MECHANICAL ENGINEERING

h	enthalpy, J/kg
H	total equivalent heat, J
k	mass transfer coefficient, $m^{-2}.s^{-1}$
K	affinity constant for adsorption equilibrium
L	latent heat of evaporation of water, J/kg
m	mass of evaporated water during regeneration, kg
M	mass of desiccant or bed, kg
$\overline{M}$	mass ratio
p	vapour pressure, mmHg
$\overline{P}$	dimensionless pressure drop
q	heat added to vapour, J
Q	heat added, J
t	ambient temperature, °C
T	desiccant temperature, K
v	air stream velocity, m/s
$\overline{V}$	dimensionless velocity
X	desiccant mass concentration
$\overline{X}$	concentration ratio
Z	height of desiccant bed, m

Greek symbols

Δ	pressure drop
ε	porosity
η	efficiency
φ	relative humidity
μ	dynamic viscosity
ρ	density
τ	time
Ψ	dimensionless time

Subscripts

a	condition at the end of adsorption
b	bed
d	desiccant
cyc	cycle
e	equivalent
o	initial, inlet
r	condition at the end of regeneration
s	saturation condition
sys	system
t	total
v	vapour

ABBREVIATIONS

ADS	Absorption-desorption system
AEV	Air exhaust valve
AIV	air inlet valve
VV	vapour valve

INTRODUCTION

Atmospheric air is a huge and renewable reservoir of water in vapour form. This endless source of water is available every where on the earth surface Several investigators [1-6] had studied the proce~~~ for the production of domestic water from ambient atmosphere. Desiccant based water recovery from atmospheric air systems are finding increasing demand in research work [7-12]. In addition, research activities in the field of using desiccant-based air conditioning systems are finding applications in humidity control devices With some modifications, these systems may be used for recovering water from air in arid areas. Analysis of adsorption /desorption cycle producing water from air with application of Calcium Chloride as the working desiccant is presented in [11] In the adsorption /desorption system (ADS), air is passed over an adsorbing material where water vapour is isothermally adsorbed In the desorption (regeneration) process, the sorbent is heated, while water vapour is evaporated and condensed on a cooled surface.

In recent years, desiccant systems have significant changes in their design to increase the weight of adsorbed water from air per unit weight of sorbent material [10]. Packed

porous adsorbing material can be used to produce compact units operating on the principles of the (ADS). In this case, forced convection adsorption is necessary. Solar energy as a clean and renewable energy source can be applied to power the (ADS). In addition to solar energy, waste heat of some projects in desert areas, such as mining projects and gas turbines, can be used to regenerate the desiccant. When waste heat is applied, such systems can operate continuously and the productivity is not restricted by the intensity of solar radiation and radiation collection area. Moreover, continuous operation of such systems offers the advantages that the equipment is small relative to the quantity of product. The system daily productivity is simply equals the cyclic productivity multiplied by the system frequency (number of cycles per day). Increasing the mass transfer rate by forced convection decreases the sorption period and consequently increases the system frequency. Also, it is necessary to operate with minimum power consumption to keep the cost of produced water as minimum as possible.

The aim of the present work is to evaluate the effect of system design parameters and ambient conditions on the performance, when forced adsorption is applied. Also, it is objected to determine the adsorption limits at which maximum system efficiency can be attained.

THE PROPOSED SYSTEM AND ITS OPERATION

The ADS, presented in this study operates on the basis of the adsorption / desorption cycle. Figure 1 shows a typical plant layout arranged for this method. The system
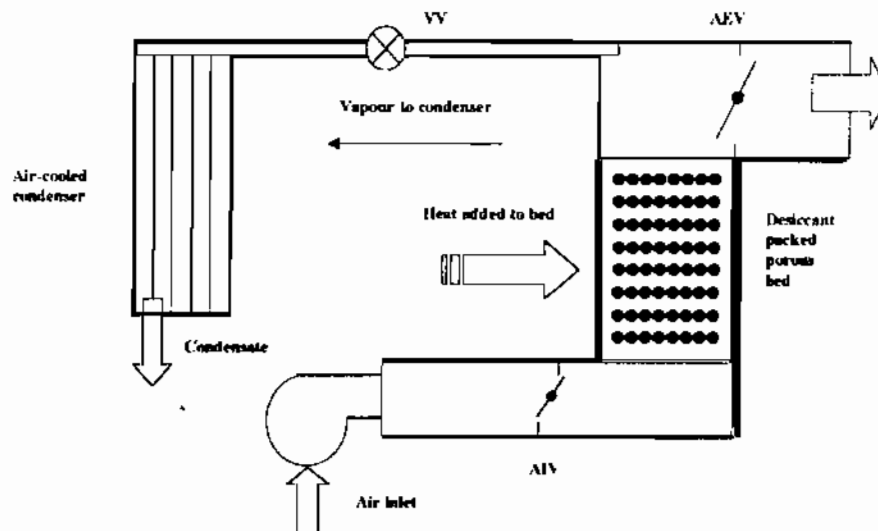

Fig. 1 Typical layout of the adsorption/desorption system producing water from air

operates in two modes; namely adsorption mode and desorption mode. In the adsorption mode, ambient air is forced onto the sorbent bed where the moisture is adsorbed and desiccant concentration decreases with time. At the top of the sorbent bed, air is exhausted outside the system through the air exhaust valve, which is opened during this mode of operation. At the end of this stage, air inlet valve (AIV) and air exhaust valve (AEV) are closed. During the desorption mode, sorbent bed is heated and desiccant is regenerated. Vapour pressure on the desiccant air surface increases and as a result water vapour flows to an air-cooled condenser through the vapour valve (VV). Evaporation from the bed with subsequent condensation on the condenser surface take place during desorption mode. The condensate is collected through the condenser opening shown in figure 1. Regeneration ends when desiccant concentration in the bed reaches its initial value at start of adsorption process. New cycle starts when bed temperature decreases to the initial sorption temperature (ambient temperature)

SYSTEM MODEL

Because of the abundance of parameters involved in the system operation, some sort of systematic approach must be employed in order to evaluate the effect of various factors. Some parameters such as ambient air temperature and humidity are uncontrollable and determine an operation limits for the system. Other system parameters, such as initial concentration of desiccant, concentration at the end of adsorption, and design characteristics of the desiccant bed can be selected for optimum system performance.

An important aspect of any system simulation is the determination of the conditions for optimized performance. When sorption / desorption cycle is applied with natural absorption of water vapour from air, system efficiency can be simply evaluated from the multiplication of the cycle efficiency by the efficiency of the heat transfer equipment (ex. collector efficiency, when solar energy is applied) In case of forced air adsorption, when packed bed is applied, energy added to forced air stream must be accounted in definition of system efficiency. Therefore, system efficiency is defined as the ratio of heat added to generated water vapour q_v to the total equivalent heat added to the system H, i.e

$$\eta_{sys} = q_v / H \tag{1}$$

Total heat added to the system can be expressed as

$$Q_t = Q_b + Q_d \tag{2}$$

where Q_b is the heat added to bed material and Q_d is the heat added to desiccant and vapour,

$$Q_b = M_b Cp_b (T_r - T_a) \tag{3}$$

where M_b and Cp_b are the mass and specific heat of bed material; respectively,
T_r and T_a are the bed temperatures at the end of regeneration and end of adsorption; respectively.

The heat added to desiccant and water vapour during the desorption process can be expressed as given in [11] as

$$Q_d = \left[mh_v + M_d h_r - (M_d + m) h_a \right] \tag{4}$$

where h is the enthalpy. Subscripts v, r and a denote water vapour, desiccant condition at the end of regeneration and desiccant condition at the end of adsorption, respectively.

Knowing desiccant concentration limits and mass of desiccant M_d one can evaluate the mass of adsorbed (or regenerated) water vapour as follows.

$$m = \left(\frac{X_r - X_a}{X_a} \right) M_d \tag{5}$$

where X_r and X_a are desiccant concentration at the end of regeneration and end of adsorption, respectively. As the mass of desiccant changes during the processes, in equation (5), M_d is taken at start of adsorption

The heat equivalent to energy added to air stream during adsorption can be evaluated by dividing the energy by the Carnot energy factor Ca.

$$Q_e = \frac{1}{Ca} \left(v_o A \right) \Delta P (\tau_a) \tag{6}$$

where v_o is the air velocity at bed entrance, A is the free cross sectional area of the packed column, ΔP is the pressure drop through the bed, and τ_a is the adsorption time. Carnot energy factor is dependent on the operating temperature limits of the cycle, ambient temperature, which is equal to the adsorption temperature T_a and maximum regeneration temperature, which is equal to the desiccant temperature at the end of regeneration process T_r. Consequently, Carnot energy factor can be expressed as

$$Ca = \left(\frac{T_r - T_a}{T_r} \right) \tag{7}$$

The total equivalent heat added to the system is expressed as

$$H = Q_n + Q_d + Q_e \tag{8}$$

Ambient conditions (temperature and relative humidity) are outside controlling parameters, which determine the maximum possible mass of vapour adsorbed by the desiccant In other words, for specific sorbent the lower value of desiccant concentration at the end of sorption process is dependent on ambient parameters

When Calcium Chloride is the working desiccant, The lower concentration can be expressed as given in [11] by

$$X_{min} = \left[\ln p_v - \left(a_o - \frac{b_o}{t+111.9}\right)\right] / \left(a_1 - \frac{b_1}{t+111.9}\right) \quad (9)$$

where, t is the ambient temperature, °C, a_o, b_o, a_1, b_1 are regression constants given in [11]. The vapour pressure in ambient atmosphere is dependent on the relative humidity φ and saturation pressure of water vapor at ambient temperature, $p_s(t)$, i.e

$$p_v = \varphi p_s(t) \quad (10)$$

Cycle efficiency is defined as the ratio of heat added to generate vapour to the heat added to desiccant during regeneration process, i.e.,

$$\eta_{cyc} = q_v / Q_d \quad (11)$$

where

$$q_v = m L \quad (12)$$

In terms of desiccant parameters, cycle efficiency can be expressed as given in [ ]

$$\eta_{cyc} = L / \left[h_v + \frac{X_s h_s - X_r h_a}{X_s - X_r}\right] \quad ( )$$

where L is the latent heat of evaporation of water at the condensation pressure, h_v is the enthalpy of generated vapour, X and h are the concentration and enthalpy of desiccant, respectively. Subscripts s and r denote the conditions at the end of adsorption and regeneration, respectively

Referring to Eq.(8) and substituting by Q_d, Q_b, and Q_a from equations ( ), (4) and ( ) respectively, yields

$$H = \left[mh_v + M_d r - (M_a + a)h_a + M_b Cp_b (T_r - T_a) + \frac{(v_o A \Delta P \tau_o)}{Ca}\right] \quad ( )$$

Substituting by Eqs. ( ), ( ), ( ) and (14) in Eq. (1), system efficiency can be expressed as

$$\eta_{sys} = 1 / \left[\frac{ }{p_o} + \frac{ }{\eta_?} + \frac{ }{} - \frac{v_o A \Delta P \tau_o}{mLCa}\right] \quad ( )$$

Substituting (m) from Eq. ( ) in Eq. (15), yields

$$\eta_{sys} = 1 \Big/ \left[\frac{1}{\eta_{oc}} + \frac{M_L Cp_b (T_r - T_a)}{M_d [(X_r - X_a) X_a] L} + \frac{v_o A \Delta P \tau_a}{L M_d Ca[(X_r - X_a) X_a]} \right] \qquad (16)$$

To evaluate the effect of system parameters and ambient conditions on the system efficiency η_{sys} in Eq (16) the pressure drop ΔP and adsorption time τ_a must be expressed in terms of system operating parameters.

The pressure drop ΔP suffered by a fluid in flowing through a bed of packed solids such as spheres, cylinders, etc is dependent on bed height Z, porosity ε and reasonably well correlated by the Ergun equation [13]

$$\frac{\Delta P}{Z} \frac{\varepsilon^3 d_p \rho_a}{(1-\varepsilon) G^2} = \frac{150(1-\varepsilon)}{Re} + 1.75 \qquad (17)$$

where

$$Re = \frac{d_p G}{\mu} \qquad (18)$$

and d_p is the effective diameter of the particles and G is the mass velocity of stream.

According to the analysis of the adsorption process through porous bed impregnated with liquid desiccant [11], the dimensionless adsorption time ψ is dependent on the mass transfer potential ratio and can be expressed in the following dimensionless form.

$$\Psi = \ln \left(\frac{C - C_o^*}{C - C^*} \right) \qquad (19)$$

where C and C^* are the molar concentration of water vapour in ambient air and concentration at equilibrium with adsorbed phase, the subscript o denotes the initial condition of desiccant. The dimensionless time ψ is defined in terms of the mass transfer coefficient k, total interfacial area per unit volume a, adsorption time τ_a, bed height Z, bed porosity ε and air stream velocity v_o, which is given in [14] as

$$\Psi = \frac{ka}{K(1-\varepsilon)} \left(\tau_a \cdot \frac{Zc}{v_o} \right) \qquad (20)$$

where K is the an affinity constant for adsorption equilibrium. From equations (19) and (20) it can be noticed that, for specific bed characteristics and ambient conditions, the adsorption time is dependent on the solution concentration in the bed.

However, it is more convenient to express the system efficiency in terms of non-dimensional parameters. This expression can be obtained by substituting equations (19) and (20) in Eq. (16) and rearranging.

$$\eta_{wm} = 1 \left/ \left[\left(\frac{1}{\eta_{cyc}} \right) + \overline{X}\ \overline{M} \left[\overline{C}p + \frac{\overline{P}}{Ca}(1 + \overline{V}\psi) \right] \right] \right. \tag{21}$$

The dimensionless parameters presented in Eq.(21) can be defined in two groups: The first group represents the ambient conditions and operating concentration limits of the applied desiccant, this group includes the cycle efficiency η_{cyc}, the dimensionless concentration ratio $\overline{X}$, the Carnot faetor Ca and the dimensionless time ψ. The second group of parameters, which represents the bed and air stream conditions, includes the mass ratio $\overline{M}$, dimensionless specific heat of bed material, $\overline{C}p$, dimensionless pressure drop $\overline{P}$ and dimensionless velocity $\overline{V}$

The dimensionless parameters are defined as follows.

$$\overline{X} = \frac{X_a}{X_r - X_a}; \tag{22}$$

$$\overline{M} = \frac{M_b}{M_a}. \tag{23}$$

$$\overline{C}p = \frac{Cp_b(T_r - T_a)}{L}; \tag{24}$$

$$\overline{P} = \frac{\rho\Delta P}{L\rho_b} \quad \text{and} \tag{25}$$

$$\overline{V} = \left(\frac{Kv_o}{k_aZ} \right)\left(\frac{1-\varepsilon}{\varepsilon} \right) \tag{26}$$

where ρ_b is the bed average density, defined as

$$\rho_b = \frac{M_b}{AZ} \tag{27}$$

The operating parameters affecting the system performance are summarized with the corresponding dimensionless groups and presented in Fig. 2
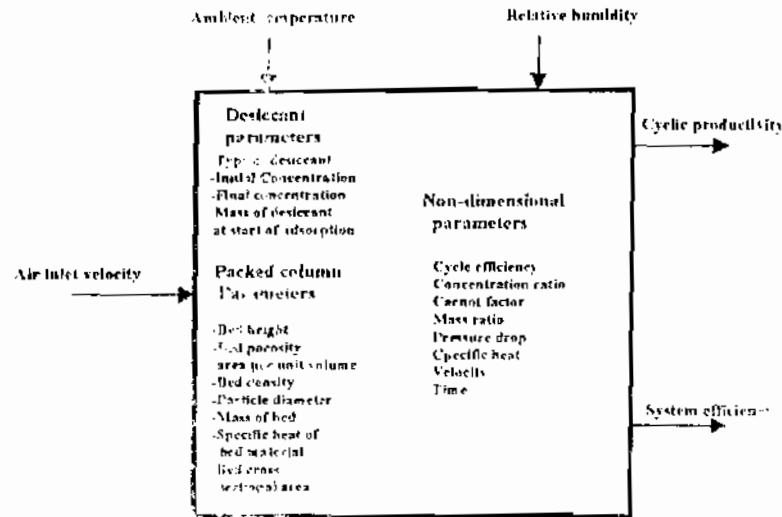

Fig. 2 System operating parameters

In the present work it is interested to set a limit for the desiccant concentration at the end of adsorption process (lower value of concentration) to maximize the system efficiency For this purpose, the foregoing equations have been introduced into a computer model for simulation of the proposed system (Fig. 1). The simulation model may be described as follows. Knowing the ambient conditions (temperature and humidity), equilibrium properties of operating desiccant are evaluated from property tables or correlation [11]. Hence, desiccant concentration at start of adsorption is assumed. This value is usually higher than the equilibrium value, corresponding to the ambient conditions, and lower than the crystallization limit. The packed bed parameters, presented in Fig. 2 are introduced into the model as well as the air velocity. From eqs. (22-26), the dimensionless parameters of eq (21) are calculated. Calculations are performed for different values of ambient temperature and humidity.

RESULTS AND DISCUSSION

As the sorbent concentration at the end of adsorption process plays a decisive role in determining the system performance, the lower value of this concentration is limited by the ambient conditions. Adsorption process continues until the vapour pressure on the desiccant surface equals that of ambient air. The humidity ratio of ambient air determines the equilibrium vapour pressure at which adsorption occurs. The sorbent lower possible concentration is evaluated by knowledge of equilibrium pressure and the adsorption temperature Fig. 3 demonstrates the effect of ambient parameters on the minimum possible value of adsorption concentration. As shown in figure 3, for a constant value of humidity ratio in atmospheric air, it is well known that the relative humidity decreases with temperature rise while the adsorption

concentration increases It can be observed that the increase in humidity ratio, for a given ambient temperature, decreases the value of equilibrium concentration, which equals the lower possible value at the end of adsorption.

Analysis of the adsorption/desorption cycle [11] shows that lower values of sorbent final concentration at the end of sorption results in higher values of cycle efficiency and mass of sorbed water per cycle. Fig 4 illustrates the effect of desiccant concentration at the end of sorption on the thermal efficiency of the adsorption/desorption cycle and the dimensionless adsorption time. It can be observed that the cycle efficiency has its highest value at the lower adsorption concentration. On the other hand, adsorption time exponentially increases with decrease in sorbent concentration, which means an exponential increase in the energy, added to air stream flowing through the bed. However, in condition of natural adsorption, higher system efficiency is attained at higher cycle efficiency, because no work is added to the system during the adsorption mode.

For forced convection adsorption, energy is added to the system in two forms namely power added to air stream during adsorption process and heat added to the desiccant bed to reconcentrate the desiccant and regenerate vapour For specific system parameters and ambient temperature, the ratio of heat to work added to the system is presented in Fig.5, for different values of relative humidity of ambient air It can be noticed that the value heat/work ratio decreases with decrease in concentration at the end of adsorption. The influence of relative humidity of inlet air, for a given temperature, shows an increase in this ratio for higher values of relative humidity For the same operating conditions, system efficiency is plotted versus desiccant concentration during sorption (Fig. 6). It is shown that a maximum value of system efficiency exists at specific value of concentration, for a given value of relative humidity. In addition, system efficiency generally increases with increase in humidity of air. Therefor, desiccant minimum concentration must be selected to maximize the system performance in case of forced adsorption

In addition to ambient conditions, the optimal selection for the desiccant concentration X_a is also dependent on the system operating parameters As an example let us consider a system with the following operating conditions

Initial concentration = 0 4
Ambient temperature = 30 °C
Relative humidity =0.8
Bed mass/desiccant mass = 10
Dimensionless specific heat of bed material =0 012

Plot of the system efficiency versus desiccant concentration X_a is shown in Fig 7. for different values of dimensionless pressure drop $\overline{P}$ Generally, higher values of system efficiency can be attained with lowering the dimensionless pressure drop
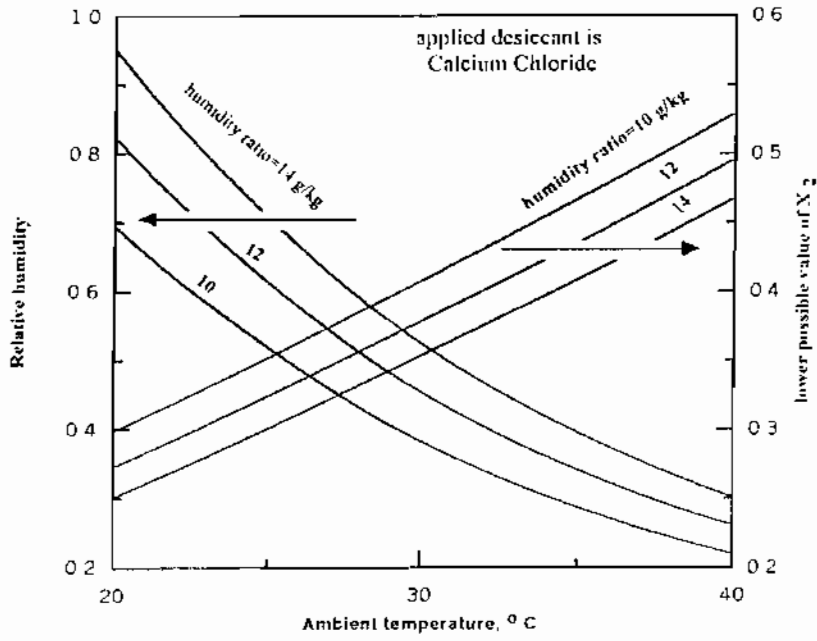
Fig. (3) Effect of ambient air parameters on the lower possible value of X_2
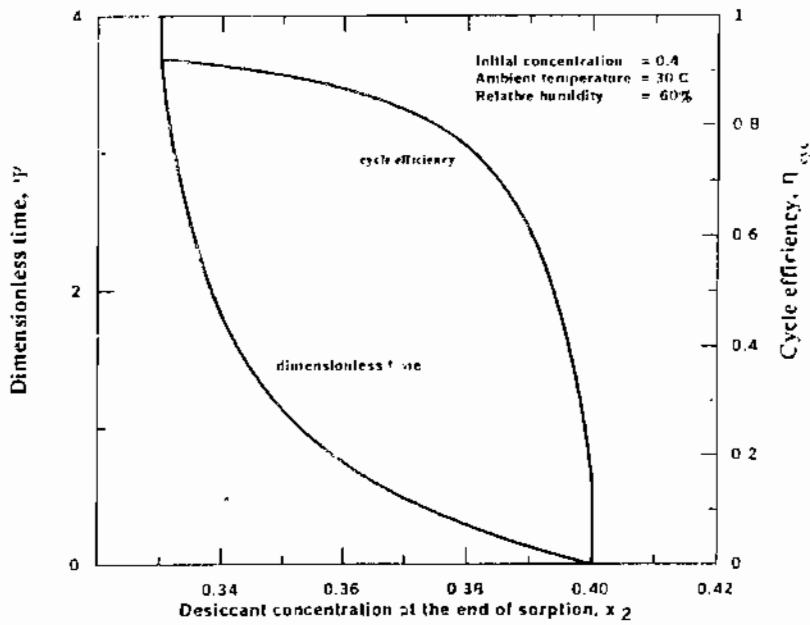

Fig. (4) Variation of dimensionless time and cycle efficiency with desiccant concentration at the end of sorption
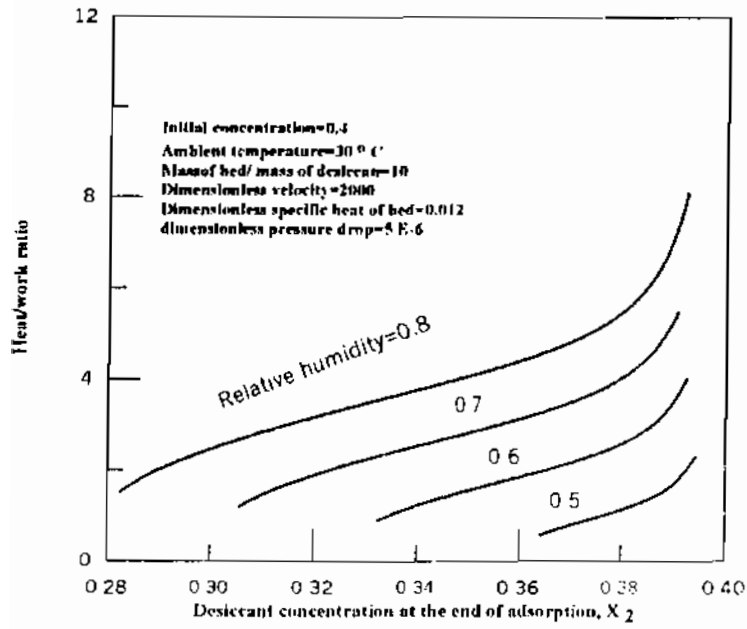
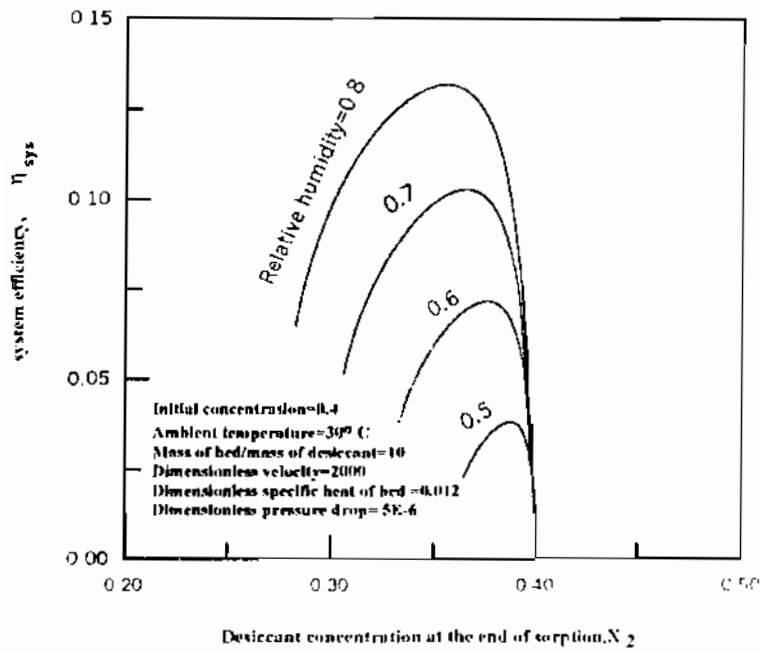Fig. 5 Variation of heat/work ratio with adsorption concentration, X_2

Fig. 6 System efficiency versus concentration at the end of adsorption process
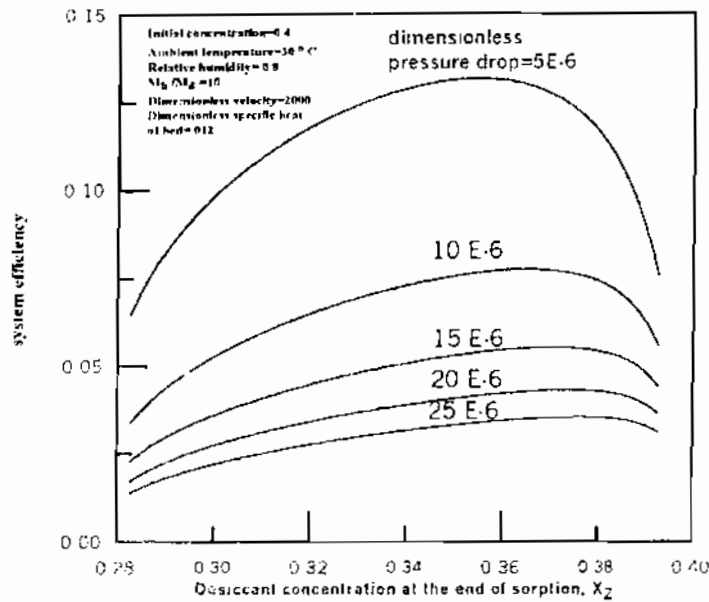at different values of relative humidity

Fig. 7 System efficiency versus desiccant concentration
at the end of adsorption

CONCLUSIONS

Analysis of the operation of the adsorption/desorption system (ADS) for production of water from ambient air, with forced convection adsorption has been developed. The effects of meteorological conditions and system design parameters are well defined. Also, system efficiency is defined in terms of operating cycle efficiency and system design parameters. The appropriate selection of desiccant concentration at the end of adsorption has been discussed. Based on the obtained simulation results, the following conclusions can be drawn:

- Cycle efficiency and system efficiency don't reach maxima at the same value of desiccant concentration at the end of adsorption
- The lower concentration for the operating desiccant is strongly dependent on the ambient temperature and humidity
- The optimum desiccant concentration at the end of sorption decreases with decrease in pressure drop through the system
- For a given ambient temperature, system overall efficiency is highly dependent on relative humidity

REFERENCES

[1] Sofrata H., "Non-Conventional System for Water Collection", Proc. Of Solar Desalination Workshop, 2, pp 71-87, 1981

[2] Alayli Y., Hadji N. E and Leblond, "A New Process for the Extraction of Water from Air" Desalination, 67, pp 227-229, 1987

[3] Khalil A., "Dehumidification of Atmospheric Air as a Potential Source of Fresh Water in the UAE" Desalination, 86, pp 587-596.

[4] Nebbia G., "The Problem of Obtaining Water from the Air", Proc. of the Conf on Solar and Aeolian Energy". Part V, pp 33-46,1961

[5] Sultan A.A., Hamed A.M , Sultan G I., "Comparative Study for Extracting Water from Atmospheric Air using Alternative Cooling Systems". In Proceedings of the 10th International conference of Mechanical Power Engineering, Assiut, Egypt, 1997

[6] Awad M. M., Sultan A. A. and Abdel-Raouf M. M , "Using Refrigeration Systems to Extract Water from Moist Air" In Proceedings of the I st UAE Conference on Air Conditioning in the Gulf, ACG, pp.242-255, 1996

[7] Hall R.C , "Production of Water from the Atmosphere by Absorption with Subsequant recovery in a Solar Still", Solar Energy, 10, pp 41-45, 1966

[8] Hall R. C., Rao G. V and Livingston R. J., "Prediction of Liquid holdup on an Absorption Tower for the Production of Water from the Atmosphere with Subsequent Recovery in a Solar Still", Solar Energy, 12, pp 147-161, 1968

[9] Gandhidasan P. and Abualhamayel H.I , "Water Recovery from the Atmosphere", WREC, pp.745-748, 1996

[10]-Aristov Yu. I., Tokarev M. M , Gordeeva L G.,Snytnikov V.N and Parmov V N. " New Composite Sorbents for Solar-Driven Technology of Fresh Water Production from the Atmosphere", Solar Energy, Vol. 66, No 2, pp 165-168, 1999

[11] Hamed A M , "Absorption-regeneration Cycle for Production of Water from Air-Theoretical Approach", Renewabl Energy, No 19, pp 625-635, 2000

[12] Gad H.E., Hamed A M. and I.I. El-Sharkawy, "Application of Desiccant/ Collector System for water Recovery from Atmospheric Air", Accepted for publication, Renewable Energy, 2000

[13] Treybal R.E , "Mass Transfer Operations", McGraw-Hill, Third Edition, 1981

[14] Hamed, A.M., "Theoretical and Experimental Study on the Transient Adsorption Characteristics of Vertical Packed Porous Bed", Proc Of Mansoura Third International Engineering Conference, El-Mansonra, Egypt, 2000