy equation. For instance, Won et al. (2012) modeled heat and mass transfer in an open fixed-bed adsorber for CO_2 capture by using zeolite 13X. They assumed a local thermal equilibrium condition between zeolite 13X particles and gas phases and solved a single heat transfer equation involving both phases. Bart et al. (1996) performed a computational study on toluene adsorption in an open fixed-bed adsorber filled with activated carbon particles. A local thermal equilibrium between solid and gas phases was considered and a single energy equation was solved to determine the temperature distribution in the bed. Similarly, the assumption of local thermal equilibrium condition between solid and gas phases was employed by Xiao et al. (2013) who simulated hydrogen storage tank packed with metal-organic framework (i.e., MOF). Recently, Vasiliev et al. (2014) performed numerical and experimental study on the storage of a hydrogenous gas in an activated carbon fibrous material. The local thermal equilibrium assumption was also employed in their computational study. Our literature survey showed that most of recent computational studies on heat and mass transfer in the adsorbent bed of adsorption heat pump also employed the assumption of local thermal equilibrium between solid and fluid. For instance, Leong and Liu (2004, 2008) who numerically analyzed heat and mass transfer in the adsorbent bed of an adsorption heat pump operates with zeolite NaX and 13X /water pairs assumed a local thermal equilibrium between solid adsorbent particle and water vapor. The performance of adsorption heat pump system with active carbon/ammonia pair was analyzed by Chahbani et al. (2002). A local thermal equilibrium condition between the active carbon and ammonia vapor were assumed and a single heat transfer equation was derived based on this assumption. The assumption of local thermal equilibrium between solid and fluid phase in porous media is a controversial issue and this leads researchers to perform studies on the validation of local thermal equilibrium assumption in porous media and adsorbent bed (e.g., Chua

et al. 1999, Saha et al. 2003, Wang and Chua 2007, Cacciola et al. 1993). The results of these studies show that the assumption of local thermal equilibrium depends on various parameters such as porosity, thermal conductivity ratio, particle based Peclet number.

Furthermore, the assumption of the uniform pressure approach was also used in some studies performed on the analysis of heat and mass in closed type fixed adsorbent bed. The interparticle mass transfer resistance was neglected and the entire adsorbent bed was assumed under uniform pressure. For instance, Ilis et al. (2010, 2011) used the assumption of the uniform pressure to study heat and mass transfer in an annular type adsorbent bed filled with silica gel granules for an isobaric adsorption process. Chua et al. (1999) studied transient modeling of a double bed silica gel–water of adsorption chiller. They assumed that the pressure in the bed is uniform and the entire bed is at evaporator pressure during the adsorption and in condenser pressure during desorption processes. The validation of uniform pressure approach in closed type adsorbent bed was investigated by Ilis et al. (2013) on the other hand they had many studies based on non-uniform pressure approach (2009). Ilis et al. (2013) found that the results of uniform and non-uniform pressure approach match each other for the large size of adsorbent particle (such as 2 mm diameter), however by reducing of adsorbent particle size (such as 0.02 mm diameter) a difference between the temperature and concentration distributions of uniform and non-uniform pressure approaches appears. Also, Solmus and Yildirim (2014) analyzed the performance of an adsorption cooling system for various adsorbent-adsorbate working pairs for different adsorption, desorption, evaporator and condenser temperatures. The amount of energy supplied to the system during regeneration period was evaluated by the heat of adsorption of the working pair. They found the performance of the system is significantly getting better with increasing evaporator-desorption temperatures and with decreasing condenser-adsorption temperatures.

The aim of the present study is a) to design and construct a closed type adsorbent bed operates at low pressure and to measure the local temperature at different locations and consequently to observe the gradient of temperature with time in the bed , b) to experimentally show that the uniform pressure approach can be used for the beds with sufficiently large size adsorbent particles, c) to prove that the local thermal equilibrium condition is valid assumption for the designed closed type adsorbent bed. In order to attain the aforementioned aims, an experimental set up with special design having very low leakage rate was constructed and the thermocouples for measuring local temperature were located inside the bed. Furthermore, heat and mass transfer equations are derived and solved numerically for determination of the temperature and concentration variations with time during adsorption process under the assumptions of uniform pressure and local thermal equilibrium. The numerical and experimental results are compared with each other and good agreement is observed indicating that the local thermal equilibrium condition between the adsorbent particle and water vapor exists and

uniform pressure approach is a valid assumption for the studied bed. It should be mentioned that validation of results obtained numerically for heat and mass transfer in adsorbent bed is troublesome issue due to difficulties in measuring of local temperature in the closed type adsorbent bed. Hence, for other researchers, the presented experimental results are valuable data for the validation of their computational studies.

EXPERIMENTAL STUDY

In this section, the designed experimental setup and adsorbent bed are explained in details and the followed experimental procedure is also described.

The Designed Setup

The constructed setup and its components are shown in Figure 1. The setup had two main components as an adsorbent bed and a water vessel. The adsorbent bed and water vessel were fixed by a steel frame. The water vessel was filled with water while the adsorbent bed was filled with silica gel particles. The water vessel had a volume of 10 lt and the level of water in the water vessel could be observed from the sight glass mounted on the casing of water vessel. The temperature of the water in the vessel is decreased during the evaporation. That's why a heat exchanger was located inside the water vessel to transfer heat to the water. This heat exchanger used to fix the temperature of water inside the vessel at the desired value. The heating water inside the heat exchanger was circulated between a constant temperature water bath and the water vessel. A thermocouple located inside the water vessel to measure the evaporation temperature. A vacuum tight valve was mounted between the adsorbent bed and water vessel.
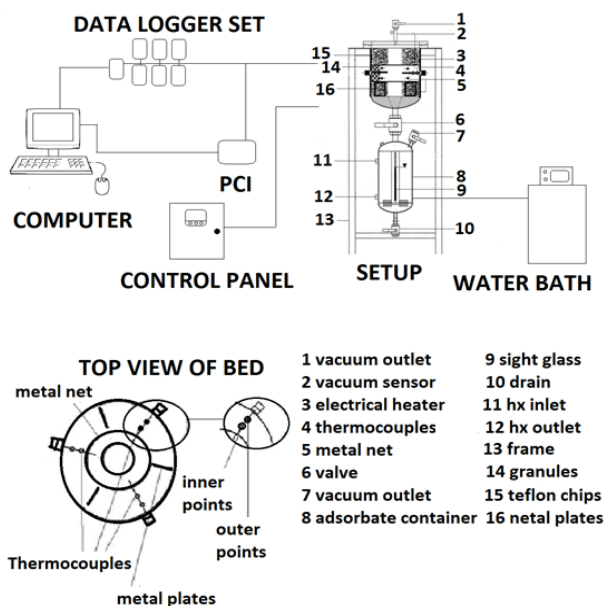
Figure 1. A schematic view of the designed setup

The adsorbent bed was made of an annular steel container (type 304) with 4 mm thickness, 309 mm inner diameter and height of 290 mm. In the center of the adsorbent bed, a free space with 80 mm radius in the vertical direction was provided for easy transferring of water vapor in axial direction. There were three outlets at the circumferences of the container with 120° angle between them for the thermocouples located in the adsorbent bed (Figure 2).

Figure 2. A top view of the adsorbent bed to show the location of the thermocouples

The adsorbent bed consists of three parts. The bottom and top parts of the bed were filled with Teflon chips as thermal insulator. Totally 3.2 kg silica gel was located in the mid part of the bed and the height and thickness of silica gel layer were 100 and 75 mm. The Teflon sheets were used and located tightly between the insulation parts and adsorbent particles part. Thermocouples were placed on different points of the surface of the Teflon sheet for measuring the Teflon sheet temperature. To obtain the temperature variation inside the adsorbent bed, totally 6 thermocouples were located inside of the bed. The locations of thermocouples are shown both in Figure 1(b) and Figure 2. The thermocouples were located at 0, 120, and 240 degrees in angular direction and their locations from the center of adsorbent bed were 105 and 130 mm. The silica gel used in the adsorbent bed was supplied from Merck Co., the physical adsorption of gas molecules on a solid surface (i.e., BET), surface area and average pore diameter of silica gel were given as 626 m^2g^{-1} and 2.0-2.5 nm, respectively. The specific heat and the density of the silica gel were given as 1 kJ/kg^{o}C and 750 kg/m^3, respectively. The heat of adsorption of the silica gel- water pair was measured as 2644 kJ based on Ref (Demir et al. 2011).

The Experimental Procedure

Three steps were followed to perform an experiment. In the first step, the water vessel was filled with 9 lt deionized water. Air inside the water vessel was evacuated and the pressure of water vessel was reduced to the set pressure of the adsorption process by using a vacuum pump. After the evacuation of the air, the adsorbent bed was evacuated while being heated to remove water content and other gases in the silica gel particles. The adsorbent bed was heated by the electrical resistance on its outer surface. The drying process of silica gel continued for four days while its temperature was maintained at 100°C. In the second step, the temperatures of bed and water vessel were stabilized to the desired initial temperature. The second step was finished when the bed and water vessel temperatures became uniform and steady. It should be

mentioned that, during the second step, the evacuation process from the adsorbent bed was continued. Finally, the adsorption process was performed in the third steps. When the entire adsorbent bed and water vessel temperatures were fixed to the desired temperature, the valve between water vessel and adsorbent bed was fully opened and adsorption process was started. The evaporated water in the vessel flowed into the adsorbent bed and adsorbed by silica gel granules. Throughout the adsorption process, the outer surface temperature of adsorbent bed was not permitted to be dropped from the desired temperature. The cooling of adsorbent bed was done by natural convection from the outer surface of the adsorbent bed. The water level inside of the evaporator was marked in certain time intervals, during the adsorption process and by this way the evaporated water amount was measured. The isobaric adsorption process was continued until the level of water inside the water vessel was not changed indicating that the adsorption process reaches into equilibrium condition. During the adsorption process, the temperatures at different locations of the bed were measured. After completing of adsorption process, the valve between the adsorbent bed and the water vessel was closed. These pressure gauges have ±0.4% accuracy. All thermocouples were calibrated by using Fluke 714 temperature calibrator which has 0.025% accuracy. The response time of the K type thermocouples is 0.5 sec.

NUMERICAL STUDY

The made assumptions for numerical study in the present study are; 1) the adsorbent bed consists of uniform size spherical adsorbent particles, 2) the bed porosity is constant for different particle sizes, 3) the interparticle resistance between the particles is neglected and uniform pressure approach is used, 4) a local thermal equilibrium exits between the silica gel particles and water vapor 5) the thermal resistance within the adsorbent particle is neglected, 6) thermal properties of the adsorbent, adsorptive and adsorbate are constant, 7) heat transfer at the inner radius of bed (i.e., $R = R_i$) is negligible, 8) wall thermal resistance between the bed surface and particle is not considered, 9) the heat of adsorption is assumed constant.

Governing Equations

The governing equations for the problem are heat transfer equation for adsorbent bed and mass balance equation for the silica gel particle. The heat transfer equation was written for radial and axial directions of the bed. The heat transfer equation for the adsorbent bed can be written as:

$$(\rho C_p)_{eff} \frac{\partial T}{\partial t} =$$
$$\lambda_{eff} \frac{1}{R} \frac{\partial}{\partial R}\left(R\frac{\partial T}{\partial R}\right) + \lambda_{eff} \frac{\partial}{\partial z}\left(\frac{\partial T}{\partial z}\right) + (1-\varphi)\rho_s \Delta H_{ads}\frac{\partial \overline{W}}{\partial t} \quad (1)$$

where $(\rho C_p)_{eff}$ and λ_{eff} are the effective thermal capacitance and conductivity of the adsorbent bed, and defined as:

$$(\rho C_p)_{eff} = (1-\varphi)\left\{(\rho C_p)_s + \rho_s C_{p_l}\overline{W}\right\} + \varphi(\rho C_p)_v$$
(2)
$$\lambda_{eff} = (1-\varphi)\lambda_s + \varphi\lambda_v \quad (3)$$

Numerical results showed that (Ilis et al. 2010) the Linear Drive Force (LDF) and solid diffusion models provide similar results. Although the analytical solution of solid diffusion model provides exact solution for the changes of adsorbate concentration in the particle, the LDF model is more preferable due to saving of computational time. That's why LDF model that also includes the effect of intraparticle resistance is used to determine the change of mean water concentration in the particle with time.

$$\frac{\partial \overline{W}}{\partial t} = \frac{15 D_{eff}}{r_p^2}\left(\overline{W}_\infty - \overline{W}\right) \quad (4)$$

where D_{eff} and r_p represent effective diffusivity and radius of the adsorbent particle. The following isotherm equation can be used to determine adsorbate equilibrium concentration in the silica gel particle for a given pressure and temperature (Won et al. 2012, Sakoda and Suzuki 1984, 1986):

$$\overline{W}_\infty = k\left(P/P_{sat}\right)^{1/n} \quad (5)$$

where k and n are the constants for the specific adsorbent-adsorbate pair. The symbol P_{sat} represents water vapor saturation pressure at the considered temperature. Based on the suggested isoster by Ref. (Demir 2008), the values of k and n are found. When P/P_{sat} ratio is less than 0.1233, the values of k and n are found as 0.3092, 0.8565. For P/P_{sat} greater than 0.1233, the values of k and n are 0.1543, 0.5384, respectively. The initial and boundary conditions of the problem for uniform pressure approach in radial and axial directions are given in Table 1.

Table 1. The initial and boundary conditions of the problem for the uniform pressure approach in r and z directions

Uniform Pressure Approach				
Dependent variable	B.C at $R=R_i$	B.C at $R=R_o$	B.C at Z = 0 B.C at Z=100 mm	Initial conditions
Temp. (K)	$\partial T/\partial R = 0$	$T = T(t)$	$T = T(t)$	$T = T_{init}$
Water vapor pressure (kPa)	$P = P_{vessel}$	$P = P_{vessel}$	$P = P_{vessel}$	$P = P_{vessel}$
Adsorbate concentration (kg$_v$ kg$_s^{-1}$)	$W = f(P,T)$	$W = f(P,T)$	$W = f(P,T)$	$W = 0$

The bed porosity was measured as 0.45. The density and the specific heat of the silica gel were taken from the silica gel product manual as 750 kg/m^3 and 1 kJ/kg^{o}C, respectively. The heat of adsorption for the silica gel-water pair was taken as 2644 kJ/kg (Demir et al. 2011). The effective thermal conductivity was 0.106 W/mK

(Demir et al. 2011). The average diameter of the silica gel particles inside of the bed was measured as 3.5 mm. The adsorption rate in a single adsorbent particle is not constant during adsorption period. The period can be divided into two regions as long and short term regions in order to provide an accurate correlation and determine effective mass diffusivity precisely. The effective mass diffusivity equations, given in Ref (Demir 2008), for the employed silica gel-water pair were used. Two mass diffusivity equations were suggested in that study for the short and the long terms as;

For short term (if $W_t/W_\infty < 0.3$)

$$D_{eff} = 1.28x10^{-2} e^{(\frac{-57758}{RT})} \qquad (6)$$

For long term ($W_t/W_\infty > 0.7$)

$$D_{eff} = 2.48x10^{-6} e^{(\frac{-29066}{RT})} \qquad (7)$$

These equations were used for determination of effective thermal diffusivity in the present numerical study. The thermal resistance of the bed casing was taken into consideration. The stainless steel thermal conductivity and casing thickness were 16.2 W/mK and 4 mm, respectively. A polynomial relationship were obtained for determination of variation of the bed surface temperature, temperatures of the bottom and upper parts of the Teflon sheets by using the measured temperatures during the experiments. The following polynomial used to represent those temperatures for different experiments presented in this study:

For $t < A$ then

$$T(\tau) = a_1\tau^6 + a_2\tau^5 + a_3\tau^4 + a_4\tau^3 + a_5\tau^2 + a_6\tau + a_7 \qquad (8)$$

For $t > A$ then

$$T(\tau) = b_1\tau^4 + b_2\tau^3 + b_3\tau + b_4 \qquad (9)$$

$T(\tau)$ shows the average temperature of the upper and lower plate. The parameters of A, a and b are constant and their values vary with the experiment. The values of these coefficients are given in Table 2 for the each presented experiment in this study. It should be mentioned the value of τ is minute in Eq. (8), (9) and Table 2.

Solution Procedure

Finite difference method was used to solve the governing equations. The heat transfer equation (Eq. (1)) was solved to determine the local temperature in the adsorbent bed. Then, the obtained temperature values were used to solve the mass transfer equation of the silica gel particles (Eq. (4)) and to determine the water concentration in the silica gel particle. An inner iteration was used to obtain the simultaneous solution of the mass transfer equation for the silica gel particle and heat transfer equation for the adsorbent bed. After obtaining the simultaneous solution for a time step, the procedure

Table 2. Values of the coefficients for polynomial equation obtained from experimental measured temperatures for determination of outer surface of the bed and upper and bottom parts of the Teflon sheets.

	For experiments with T_{min-os} = 63°C			For experiments with T_{min-os} = 73°C		
	T_{surf} (°C)	T_{upper} (°C)	T_{bottom} (°C)	T_{surf} (°C)	T_{upper} (°C)	T_{bottom} (°C)
	A=100	A=150	A=150	A=100	A=150	A=150
a1	-1.2959 e-10	-1.9898e-10	-3.065e-10	-1.6679e-9	-1.8316e-10	-2.7517e-10
a2	6.3439e-8	1.0174e-7	1.5168e-7	5.3742e-7	9.3767e-8	1.3671e-7
a3	-1.1943e-5	-2.0588e-5	-2.9327e-5	-6.6393e-5	-1.8968e-5	-2.6536e-5
a4	1.0668e-3	2.096e-3	2.7918e-3	3.8809e-3	1.9249e-3	2.5351e-3
a5	-4.3681e-2	-0.11277	-0.1348	-0.10424	-0.1026	-0.12255
a6	0.53695	2.9897	2.9102	0.90066	2.6593	2.6188
a7	66.805	57.812	73.896	76.008	67.108	82.422
b00	0	-0.14766	-0.12853	0	-0.10865	-8.7369e-2
b0	0	0	0	0	0	0
b1	0	1.6956e+2	1.5546e+2	0	1.4769e+2	1.3576e+2
b2	0	0	0	0	0	0
b3	63	0	0	73	0	0
b4	0	0	0	0	0	0

	For experiments with T_{init} = 73°C, T_{min-os} = 60°C			For experiments with T_{init} = 80°C, T_{min-os} =60°C		
	T_{surf} (°C)	T_{upper} (°C)	T_{bottom} (°C)	T_{surf} (°C)	T_{upper} (°C)	T_{bottom} (°C)
	A=110	A=150	A=150	A=110	A=150	A=150
a1	-9.8675e-10	-1.833e-10	-2.8032e-10	-5.8656e-10	-1.9755e-10	-2.7265e-10
a2	3.611e-7	9.3903e-8	1.3914e-7	2.0826e-7	1.0092e-7	1.3547e-7
a3	-5.1205e-5	-1.9034e-5	-2.7007e-5	-2.8561e-5	-2.0378e-5	-2.6345e-5
a4	3.5051e-3	1.9431e-3	2.589e-3	1.8949e-3	2.0673e-3	2.5316e-3
a5	-0.11407	-0.10521	-0.12684	-5.9998e-2	-0.11026	-0.12383
a6	1.0732	2.8023	2.786	0.4425	2.8021	2.6252
a7	83.845	65.357	81.081	80.935	67.817	85.296
b00	2	-0.17508	-0.15365	2	3	3
b0	0	0	0	0	2	2
b1	-.3401e-6	2.0128e+2	1.822e+2	3.9215e-7	-1.8021e-8	-1.4822e-8
b2	2.8185e-3	0	0	9.4037e-4	6.0833e-5	5.1407e-5
b3	58.806	0	0	61.639	-7.3988e-2	-6.4593e-2
b4	0	0	0	0	91.174	91.004

continued for the next time step. The following convergence criterion was used for the inner iterations;

$$\left|\frac{\xi^{n+1} - \xi^n}{\Delta t}\right| < 10^{-5} \qquad (10)$$

where ξ represents $\overline{W}$ and T. The procedure was terminated when the adsorbate concentration and temperature reached the final values of $\overline{W} = 0.995\overline{w}_a$ and T = 0.005T_a.

RESULT AND DISCUSSION

In this paper, the obtained results are presented for four adsorption processes which their initial and final temperatures are different. In the first part of this section, the obtained experimental results are discussed and in the second part the comparison of numerical and experimental results is given. During this study, one of important points taken into account was achievement of the reproducible results. That is why; two or more experiments were performed for the same experiment conditions to be sure of the obtained results. For all performed experiments, the temperature of the adsorbent bed was not permitted to be below of a fixed temperature (e.g. 60 or 63°C). The evaporation temperature of water inside the vessel was as 40°C. As it was mentioned, the temperature at three different angles of 0, 120 and 240 degrees for two different radiuses of R = 105 mm and R=130 mm were measured during the adsorption process.

Experimental Results

The results of two representative experiments are shown in Figures from 3 to 6. The temperatures at three

different angles (0, 120 and 240 degree) of R = 105 mm can be seen from Figure 3 when the initial temperature of bed is at 63 °C (T_{init} = 63 °C), the permitted minimum outer surface temperature is also 63 °C (T_{min-os} = 63 °C), and T_{vessel} = 40 °C. The temperatures at different angles of inner radius steeply increases at the beginning of adsorption process and attain to a maximum temperature and then starts to decrease due to the heat transfer from the outer surface of bed to the surroundings. The local temperatures are around 63°C at the end of adsorption process. As can be seen from Figure 3, the temperatures of different points on the same radius are very close to each other showing that there is almost no temperature gradient in the angular direction. That is why; the heat and mass transfer in the bed can be accepted as axisymmetric. It should be mentioned that some thermocouples may touch the silica gel particles while others may be in contact with water vapor. The same measured temperature for all thermocouples located in the same radius but at different locations show that the local thermal equilibrium condition is valid for the adsorption process in the studied adsorbent bed. For the same experiment, the measured temperatures of the bottom and the upper Teflon sheets covering the silica gel layer and bed outer surface temperature are illustrated in Figure 4. As can be seen from the figure, temperature at Teflon sheet is changed by time. That is why; the temperature gradient in axial direction is taken into account and heat transfer equation (Eq. (1)) is written involving both radial and axial temperature gradients.
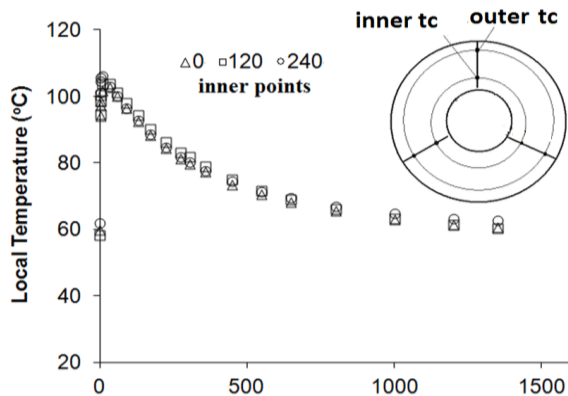

Figure 3. The variations of inner points' temperature (R = 105 mm) during the adsorption process for T_{min-os} = 63°C
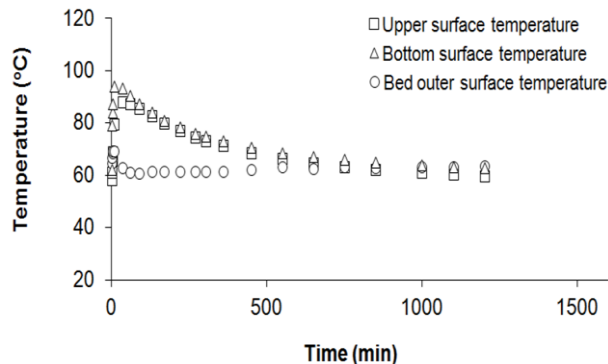
Figure 4. The temperature variations of the bottom and upper surface of the silica gel volume and bed outer surface during the adsorption process for T_{min-os} = 63°C

Moreover, by increasing the temperature of the adsorbent particles in the bed, the temperature of bed outer surface increases. It should be mentioned that the bed outer surface temperature was measured and the measured values are used as boundary condition for the heat transfer equation.

The pressure variation of the bed and water vessel, and water vessel temperature during the adsorption process are plotted for the same experiment of Figure (3) and (4) (T_{min-os} = 63 °C, T_{vessel} = 40 °C). As seen from Figure 5, the evaporation temperature is almost constant and it is around 40°C. The average pressure of water vessel and adsorbent bed are around 5 kPa, showing an isobaric adsorption process. As it was mentioned before, there is no temperature variation in angular direction of the studied bed. Hence, the average of measured temperatures at angles of 0, 120, and 240 degrees are calculated. The next diagrams in this section are plotted based on the average temperature at different angles but at the same radiuses. The change of angular averaged temperature of two experiments for the same conditions of T_{min-os} = 63 °C and T_{vessel} = 40 °C are presented in Figure 6. As seen from Figure 6, the results of two experiments (having the same conditions) overlap each other showing the reproducibility of the results. At the beginning of the experiment, the water vapor adsorbed
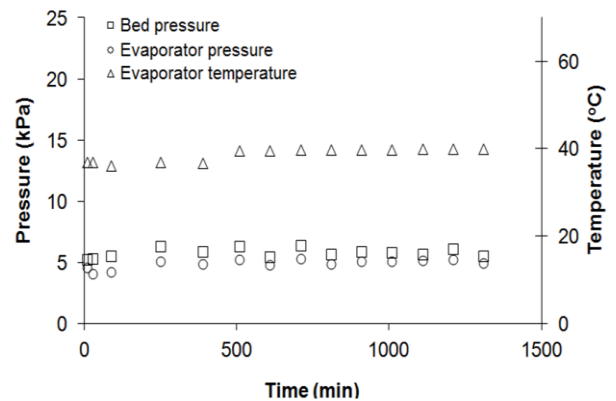
Figure 5. The variations of temperature and pressure in the evaporator, and the bed pressure during the adsorption process for T_{min-os} = 63°C

by the silica gel granules bed and the temperature increases due to the heat of adsorption. The temperatures at inner and outer regions (temperatures at R = 105 mm and R = 130 mm) increase approximately to 104.2 and 104.7 °C. Then, the generated heat is transferred from the bed outer surface (which is not permitted to be below 63°C) to the surroundings and the temperatures of the inner and outer regions decrease to 63°C at the end of the adsorption process. The total adsorption period is 1440 minute for this experiment. Figure 6 also shows that the temperature at the outer region (R = 130 mm) decreases faster than inner region (R = 105 mm).
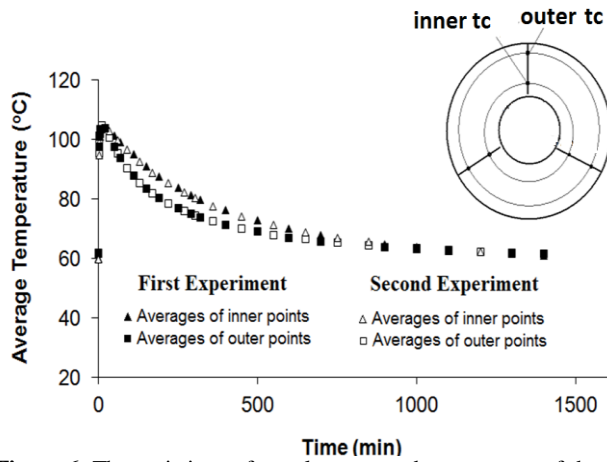
Figure 6. The variations of angular averaged temperature of the inner and outer points (R = 105 and 130 mm) during the adsorption process for the two different experiments when $T_{min-os} = 63\,^{o}C$

Comparison of Numerical and Experimental Results

In this section, the comparison of numerical and experimental results is given in order to show that the uniform pressure approach and the thermal equilibrium condition are valid for the studied bed.

Comparison of the Inner and Outer Regions Temperature

Figure 7 shows the comparison between the numerical and experimental results for four different experiments. The comparisons between the experimental and numerical results for the experiments with condition of a)$T_{init} = 63\,^{o}C$, $T_{min-os} = 63\,^{o}C$, $T_{vessel} = 40\,^{o}C$, and b) $T_{init} = 73\,^{o}C$, $T_{min-os} = 73\,^{o}C$, $T_{vessel} = 40\,^{o}C$ are illustrated in Figure 7(a) and 7(b), respectively. The average temperatures at R = 105 and 130 mm obtained from numerical and experimental studies are compared. As seen, the temperature at the beginning of adsorption process is considerably increases and then it slowly decreases to the minimum permitted temperature (T_{min-os}). Figure 7 shows that there is a good agreement between the experimental and numerical results showing correctness of the employed approach and accuracy of the performed experiment.

The initial and final conditions of the experiments, shown in Figures 7(c) and (d), are different than Figures 7(a) and (b).   The adsorption process is started at $T_{init} = 73\,^{o}C$, $T_{min-os} = 60\,^{o}C$ for the Figure 7(c) and $T_{init} = 80\,^{o}C$, $T_{min-os} = 60\,^{o}C$ for the Figure 7(d). For both experiments, the evaporation temperature was at $40\,^{o}C$. Again, the average temperature of at R = 105 and 130 mm obtained from numerical and experimental studies are compared in these figures. The increase of bed temperature at the beginning of adsorption process is also observed for these experiments. For experiments shown in Figure 7(c) and (d), after starting of adsorption process, the inner and outer regions temperatures reach up to 109 and $110.3\,^{o}C$, respectively and then decreases to outer surface temperature.
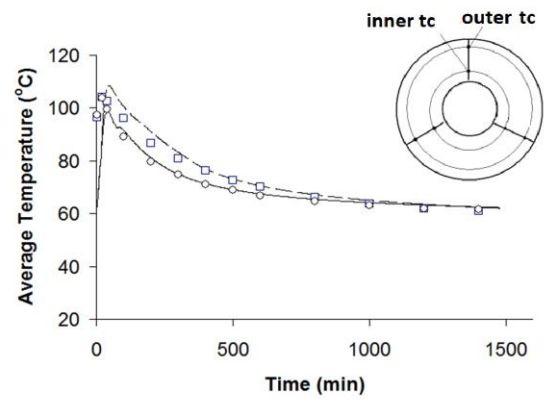
(a)

(b)

(c)
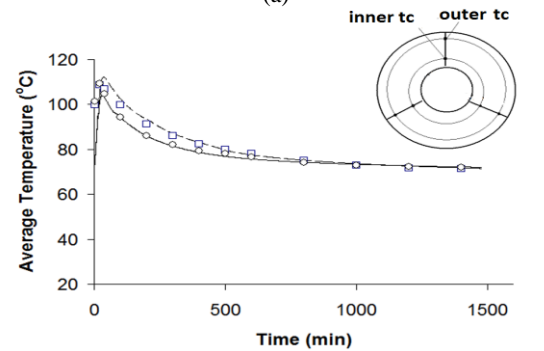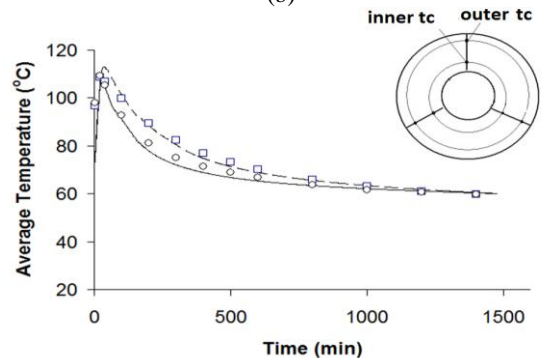
(d)

Figure 7. The comparison of numerical and experimental temperatures at the inner and outer points during the adsorption process for the experiment with a) $T_{min-os} = 63\,^{o}C$, b) $T_{min-os} = 73\,^{o}C$, c) $T_{init} = 73\,^{o}C$, $T_{min-os} = 60\,^{o}C$, d) $T_{init} = 80\,^{o}C$, $T_{min-os} = 60\,^{o}C$

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For the experiments shown in Figure 7, the difference of the experimental and numerical results at the same time steps varies between 0.1% and 2.9%.

Comparison of Adsorbed Water

The water level inside of the evaporator was measured during the adsorption process from the sight glass on the water vessel. During reading the water level, measurement errors occurred since the water level was not stables. Our observations showed that a measurement error with the range of ±1.5% occurred during reading of water level. The ratio of the measured amount of adsorbed water with the amount of the dry silica gel yields the average of water concentration in the bed. The variation of average concentration for the whole of adsorbent bed with time was also found numerically. The comparisons of water concentration of the bed obtained by the experimental and numerical methods for different experiments of Figure 7 are illustrated in Figure 8.In Figure 8(a), the vertical lines shows the range of the water concentration of the bed throughout the experiment for $T_{init} = 63\ ^oC$, $T_{min-os} = 63\ ^oC$, $T_{vessel} = 40^oC$. The cross and plus symbols illustrate the tolerances occur during reading of the water level in evaporator. Similarly, the water concentration in the bed

for three experiments ($T_{init} = 73\ ^oC$, $T_{min-os} = 73\ ^oC$), ($T_{init} = 73\ ^oC$, $T_{min-os} = 60\ ^oC$) and ($T_{init} = 80\ ^oC$, $T_{min-os} = 60\ ^oC$) are presented in Figure 8(b), (c), and (d), respectively. The changes of water concentration of the bed with time obtained by numerical method have good agreement with those of experimental results. The good agreement between the numerical and experimental results shows that the thermal equilibrium condition and uniform pressure approach are valid for the isobaric adsorption process occurs in the designed bed.

CONCLUSION

In order to understand the mechanism of heat and mass transfer in the adsorbent bed, an experimental setup was constructed and experiments for the isobaric adsorption at different initial and boundary conditions were performed. The heat transfer equation for adsorbent bed and mass transfer equation for the adsorbent particle were written based on the uniform pressure approach and local thermal equilibrium assumption and solved numerically to obtained temperature and concentration in the bed. Literature survey shows that number of experimental studies on the adsorption process in closed type adsorbent bed in which the local temperature in the bed were measured is limited due to measuring
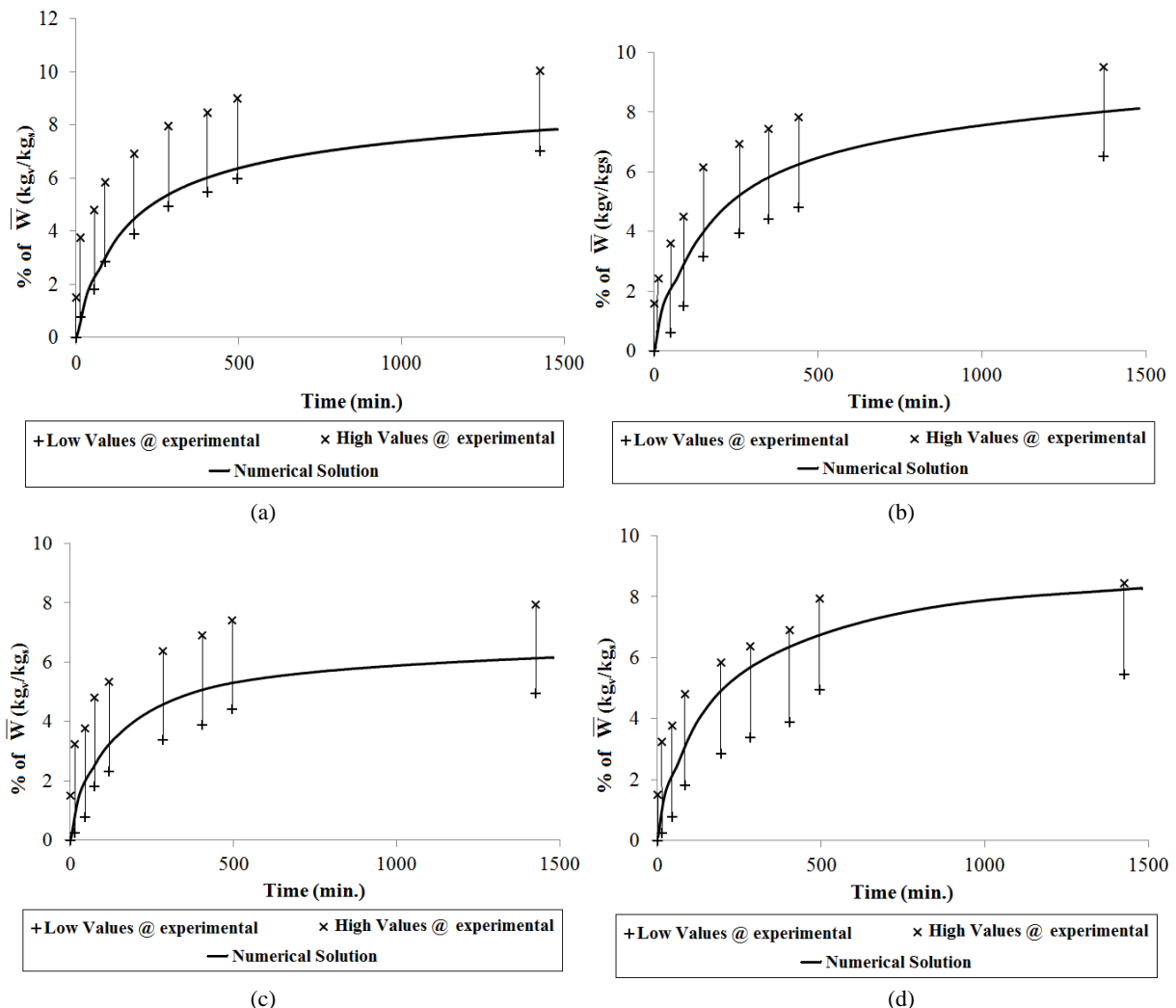
Figure 8. The comparison of average water concentration in the bed obtained numerically and experimentally when a) $T_{min-os} = 63^oC$, b) $T_{min-os} = 73^oC$, c) $T_{init} = 73^oC$, $T_{min-os} = 60^oC$, d) $T_{init} = 80^oC$, $T_{min-os} = 60^oC$

difficulties. In the present study, the local temperature could be measured and compared with numerical results, successfully. A good agreement was observed between the numerical and experimental results for different initial and boundary conditions of the adsorption process. The good agreement between the experimental and numerical results was observed not only for temperature variation inside the bed but also for the change of average water concentration with time. The good agreement between the numerical and experimental results shows that the interparticle mass transfer resistance can be neglected and uniform pressure approach can be applied for the similar adsorbent beds due to the large size of adsorbent particles. For the designed bed, local thermal equilibrium between the solid and vapor phases exists, thus a unique heat transfer equation can be used to determine temperature distribution in the bed. For further studies, the size of the particles in the bed can be reduced and the same experiments can be performed to find out a criterion for the application of uniform pressure approach and local thermal equilibrium assumptions.

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