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Ahmed Mohamed Kandel

*Mechanical Power Engineering Department., Faculty of EEngineering., El-Mansoura University., Mansoura., Egypt.*

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## ABSORPTION-REGENERATION CYCLE FOR PRODUCTION OF WATER FROM AIR-THEORETICAL APPROACH

دورة الامتصاص والتوليد الخاصة بالحصول على الماء من الهواء الجوى - مدخل نظري

AHMED M. HAMED

Mechanical Power Engineering Department, Faculty of Engineering,  
Mansoura University, EL-Mansoura, Egypt

خلاصة:

لى هذا البحث تم وصف وتحليل الدورة النظرية الخاصة بامتصاص الرطوبة من الهواء الجوى ثم إعادة توليد البخار من المادة الماصة عن طريق التسخين. كما تم الحصول على العلاقة بين خواص المحلول المنحل المستخدم فى الدراسة وهذه العلاقة يمكن استخدامها لى تحليل الدورة باستخدام الحاسب الآلى. ودراسة تأثير الظروف الجوية على حدود عمل الدورة لقد تم صياغة النموذج الرياضى الناتج عن عمل ايزان حرارة وكتلة لإجراءات الدورة. كما يمكن تعريف الكفاءة النظرية للدورة، وقد بينت الحسابات النظرية مدى تأثير تركيز المحلول المنحل المستخدم على كفاءة الدورة ودرجة الحرارة اللازمة لتوليد البخار.

### ABSTRACT

Description and analysis of the theoretical cycle for absorption of water vapour form air with subsequent regeneration, by heating, is presented. Properties of desiccant applied in the study are correlated in a simplified form, which can be used in computational analysis of the cycle performance. To predict the effect of ambient conditions on the operating limits of the cycle, heat and mass balance equations are developed. In addition, an expression for the efficiency of the simple cycle is introduced. Theoretical analysis shows that strong and weak solution concentration limits play a decisive role in the value of cycle efficiency. The limits of regeneration temperature and mass of strong solution per kg of produced water vapour are found highly dependent on the operating concentration of desiccant.

### KEYWORDS

Absorption-regeneration cycle, atmospheric air, desiccant

### NOMENCLATURE

a, b, c, d	empirical constants, Eqns. 1,2,4,5 and 7
$c_p$	specific heat, kJ/kg. $^{\circ}$ C
h	specific enthalpy, kJ/kg
$L_e$	Latent heat of evaporation of water, kJ/kg
M	mass of strong solution per kg vapour, kg
m	mass of evaporated water, kg
$P_v$	vapour pressure on the absorbent surface, bar
$p_a$	atmospheric pressure, bar
$p_s$	condensation pressure, bar
$q_v$	heat added to regenerated vapour, kJ/kg
Q	total heat added in the cycle, kJ
t	temperature, $^{\circ}$ C
x	solution concentration ( mass of $CaCl_2$ per kg of solution)
$\eta_{cyc}$	cycle efficiency

## INTRODUCTION

The limiting condition for the need of population growth and development in many areas of the world is the fresh water supply. The problem of providing arid areas with fresh water, from our point of view, can be solved by the following methods:

- 1- Transportation of water from other locations,
- 2- Desalination of saline water (ground and underground) and
- 3- Extraction of water from atmospheric air.

The extraction of water from atmospheric air, however, has several advantages compared with other methods. Air as a source of water is renewable and clean. Amount of water in atmospheric air is evaluated as  $14000 \text{ km}^3$ , whereas the amount of fresh water in the earth is only about  $1200 \text{ km}^3$  [1]. It is preferred to solve water problem in arid areas using the natural resources and the renewable energy sources like solar energy, where the available area to collect solar radiation and volumes of air are infinite.

Water can be extracted from air by cooling it to a temperature lower than its dew point where the moisture is condensed. Several investigators [2-8] have studied this method. Generally, it is reported that the energy consumption was high specially when solar energy is used due to low conversion efficiency. Another approach for extraction of water from atmospheric air is by absorption of water from the moist air into a solid or liquid desiccant with subsequent separation of water from the desiccant by heating and condensation of water vapour [9-10].

Application of solar energy for regeneration of absorbent was investigated [11-13]. Comparative study for economical evaluation of the two methods mentioned above shows that, the second system is economic [8]. This comparison was carried out when solar energy is used as the power supply to drive any of the two systems, with the use of Li-Br absorption cycle for the cooling system and applying  $\text{CaCl}_2$  as the working desiccant for the absorption-regeneration system.

In addition, it is observed that the design and operation of the absorption-regeneration system is simpler than that of the cooling system. An analytical procedure for calculation of the mass of water absorbed by the desiccant from the ambient atmosphere as a function of meteorological parameters (temperature and humidity) and the desiccant initial condition (mass and concentration) has been presented in [8].

We are interesting in setting a theoretical limit on the maximum possible amount of water, which can be collected from air using desiccant through the absorption-regeneration cycle at certain operating limits of: ambient conditions, heat to be added to desiccant during regeneration and maximum available heating temperature. This theoretical limit can be evaluated through the definition of cycle efficiency. Definition of cycle efficiency based on the rigorous heat and mass balance calculations is presented. This paper also studies the influence of relevant parameters on the cycle performance.

## THE ABSORPTION-REGENERATION CYCLE

The absorption-regeneration cycle, which can be applied, for the production of water from atmospheric air, is shown in Fig. 1. The theoretical cycle is plotted on the vapour pressure-

concentration diagram for the operating absorbent and consists of four thermal processes which are:

- Process 1-2: isothermal absorption of water vapour from air,
- Process 2-3: constant concentration heating of the absorbent,
- Process 3-4: constant pressure regeneration of absorbent and
- Process 4-1: constant concentration cooling of absorbent.

The thermal processes of this cycle are carried out between two concentration limits;  $x_1$  and  $x_2$  and the cycle has another operation limits which are its maximum regeneration temperature  $t_4$ , condensation pressure  $p_s$ , and maximum absorption pressure  $p_v$ . Evaluation of these operation limits is important from the point of view of system design and construction. Therefore, description of the effect of weather conditions on the cycle operation will be presented. If the ambient temperature is equal to  $t_1$ , and strong solution concentration is  $x_1$ , absorption process starts only when the vapour pressure on the absorbent surface is lower than the vapour pressure in the atmospheric air  $p_v$  (Fig. 1). Theoretically, absorption continues from 1 to 2, i.e. ends at equilibrium condition when the pressure of water vapour on the absorbent surface is the same as that in atmospheric air. When the absorption process ends, absorbent is isolated from air and to be heated by an external source. Regeneration of weak absorbent can be carried out with instantaneous condensation of vapour separated from the solution at constant pressure. The vapour pressure on the absorbent surface at point 2 is equal to  $p_v$ . Constant pressure condensation at this pressure requires that the condensation temperature is the saturation temperature of water vapour corresponding to  $p_v$  which will be lower than ambient temperature, when the relative humidity of atmospheric air is lower than 100%. If condensation is assumed to be at ambient temperature, weak solution must be heated from  $t_2$  to  $t_3$  with constant concentration and water vapour pressure increases from  $p_v$  to  $p_s$ , i.e. the saturation pressure of water vapour corresponding to ambient temperature. The increase in temperature from  $t_2$  to  $t_3$  depends on the relative humidity of air or the weak solution concentration  $x_2$ , which depends also on the relative humidity at the given ambient temperature.

During the constant pressure condensation, solution concentration increases from  $x_2$  to  $x_4$ . The maximum regeneration temperature depends on the available heat source and the limits allowed for desiccant concentration. Strong solution at point 4 is not able to absorb water vapour from air due to its higher vapour pressure, therefore pressure is reduced again to  $p_1$  by cooling from  $t_4$  to the ambient condition, where the cycle ends at point 1.

## THEORETICAL ANALYSIS

### (1) Absorbent properties

The absorption equilibrium relation of the calcium chloride, which is used as a working absorbent in this study, is correlated for computer calculation purposes. The actual mathematical relationship between the equilibrium thermophysical properties (water vapour pressure, temperature and concentration) is complex. However, when the concentration  $x$  is constant [14], the relation between water vapour pressure and solution temperature is given as.

$$\ln p = a - \frac{b}{T} + c \ln T + d T^n \quad (1)$$

and the approximate form of equation (1) can be written as

$$\ln p = a' - \frac{b'}{T} \quad (2)$$

where  $a$ ,  $b$ ,  $c$ ,  $d$ ,  $a'$  and  $b'$  are empirically determined constants for the ranges of temperature and concentration of interest.

During the isothermal absorption in the cycle, water vapour pressure and solution concentration varies over a wide range, therefore a mathematical relationship between water vapour pressure and concentration is required. On the other hand, during the regeneration process 3-4, in Fig.1, temperature and concentration are also varied, consequently a concentration-temperature correlation is important for the analysis of regeneration process. In the light of equation (2), with the help of  $\text{CaCl}_2$  data [15], the following correlation is obtained as a result of treatment of the available data,

$$\ln p = A(x) - \frac{B(x)}{t + 111.96} \quad (3)$$

where  $p$  in mm Hg and  $t$  in  $^\circ\text{C}$ ,  $A(x)$  and  $B(x)$  are concentration dependent parameters and can be expressed as linear functions of  $x$  as

$$A(x) = a_0 + a_1 x \quad (4)$$

$$\text{and } B(x) = b_0 + b_1 x \quad (5)$$

Where  $a_0$ ,  $a_1$ ,  $b_0$  and  $b_1$  are the regression constants, given in table 1 for the corresponding range of  $P$ ,  $t$  and  $x$

Tab. 1 Regression constants for Eqns. 4 and 5

Constant	Value	Variable	Range
$a_0$	10.0624	$p$	8 - 75 mm Hg
$a_1$	4.4674	$t$	10 - 65 $^\circ\text{C}$
$b_0$	739.828		
$b_1$	1450.96	$x$	0.2 - 0.5

For the absorption process, the final concentration, at which absorption ends, depends on the vapour pressure in the atmosphere and the absorption temperature, i.e

$$x = f(p_a, t_a) \quad (6)$$

An expression for  $x$  can be derived as a function of  $P$  and  $t$  by solving eqns. (3), (4) and (5) for  $x$ , i.e

$$x = \left[ \ln p - \left( a_0 - \frac{b_0}{t+111.9} \right) \right] / \left( a_1 - \frac{b}{t+111.9} \right) \quad (7)$$

During the regeneration process, solution temperature increases with increase in concentration of absorbent. The regeneration temperature can be evaluated by solving equation (3) for  $t$

The group of equations from 1 through 7 can be used to evaluate the operating limits of the cycle for a given ambient conditions, and can be applied also for a parametric study to evaluate the effect of various operating parameters on the cycle performance

## (2) Calculation of regeneration heat

During regeneration, heat must be applied to the desiccant to accomplish the following:

1. heat the solution to minimum regeneration temperature (process 2-3);
2. vaporize the water;
3. heat the solution to its final temperature in the process 3-4 and
4. heat the regenerated vapour to its final temperature.

Item 1 represents the increase in enthalpy of solution through the constant concentration heating process 2-3, item 4 is often negligible compared with items 2 and 3

Referring to Fig. 2 which represents the input and output parameters during the regeneration process, if the analysis is carried out per one kg of regenerated water vapour from the absorbent, the quantity of heat transferred during the process will be,

$$Q = h_v + M h_4 - h_2 (M + 1) \quad (8)$$

where  $h_v$  is the enthalpy of water vapour generated from solution,

$M$  is mass of solution per kg water vapour, which can be expressed as mass ratio.

$h_2$  is the enthalpy of weak solution at point 2.

$h_4$  is the enthalpy of strong solution at point 4.

The mass ratio  $M$  can be evaluated from the mass balance of the working desiccant, i.e

$$M = \frac{x_2}{x_1 - x_2} \quad (9)$$

where  $x_1$  and  $x_2$  are the concentrations of strong and weak solution respectively.

Substituting by  $M$  in eqn (8),

$$Q = h_v + \left( \frac{h_4 x_2}{x_1 - x_2} \right) - \left( \frac{h_2 x_2}{x_1 - x_2} \right) \quad (10)$$

or

$$Q = h_v + \left[ \frac{x_2 h_4 - x_2 h_2}{x_1 - x_2} \right] \quad (11)$$

The enthalpy of water vapour,  $h_v$ , can be expressed as,

$$h_v = h_{g,c} + \int_{t_c}^{t_a} c_{p,r} dt \quad (12)$$

where  $h_{g,c}$  is the enthalpy of dry saturated water vapour at condensation temperature and  $t_c$  is the condensation temperature. However, the second term in the right hand side of Eqn (12) is often negligible and, accordingly it will be ignored in calculations. The enthalpy of solution can be evaluated by knowledge of specific heat of solution at the working temperature [16]

As the purpose of this cycle is to produce water from air and the input energy to the system is the heat added during the regeneration process. Then the efficiency of the cycle can be defined as the ratio of heat added to regenerated vapour to the total heat added, i.e.

$$\eta_{cr} = \frac{q_v}{Q} \quad (13)$$

In the calculation of the cycle efficiency,  $q_v$  will be assumed equal to the latent heat of generated water vapour  $L_c$  at the corresponding condensation temperature  $t_c$ .

Substituting by  $Q$  from eqn. (11) taking into account that  $x_1 = x_2$  then,

$$\eta_{cr} = L_c \left/ \left[ h_v + \frac{x_2 h_1 - x_1 h_2}{x_1 - x_2} \right] \right. \quad (14)$$

## RESULTS AND DISCUSSION

During regeneration. The temperature of the regenerated solution increases from a minimum temperature to a maximum regeneration limit. When the condenser temperature is the same as that of the ambient, the maximum regeneration temperature depends only on the initial (strong) solution concentration  $x_1$ . The minimum temperature required for solution regeneration is dependent on the concentration of absorbent at the end of absorption process. Fig. 2 shows the effect of solution concentration on the regeneration temperature at different condenser temperatures. From the figure, it can be observed that the constant condenser temperature lines are nearly parallel where the regeneration temperature increases gradually with increase in condenser temperature for a given solution concentration.

It can be noted also that, if the operating range of solution concentration is the same for different condensation temperatures the difference between maximum and minimum regeneration temperatures is nearly the same. For example, if the minimum and maximum solution concentrations are 0.1 and 0.4, the differences between regeneration limits for condenser temperatures of 40 °C and 20 °C are about 16 °C and 14 °C respectively.

An important parameter for the absorption-regeneration cycle is the mass ratio, which is the ratio between the mass of generated water vapour per unit mass of strong solution. This ratio depends only on the maximum and minimum solution concentrations. Fig. 3 illustrates the effect of the concentration limits on the mass ratio. For the selected range of solution concentration (0.1-0.4), the mass ratio is plotted for different values of strong solution concentration  $x_1$ , against the weak concentration. In general, the mass ratio increases with increase in operating concentration range. However, knowledge of the mass ratio is

important for design purposes, through which the mass of strong solution required to produce a certain mass of water vapor per cycle, for a given concentration range can be determined.

The cycle efficiency, which is the ratio between heat, added to evaporated water from the weak solution to the total heat added to solution during the regeneration process, against weak solution concentration, at different strong solution concentrations and constant values of ambient temperature and condenser temperature is presented in Fig. 4. Generally, cycle efficiency increases with decrease in weak solution concentration. Higher values of cycle efficiency (more than 80%) can be realized for different values of strong solution concentrations ( $x_1$ ), but the operating concentration range increases with increase in strong solution concentration. For example, when the ambient temperature and condenser temperature are equal to 20 °C, values of efficiency of 91.5% can be obtained. For two different cases,

$$x_1 = 0.40 \text{ \& } x_2 = 0.32, \text{ i.e } (\Delta x = 0.8)$$

$$\text{and } x_1 = 0.34 \text{ \& } x_2 = 0.30, \text{ i.e } (\Delta x = 0.4)$$

This means that the concentration difference is doubled when the initial concentration increases from 0.34 to 0.4 for the same value of efficiency.

## CONCLUSIONS

From this investigation, the following conclusions are obtained:

- 1- The theoretical efficiency of the cycle, mass of strong solution required per kg of generated water vapor and regeneration temperature of desiccant are highly dependent on the concentration limits of the working desiccant.
- 2- Values of cycle efficiency higher than 90% can be obtained for different values of strong solution concentration and this value decreases suddenly when the difference between strong and weak solution concentrations is small.
- 3- Mass ratio of strong solution increases with increase of concentration difference and has maximum values at higher efficiency values.

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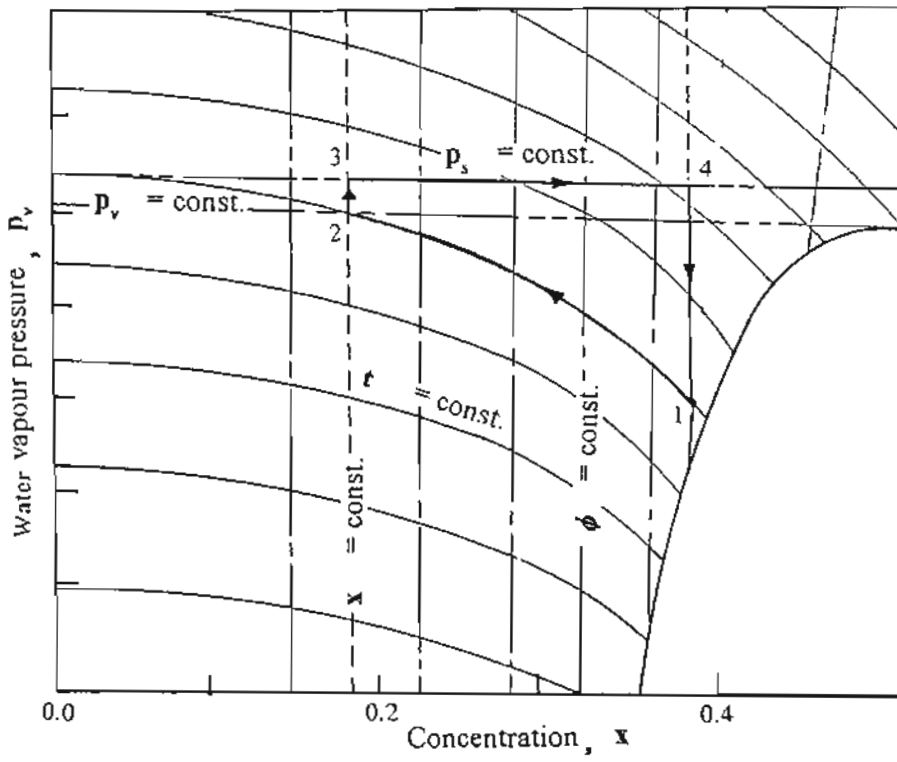


Fig. 1 The absorption-regeneration cycle for production of water from air

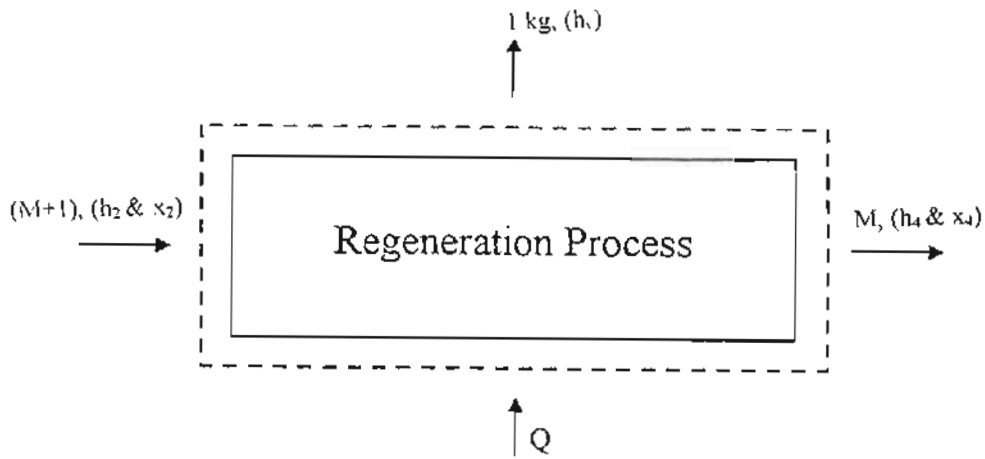


Fig. 2 Input and output parameters during regeneration process

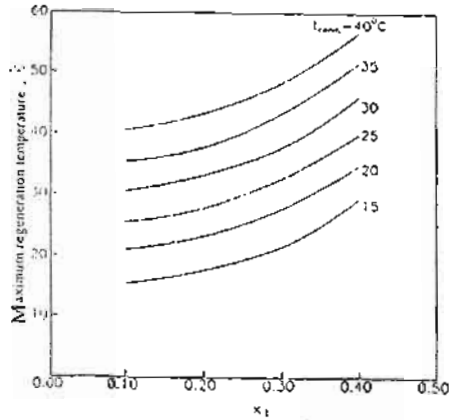


Fig. 3 Effect of strong solution concentration on the regeneration temperature at different condensation temperatures

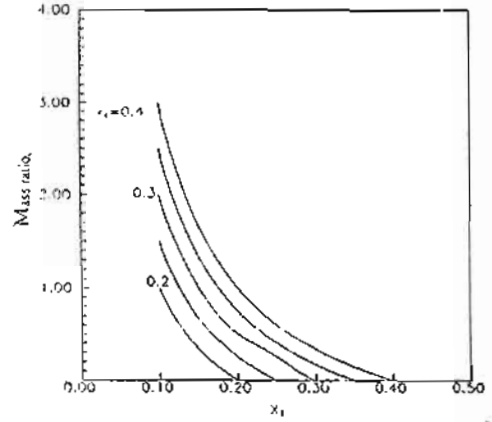


Fig. 4 Effect of weak absorbent concentration on the mass ratio for different initial absorption concentrations

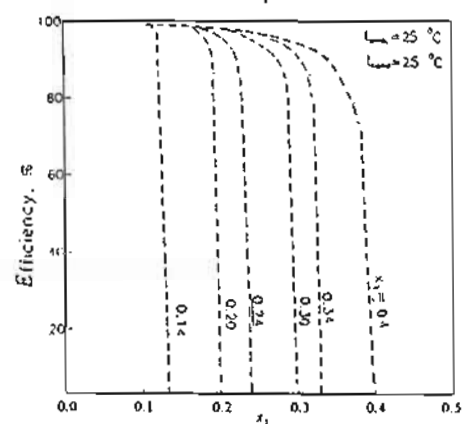
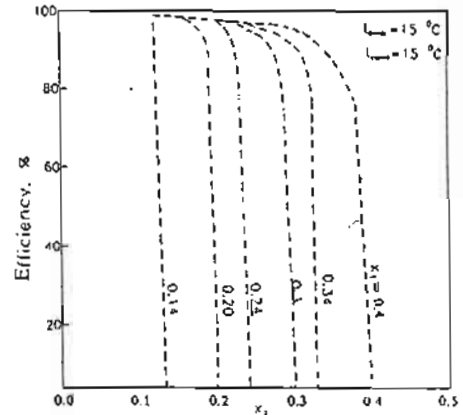
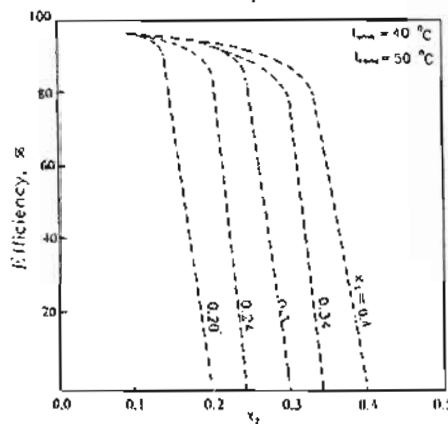
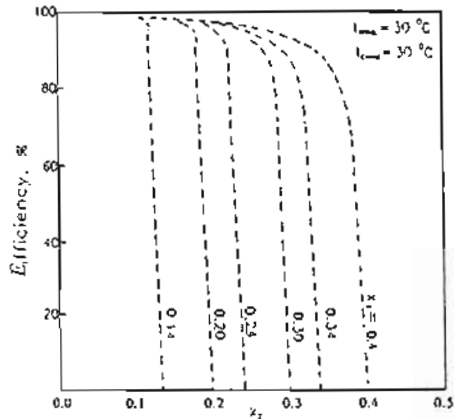


Fig. 5 Cycle efficiency at different operating concentrations and ambient temperatures