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Performance of silica gel/ water adsorption bed

Boutheina ZALLAMA, Leila ZILI GHEDIRA, Sassi BEN NASRALLAH
Université de Monastir, École Nationale d'Ingénieurs de Monastir, Laboratoire LESTE, Avenue Ibn El Jazzar 5019, Monastir, TUNISIE
zallama.boutheina@live.fr, *leilazilighedira@yahoo.fr*, *Sassi.Bennasrallah@enim.rnu.tn*,

Abstract

Various published works are dealing with the optimization of the desiccant cooling technology which is required, as example, for comfort cooling and cold storage applications. Hence, this paper deals with the enhancement of the adsorption beds performance by improving heat and mass transfers occurring in a desiccant bed filled by a saturated porous medium. For this reason, the main objective of this study is to conduct an experimental analysis accounting for the adsorption process in a desiccator filled with silica gel. The experimental setup is a climatic wind tunnel enabling us to adjust the flow rate, air temperature and relative humidity. These latter are the main parameters recorded and investigated during the experimental tests which are carried out to assess the influence of operating conditions imposed in the entrance of the packed bed. Aerodynamic and climatic tests were, then, carried out to assess the bed performance. Whether the desiccant air-conditioning system is a feasible option or not for Mediterranean climate is, also discussed.

Keywords:

Experimental study, adsorption phenomenon, aerodynamic and climatic conditions, capacity performance

1. Introduction

Many efforts were carried out to replace chlorofluorocarbons (CFC) and hydrochlorofluorocarbons (HCFC) used in traditional compression refrigeration in order to reduce the amount of energy used for domestic heating and cooling applications [1]. Literature is rich, and various reviews concerning this topic are available. For instance, an interesting review on desiccant cooling systems was reported in [2, 3] and details about the adsorption process could be found in [4, 5]. Various studies used the solar integrated design for regenerating the desiccant [6–8]. Mutsuhiro et al. [9] have proposed and studied experimentally a new type of Humidity Swing Air-conditioning system (HSA) consisting of a desorption cooling system in the adsorbate instead of a cooling system by water spraying. Packed bed systems [10] can be used in adsorption of water vapor, organic solvent and some toxic gases. For a specific adsorbed substance an adequate adsorbent needs to be selected. For example, active carbon is usually used for adsorption of oil or organic solvent. Silica gel and molecular sieves are used for adsorption of water vapor. Thus, the desorption cooling performance in silica gel was discussed within packed beds.

A theoretical model to predict the heat and mass transfer process of the honeycombed desiccant wheel has been presented by X. J. Zhang et al. [11]. The numerical results are in reasonable agreement with the experimental data. The one-dimensional coupled heat and mass transfer model is expected for use in designing and manufacturing of a honeycombed rotary desiccant wheel. Based on this model, the temperature and humidity profiles in the wheel during both the dehumidification and the regeneration processes are analyzed and verified by experimental data. The effects of velocity of regeneration air inlet temperature and velocity of process air on the hump moving speed are investigated.

The influence of the adsorbent bed dimensions, convective heat transfer coefficient between the cooling fluid and adsorbent bed and the thermal conductivity of the solid adsorbent material on the transient distributions of the solid and gas phase temperature difference, differences in the adsorbate concentration predicted by the instantaneous equilibrium and linear driving force models, solid phase temperature, gas pressure and adsorbate concentration inside the adsorbent bed of a solid sorption cooling system have been investigated numerically for a nearly isobaric adsorption process by Ismail solmus et al [12]. Silica gel/ water is selected as the working pair.

A transient two-dimensional local thermal non-equilibrium model has been developed that takes into account both internal and external mass transfer resistances. It has been found that generally, the effects of the parameters investigated on the transient distributions of the temperature difference between the phases, difference in adsorbate concentration between the instantaneous equilibrium and LDF models, and gas phase pressure gradients are negligible small. The thickness of the adsorbent bed for the given adsorbent bed length and thermal conductivity of the solid adsorbent material have a large influence on the transient distributions of the solid phase temperature and adsorbate concentration. On the other hand, the transient temperature and adsorbate concentration distributions are only slightly affected by the variation of the adsorbent bed length and convective heat transfer for the conditions studied. X. Zheng et al. [13] proposed a novel composite solid desiccant material. The focus is on enhancing thermal conductivity and adsorption performance of silica gel. This desiccant material is fabricated by combining silica gel with expanded natural graphite treated with sulfuric acid (ENG-TSA) as a host matrix. The performance of consolidated and composite adsorbents of silica gel and ENG-TSA with respect to different densities and different ratios was investigated. Analysis on pore parameters demonstrated that the compression of simple mixture of ENG-TSA with silica gel does not destroy the morphology of silica gel. In addition, both non-equilibrium and equilibrium adsorption performance of composite silica gel and pure silica gel were evaluated. Non-equilibrium adsorption performance indicated prominent enhancement of heat transfer, whilst equilibrium adsorption performance indicated a reasonable mass transfer.

The objective of the present work is to perform an experimental study to investigate the behavior of the adsorbent bed. A parametric study is also performed to assess the effect of the flow rate and the climatic conditions through the packed bed of spheres.

2. Experimental

2.1. Apparatus

We conceived and realized, within our research laboratory LESTE, a climatic wind tunnel intended for the study of desiccators with adjusted air temperature and moisture by means of a conditioning enclosure. Air flow rate is controlled with an air flow regulator designed to maintain a constant flow through the system. This installation has the advantage of ensuring air circulation, in a closed buckle, with well controlled dynamic and hygrothermic characteristics. For this study, we use silica gel as adsorbent. Silica gel is, in fact, a porous material with a high adsorbing water vapor capacity. Consequently, it is used as desiccant in various applications.

The experimental system for investigation of heat and mass transfer in a desiccator filled with silica gel is shown in figures 1 and 2.

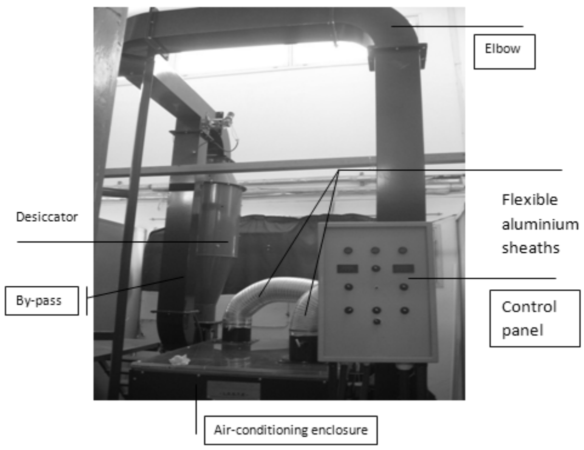


Fig. 1: Photography of the experimental set-up

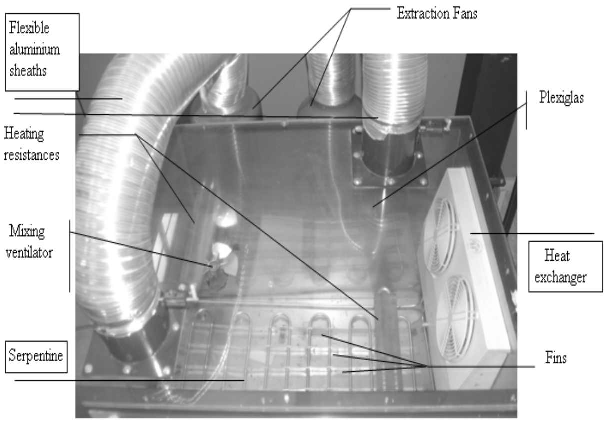


Fig. 2: Air-conditioning enclosure

In order to control air moisture and temperature, an insulated air-conditioning enclosure was designed. The air-conditioning enclosure role is detailed as following:

- Air humidity is fixed indirectly by imposing dry bulb temperature and dew point temperature.
- Dry temperature is achieved by means of heating resistances with fins, when required temperature is over atmospheric one, and a heat exchanger connected to a cryostat in the opposite case.
- Dew point temperature is the imposed one on a thin water layer in the bottom of the enclosure using a serpentine related to a cryostat.

The enclosure is, in fact, provided with two heating resistances connected to a thermoregulator, a heat exchanger commanded by a cryostat serving to fix the dry air temperature when desired value is under ambient one, two air mixing ventilators and a second heat exchanger, that is to say a copper serpentine, immersed in a low water thickness and which is also controlled by a cryostat fixing so, the dew point temperature. The dew point temperature is, thus, selected according to the desired relative humidity while knowing the dry temperature and referring to the psychrometric diagram. We ensure, then, the moisture and temperature air control by the conditioning enclosure.

Let us note that the wind tunnel is equipped with a by-pass which is used for the establishment of the required conditioning before the launching of the experiments. Once the imposed temperature, moisture and air flow rate are stabilized, the air is supplied to the desiccator. Our installation allows us to use various reactors with different diameters.

A control panel and an electrical equipment box are used to ensure the ordering of the system. The desk includes all the control knobs. In fact, it ensures the order, the visualization and the adjustment of the various existing elements. The electrical equipment box feeds all the blower elements in electricity and is provided with the air flow regulator.

2.2. Instrumentation

The experiences are led on a silica gel packed bed. Reliable sensors are then utilized : thermo-hygrometers which measure the following parameters : relative humidity Hr, absolute humidity Habs, dew point temperature Td, dry bulb temperature T, wet bulb temeprature Tw, PT100 temperature integrated in the probe.

Temperature, relative humidity and absolute humidity are the main parameters recorded and investigated during the experimental tests. The hygrometers are set upstream and downstream of the desiccator. They have a resolution of 0.1°C and 0.1% for temperature and humidity, respectively. Also, a digital balance of 0.001g resolution and 15 kg scale range is used to determine the adsorbed mass of moisture at the beginning and the end of each experiment.

3. Results and discussion

3.1. Adsorption mechanism

A parametric study of the adsorption process in a desiccator filled with a porous media, i.e. silica gel used as desiccant is performed.

At first, an insight into the mechanisms of heat and mass transfer in desiccant packed bed is conducted. Then, tests were carried out to assess the influence of different parameters on the performance of granular adsorbents, namely the flow rate through the packed bed and the climatic conditions at the entrance of the bed.

The silica gel is initially regenerated by means of electric oven for 5h at 70°C. Then, once the steady state of inlet air conditions is established, we start the adsorption mechanism.

A comprehensive study of the adsorption phenomenon in a reactor filled with silica gel is depicted in Fig. 3. The inlet air conditions have been adjusted by means of appropriate equipment as described previously and by running the supply fan at a given speed for a sufficient time to reach stable conditions. Therefore, measurements are carried out at nearly constant conditions of process air (speed, temperature and humidity at the bed entrance).

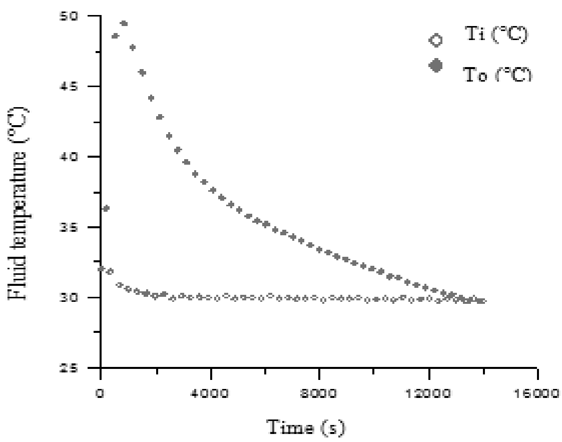
The adsorption mechanism is studied for the fixed inlet air conditions that are:

- T_i = 29.7°C ,
- Hr_i = 74.5% ,
- $Habs_i$ = 19.7 g/kg.

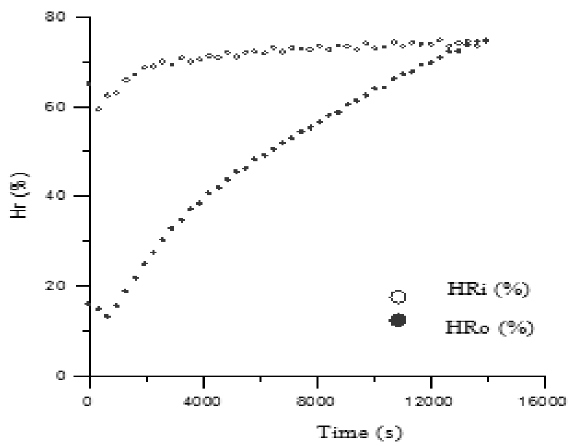
The response of the system to the imposed inlet conditions, namely the distributions of the bed temperatures, relative and absolute humidities during the adsorption mechanism is illustrated in Fig.3. Fig. 3(a) undertakes the time variation of inlet and outlet bed temperatures. Due to the higher rate of adsorption, the heat generation rate results in a rapid increase in the bed temperature which rapidly reaches a maximum value T_o= 49.2°C and then gradually decreases as the adsorption rate decreases.

It is clear that the outlet temperature tends to the value of the inlet bed temperature at the end of the essay. We can observe that the duration of such an essay is approximately four hours. In the other hand, the relative and absolute humidities profiles are plotted in Figures 3(b) and 3(c) respectively. Shortly after the test starts, the outlet humidities drop to a minimum, 14.2% as for the relative humidity and 10.6 g/kg for the absolute humidity and then rise toward the inlet values. At saturation, the adsorption process is stopped and the different parameters join the imposed values at the entrance.

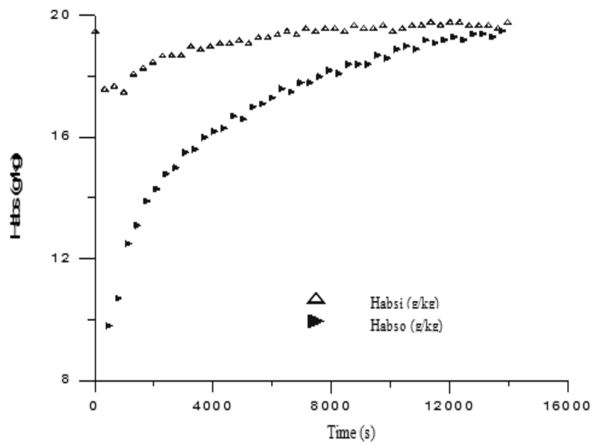
Table 1 summarizes the relevant parameters of the test and establishes a comparative study between the inlet and outlet values.



(a)



(b)



(c)

Fig. 3: Transient variation of the main parameters of an adsorption mechanism in a packed bed.

Table 1: Inlet and outlet values of the discussed parameters

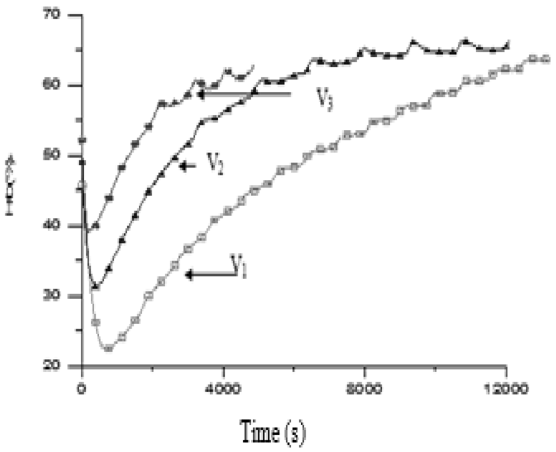
	Inlet Air Conditioning	*Adsorption Process*	*Differnce*
Ts (°C)	29.7	49.2	19.5
Hr (%)	74.5	14.2	60.3
Habs (g/kg)	19.6	10.6	9

3.2. Parametric study

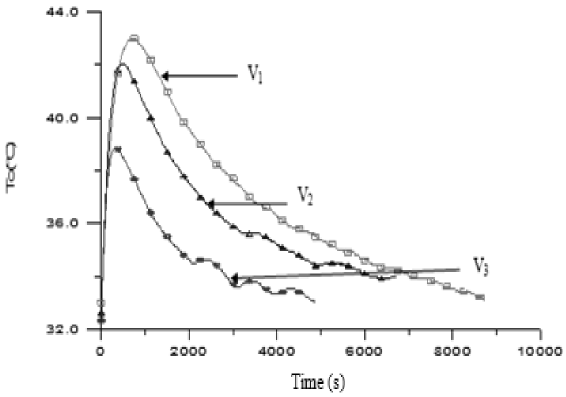
3.2.1. Effect of air inlet velocity

Fig. 4 presents the effect of the velocity on the adsorption mechanism of a packed bed of spherical adsorbent particles. The adsorption capacity and the speed of adsorption are, then, examined by means of an analysis of the transient temporal variation of the air temperature and relative humidity at the bed exit for different flow velocities. It is clear that an increase in the flow velocity leads to an increase in the process speed while the equilibrium state is reached within almost 67 min, 100 min and 134 min for 1, 2 and 3 m/s respectively. Besides, while the process is accelerated, the adsorption capacity is decreased. This impact presents an inconvenient of the adsorption process. In Fact, from Fig. 3 (a), it can be noticed that the effectiveness of the adsorbate removal attains 64.5% at the lowest velocity with comparison to 40% measured for the highest velocity entertained in this study. This can be explained by the fact that the more accelerated the flow rate is, the easiest is the passage of the air flow through the packed bed of granules, and so, the effective contact and interaction between the fluid stream and solid particles is reduced.

As the heat and mass transfer mechanisms are combined, it is obvious from Fig. 4 (b) that the exit air temperatures present the same trend as observed for the relative humidity, i.e., when the adsorption capacity is increased, the outlet air temperature presents the highest value since the adsorption process is exothermic.



(a)



(b)

Fig. 4: Effect of air velocity in the transient variation of: (a): exit relative humidity, (b) : exit air temperature of the packed bed

3.2.2. Effect of air inlet humidity

The effect of inlet absolute humidity, fixed and driven at the upstream of the porous bed (W_{1in} = 13g / kg, W_{2in} = 17.6g / kg and W_{3in} = 22.2g / kg), on the adsorption rate is illustrated in Fig. 5. The transient variation of the difference between the absolute humidity measured at the bed exit and that imposed at the inlet is presented for air velocity of 1 m/s, a bed thickness of 3 cm and a bed temperature of 31.5°C. It may be observed that the gap between inlet and exit humidity increases with the increase of inlet humidity. Thus, the hydrophilic character of silica gel is more considerable for higher concentrations of water vapor. This is explicitly illustrated in table 2 which is devoted to recapitulate the different results at the different inlet conditions. Such results may indicate that the desiccant cooling systems are valuable for even large ranges of humid climates.

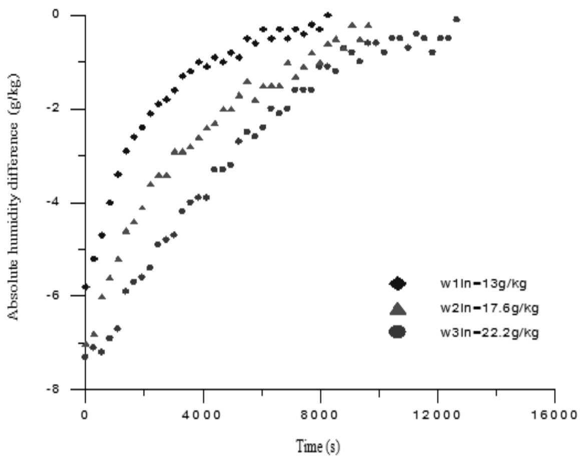


Fig. 5: Effect of inlet absolute humidity on the adsorption mechanism for air inlet conditioning of (T_i=31.5 °C, inlet velocity = 1 m/s and ξ_1=3 cm).

Table 2: Effect of inlet absolute humidity on the adsorption mechanism

	Habsi	*Habso*	***ΔHabs***
1	13	7.2	**5.8**
2	17.6	10.6	**7**
3	22.2	14.9	**7.3**

The same effect was studied for a bed thickness of 8 cm (Ti= 32.7°C, Vi=1m/s) as shown in Fig. 6 and Table 3. The curves being similar to those of Fig. 5, it is clear, however, that the process undertakes much more time to reach the equilibrium state with the increase of bed thickness. Moreover, by comparing results for the same inlet humidity (wi≈22 g/kg), it may be observed that the rate of adsorption is increased by 31.13% for the case of thicker bed (ξ_2=8cm vs ξ_1=3cm).

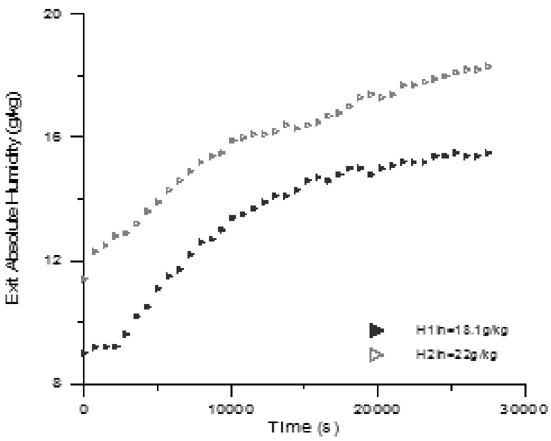


Fig. 6: Transient variation of exit absolute humidity of the packed bed during the adsorption process for different inlet humidities, inlet velocity= 7Hz, bed thickness of 8 cm and air temperature of 31.5°C.

Table 3: The effect of inlet air stream humidity on the rate of adsorption for a bed thickness of 8 cm, a velocity =7Hz and air temperature 31.5°C

	HABSE	*HABSS*	Δ*HABS*
1	18.1	9	9.1
2	22	11.4	10.6

3.2.3. Effect of air inlet temperature

Fig. 7 shows the bed exit temperature and exit relative humidity at selected operating conditions reported in Table 4. In the present study, we discuss the effect of the inlet air temperature on the adsorption mechanism, namely T_{1in}=25.8°C and T_{2in}=34.4°C, corresponding to w_{1in}=15.3g/kg and w_{2in}=18.8g/kg, respectively. Normally, as mentioned in the previous section and at the same inlet conditions, the rate of adsorption increases with the increase of the inlet humidity ratio. Whereas, as the undertaken inlet temperatures are not the same, it is clear that the performance of the bed at lower temperature is much more relevant, while the adsorption uptake reaches 44% and 38% for air inlet temperature T_{1in}=25.8°C and T_{2in}=34.4°C, respectively. Thus, the fact of decreasing the inlet air temperature may provide significant enhancement of the bed performance. Besides, we may find yet multiple investigations dealing with the enhanced efficiency of the adsorption process that study the effects of sensible and latent heat storage particles in the desiccant bed.

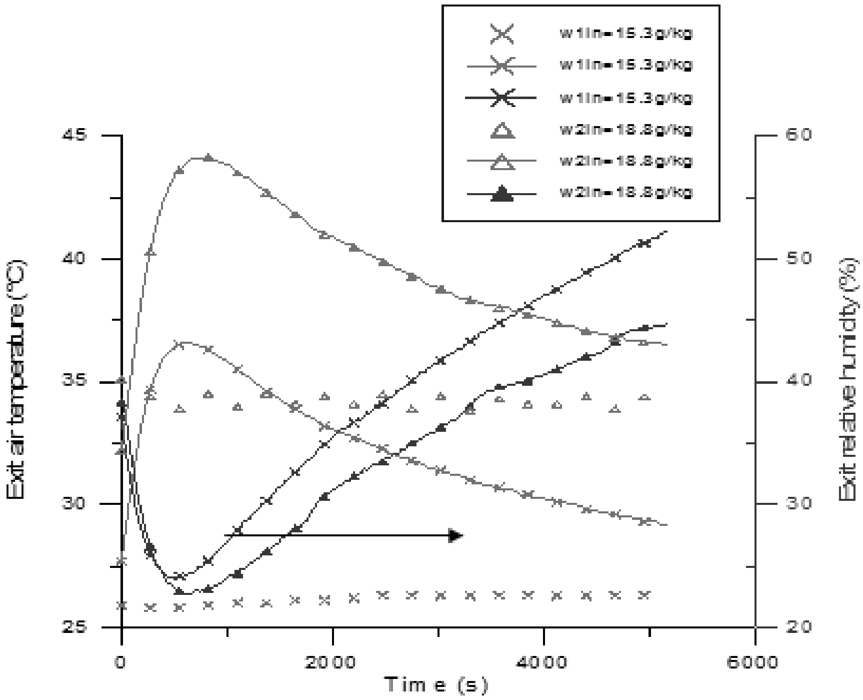


Fig. 7: Effect of inlet air temperature in the adsorption mechanism of the packed bed

Table 4: The effect of inlet air stream humidity on the rate of adsorption

	TEST 1		*TEST 2*	
	INLET CONDITIONS	*ADSORPTION*	*INLET CONDITIONS*	*ADSORPTION*
T (°C)	25.8	36.6	34.4	44.1
W (G/KG)	15.3	8.6	18.8	11.6

4. Conclusions

In the present paper, the experimental study of heat and mass transfer by forced convection in a cylindrical reactor filled with a porous medium, i.e. silica gel used as desiccant is performed. The adsorption phenomenon and then a parametric study including the effect of the velocity and the climatic conditions are experimentally investigated using a climatic wind tunnel with controlled temperature, moisture and air flow rate. Such installation ensures the air circulation, in a closed buckle, with well controlled dynamic and hygrothermic characteristics. The performances of the system in terms of air conditioning were handled. Temperature and relative humidity evolutions in the inlet/outlet of the desiccator were, also, established and analyzed.

The followings points are concluded:

- An increase in the flow velocity leads to an increase in the process cycle. Besides, while the process is accelerated, the adsorption capacity is decreased. This can be explained by the fact that the more accelerated the flow rate is, the easiest is the passage of the air flow through the packed bed of granules, and so, the effective contact and interaction between the fluid stream and solid particles is reduced.

- The gap between inlet and exit humidity increases with the increase of inlet humidity. Such result may indicate that the desiccant cooling systems are valuable for even large ranges of humid climates.

- The bed performance is improved for decreasing values of adsorbent temperature which confirms the importance of latent and sensible heat storage particles introduced in the desiccant beds.

Nomenclature

Habs (W) Absolute humidity, *g/kg*
Hr Relative humidity, *%*
t Time, *s*
T Temperature, *°C*
V Air velocity, $m\ s^{-1}$

Subscripts
i, in inlet conditions
O outlet conditions

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