Mansoura Engineering Journal

Volume 23 | Issue 4 Article 3

12-1-2020

Regeneration of Calcium Chloride in Packed Tower for Operation with Open Solar Absorption Cooling System.

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Recommended Citation

Hamed, Ahmed; Sultan, Ahmed; and Sultan, Gamal (2020) "Regeneration of Calcium Chloride in Packed Tower for Operation with Open Solar Absorption Cooling System.," *Mansoura Engineering Journal*: Vol. 23 : Iss. 4 , Article 3.
Available at: https://doi.org/10.21608/bfemu.2021.150028

Mansoura Engineering Journal, (MEJ), Vol. 23, No. 4. December 1998.

REGENERATION OF CALCIUM CHLORIDE IN PACKED TOWER FOR OPERATION WITH OPEN SOLAR ABSORPTION COOLING SYSTEM

إعادة تركيز محلول كلوريد الكالسيوم في برج مضغوط لاستخدامه في دورة التبريد المفتوحة التي تعمل بالامتصاص باستخدام الطاقة الشمسية

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خلاصة:

يستعرض البحث نتائج التجارب المعملية الخاصة بإعادة تركيز محلول مخفف من كلوريد الكالسيوم (X=0.37) باستخدام برج مضغوط وذلك لاستخدام المحلول المركز بعد ذلك للعمل كمادة ماصة في دورة التبريد بالامتصاص المفتوحة. وتم في هذا البحث إلقاء الضوء على تأثير العوامل المختلفة على إجراء إعادة التركيز وذلك باستخدام هواء ساخن لدرجات حرارة يمكن الحصول عليها من مسخنات الهواء الشمسية. ولتسهيل التعامل مع خواص المحلول تم معالجة البيانات الخاصة بالعلاقة بين درجة الحرارة ، التركيز وضغط البخار على سطح المحلول وتم الحصول على علاقة مبسطة تربط بين هذه الخواص. كما تم دراسة تأثير درجة حرارة الهواء المسخن على فعالية إجراء التوليد وتم رسم هذه العلاقة بيانيا. مما يؤكد أن فعالية الإجراء تعتمد بدرجة كبيرة على درجة حرارة الهواء وكانت هذه النتيجة متوافقة مع نتائج باحثين آخرين.

ABSTRACT:

This paper presents the experimental results of using packed tower for regeneration of weak solution (x=0.37) of calcium chloride when used as the absorbing solution in an open solar absorption cooling system. The effect of the operating parameters on the regeneration process is highlighted. Also, treatment of calcium chloride solution data is carried out and regression constants of the correlation are obtained for a wide range of operating perameters. The effectiveness of the regeneration process is dependent on the air inlet temperature. Comparison of the experimental data with theoretical investigation, given in literature, shows reasonable agreement.

KEYWORDS:

Packed tower - Open solar absorption system.

NOMENCLATURE:

A	mass transfer area, m^2
B	barometric pressure, mm.Hg
C_p	specific heat, J/kg.K
D	linear dimension or characteristic length, m
D_v	diffusivity, m^2/s
G	fluid mass velocity, $kg/m^2.s$
h_D	mass transfer coefficient, $kg/m^2.hr.mmHg$

Accepted December 26 , 1998

h_{fg}	latent heat of evaporation of water, J/kg
K	mass transfer coefficient, m/s
m	mass flow rate, kg/s
P_t	atmospheric pressure, mmHg
P	vapour pressure, mmHg
Q	rate of heat transfer, kW
T	temperature, K
t	temperature, °C
u	fluid velocity, m/s
x	solution concentration, by weight
w	humidity ratio of air, $kg_{water}/kg_{dry\ air}$
ε	effectiveness of regenerator,
μ	dynamic viscosity, kg/m.s
ρ	density, kg/m^3

INTRODUCTION:

Liquid desiccants have a great potential for use in solar air conditioning applications. The inherent advantage of using desiccants in air conditioning systems is the possibility of using waste heet or available solar energy for regenerating the desiccant. Although the coefficient of performance of such systems is very low as compared to vapour compression systems and it's initial cost is higher, the energy required for running the system can be costless (in case of 100% solar energy or waste heat utilization), which makes its usa attractive.

The concept of the open absorption solar cooling systam has received much attention due to its high feasibility. Kakabyev and Khandurdyev [1,2] first reported the concept of open absorption cooling system and their prototype experiment. Since 1969, many studies in this area have been reported [3-9]. In the first reported application, a sloped flat roof of a building was used as the regenerator.

A schematic of an open solar absorption cooling system is shown in Fig. 1. The weak absorbent solution is heated and subsequently concentrated in the solar collector, which is open to the atmosphere. The strong reganerated solution leaves the collector and passes through a liquid column, to allow the strong solution to go from etmospheric pressure to reduced pressure efficiently. The strong solution then passes through a regenerative heat exchanger on its way to the absorber, where the strong solution absorbs water from the evaporator, maintaining the reduced pressure required. In tha evaporator, water from an external source is evaporated at reduced pressure with the energy supplied by heat from the cooled space. The resultant weak solution is pumped from the absorber back to atmospheric pressure through the regenerative heat exchanger and to collector, completing the cycle. The thermodynamic equations, which describe the performance of the open system, are essentially identical to those describing the performance of closed one when the condenser is removed. An important aspect in the operation of the open refrigeration systems, however, is the unique relationship between regenerator performance and system performance. For every kilogram of water evaporated in the regenerator, one kg of water can be

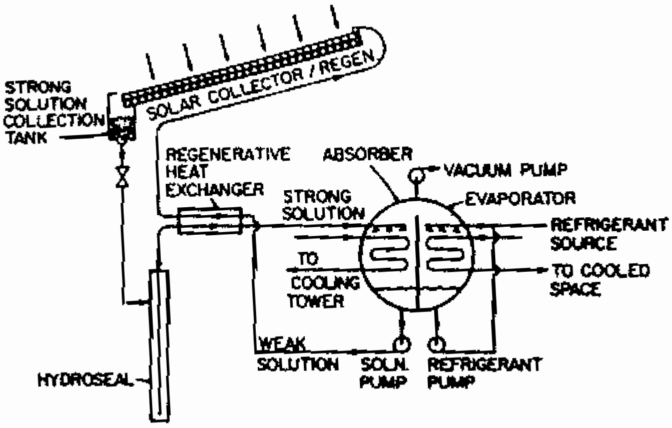


Fig.1 Open cycle solar absorption cooling system [5]

evaporated and absorbed in the absorber. That is the water evaporation rate from the regenerator determines the amount of water that can be evaporated in the evaporator and, henca, determines cooling system capacity. Increasing mass of evaporated water, for certain heat added in the generator, improves the system coefficient of performanca, C.O.P.

Packed column supplied with solar heated air as the regenerator in the solar absorption cooling system has been reported [3]. Operation of the system when packed column is applied (Fig. 2) is the same as that discussed before. Hot air and solution flow counterly, with the solution entering at the top of the column. Air from the solar collector enters at the bottom and leaves through the exhaust duct. As the packed column functions as a regenerator, the mass of water evaporated from the entering solution to hot air determines the cooling effect of the cooling system.

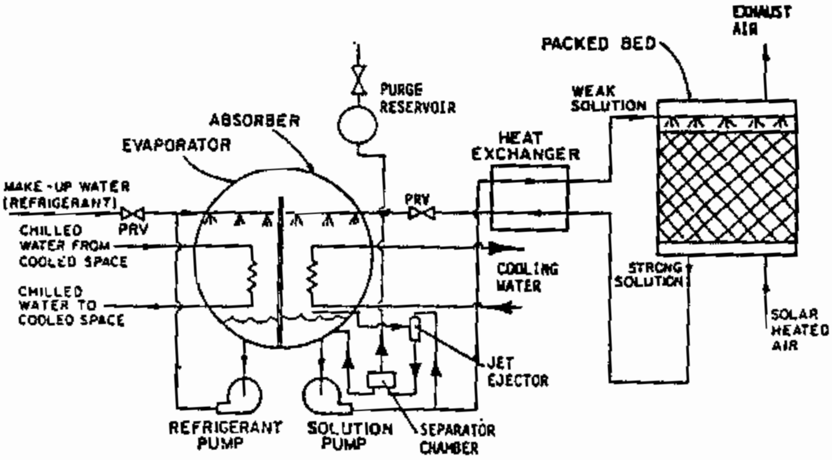


Fig. 2 Operation of open system when packed column is applied [3]

As calcium chloride is the cheapest and easily available desiccant, it is the object of this investigation to test the operation of the packed tower as a regenerator of the open absorption cooling system and $CaCl_2$ as the working solution. Also, it is aimed to obtain system performance with application of hot air in the temperature range applicable with solar heating.

THEORETICAL ANALYSIS:

Schematic of an adiabatic counterflow packed tower showing inlet and outlet properties is given in Fig. 3. Because of the abundance of variables involved with the packed bed regenarator, the analysis becomes increasingly complex and is achieved at very high computational cost [10]. From tha mechanism of mass transfer, it can be expected that the mass transfer coefficient K would depend on the diffusivity D_υ and on the variables that control the character of the fluid flow, namely, the velocity u, the viscosity μ, the density ρ, and some linaar dimension D [11]. Since the shape of the interface can be expected to influence the process, different relations may appear with each shape. For any given shape of heat transfer surface,

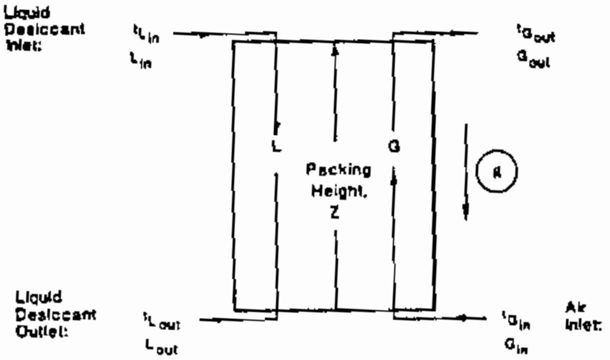


Fig.3 Schematic of an adiabatic counterflow packed tower showing inlet and outlet properties.

$$K = f\,(D_\upsilon\,,\,D\,,\,u\,,\,\mu\,,\,\rho) \tag{1}$$

Dimensional analysis [11] gives:

$$\frac{K}{u} = \phi_1\left(\frac{D\,G}{\mu},\frac{\mu}{D_v}\right) \tag{2}$$

If equation (2) is multiplied by $\left(\frac{DG}{\mu}\right)\left(\frac{\mu}{\rho D_v}\right)$ it gives:

$$\frac{K\ D}{D_v}=\Phi_2\left(\frac{DG}{\mu},\frac{\mu}{\rho D_v}\right) \qquad (3)$$

where:

$\frac{K\ D}{D_v}$	Sherwood number ;
$\frac{\mu}{\rho D_v}$	Schmidt number ;
G	Mass velocity and ,
$\frac{DG}{\mu}$	Reynolds number

The overall mass transfer coefficient h_D can be defined by the following expression:

$$h_D=\frac{m_a\ \Delta w}{A\ \Delta P_v} \qquad (4)$$

The mass transfer coefficient is expressed as evaporated mass per unit time per unit vapour pressure difference per unit area.

For regeneration of liquid desiccant in packed bed, it was possible to study the effect of individual parameters on evaporation rate and regression equation was obtained [3]. The variables used in the regression equation were the independent measurable variables, namely, entering air temperature, solution concentration, solution flow rate, and air inlet humidity. The regression equation obtained from the data of experiment carried on pecked bed reconcentrator was:

$$m_{evap}=a t_{air}^{b}\, x^{c}\, w_{in}^{-d}\, m_{sol}^{e} \qquad (5)$$

where a, b, c, d and e are the constants of regression and t_{air} is the hot air entering temperature; x is desiccant concentration ; w_{in} is inlet air humidity ratio and m_{sol} is solution flow rate.

EFFECTIVENESS FOR REGENERATION PROCESS:

The purpose of regeneration process is to reduce water content of the solution or to increase its concentration. The effectiveness of regeneration process in packed tower may be defined in terms of the change in moisture content of air. The regeneration effectiveness can be defined as the ratio of the actual change in moisture contant of air during regeneration process to the maximum possible change in moisture content under a given condition:

$$\varepsilon=\left[\frac{\left(w_{out}-w_{in}\right)}{\left(w_{out,max}-w_{in}\right)}\right]=\left[\frac{\left(w_{out}\ w_{in}\right)-1}{\left(w_{out\,max}\ w_{in}\right)-1}\right] \qquad (6)$$

We are interesting in setting a theoretical limit to the maximum possible humidity ratio of air at outlet, such that, air cannot be humidified over that limit under the prevailing conditions. For a counter flow packed tower, (Fig. 3) at air outlet we have the liquid desiccant inlet (at the top of the packing). At this cross-section one has the highest liquid vapour pressure (lower concentration). Also, the highest air vapour pressure is at the top of the tower. As long as the eir vapour pressure is lower then the liquid vepour pressure, regeneration can take place. Therefore, the liquid inlet conditions set a theoretical limit on the maximum vapour pressure, and therefore on the maximum humidity ratio that air can achieve. In the limit,

$$P_{air,\,out,\,max} = P_{liquid,\,in} \tag{7}$$

where $P_{liquid,\,in} = f\ (w_{out,\,max})$, which depends only on the properties of solution (concentration and temperature) and the humidity ratio of air at packing tower outlet.

$w_{out,max}$ can be evaluated from the following relation:

$$w_{out,\,max} = 0.622\frac{P_{liquid,\,in}}{B - P_{liquid,\,in}} \tag{8}$$

The vapour pressure on the surface of liquid desiccant at constant solution concentration depends only on solution temperature and can be expressed as given by [12] in the following form:

$$\mathrm{Ln}\,P = a - \left(\frac{b}{T}\right) + c\,\mathrm{Ln}\,T + d\,T^{e} \tag{9}$$

With approximation, the above relation can be written as:

$$\mathrm{Ln}\,P = a' - \frac{b'}{T} \tag{10}$$

Another important factor, which can be used to evaluate the performance of the packed tower as a regenerator coupled with an open absorption cooling system is the regenerator coefficient of performance (G.C.O.P), which can be defined as the ratio of cooling effect of the system to the heat input to regenerator.

In case of air heating:

$$G.C.O.P = Q_e / Q_{air} \tag{11}$$

Where:

$$Q_e = \left(\dot{m}_{air}\,\Delta w\right) h_{fg} \tag{12}$$

and $$Q_{air} = \left(\dot{m} \cdot C_p \cdot \Delta T\right)_{air} \tag{13}$$

Where h_{fg} is the latent heat of water at the operating vapour pressure in the evaporetor, and ΔT is the temperature rise of heated air when it passes through the heating system. The coefficient of performance of the regenerator may be correlated in accordance to equations (11), (12) and (13) as:

$$G.C.O.P = \Delta w\, h_{fg} / \left(C_p \cdot \Delta T\right)_{air} \tag{14}$$

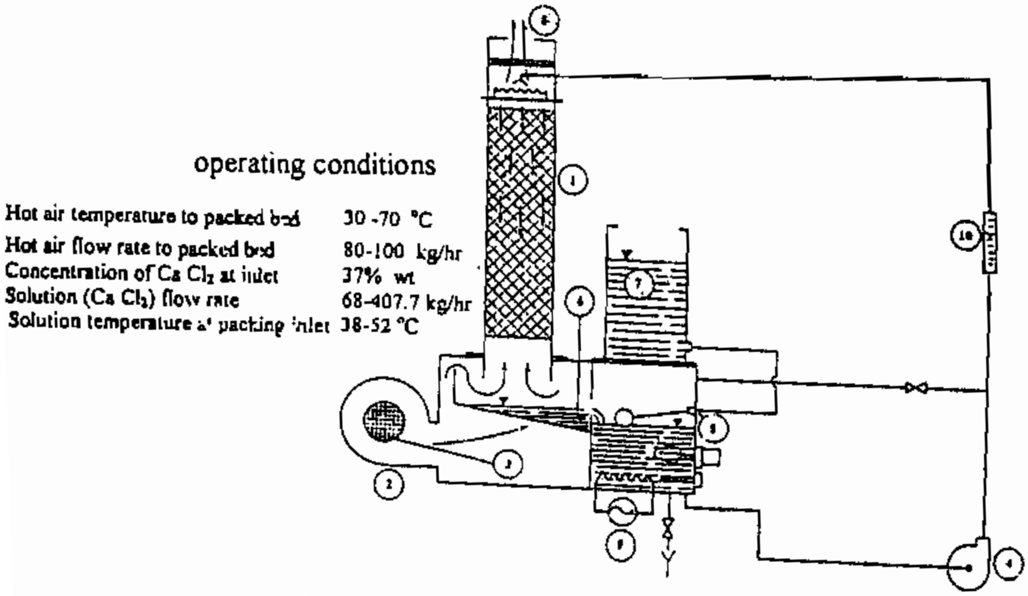
EXPERIMENTAL PROCEDURE:

A schematic layout of the experimental set-up is shown in Fig. 4. It consists of a tower 1 fitted with plastic material. The air is pushed upwards inside the tower by a cantrifugal fan 2. In order to heat the inlet air, the system has been equipped with a special air heater 3. A pump 4 circulates the strong solution from the bottom (collection basin) 5 upwards to the top of the tower. The regenerated solution leaves the tower to the collection basin, which is equipped with a make-up water valve 6 that keeps the solution level constant by drawing water from the tank 7. The hot air enters from the tower side of the column, passes through the column packing, and then leaves through the exhaust outlet 8. The column which is filled with Z shaped plastic packing is square in cross section and has the following specifications:

Filling volume = 0.0135 m^3
Exchange surface = 2.1600 m^2
Column dimension = 15x15x60 cm

Calcium chloride solution, which is used as the operating desiccant in the system, is collected in the collection basin, which is equipped with an electric heater 9 to control the solution temperature at tower inlet.

Liquid flow rate is measured with a rotameter 10 calibrated with water as the working fluid, and corrected for the difference in density between the water and the calcium chloride solution. Temperatures at different points (pump inlet, tower inlet, tower exit) are measured by Hg. in glass thermometers. Dry and wet bulb temperatures at tower inlet and exit are measured with the help of dry and wet bulb thermometers. Concentration of calcium chloride solution is evaluated by measuring the density and temperature. The measured density at a given temperature is then used to find the concentration, which is given as a function of density and temperature in reference [13]. Air velocity is measured by hot wire anemometer through the cross section of the tower exhaust outlet, to evaluate the air mass flow rate.



operating conditions

Hot air temperature to packed bed	30 -70 °C
Hot air flow rate to packed bed	80-100 kg/hr
Concentration of $CaCl_2$ at inlet	37% wt
Solution ($CaCl_2$) flow rate	68-407.7 kg/hr
Solution temperature at packing inlet	38-52 °C

Fig.4 Experimental Set-Up

RESULTS AND DISCUSSION:

With the help of the available Ca Cl_2 solution data [13], the constants of equation (10) ere rearranged and the regression constants are evaluated in the range of solution concentration from 30% wt to 50% wt as follows:

$$LnP = a - \frac{b}{t + 111.96} \qquad (15)$$

Where P is water vapour pressure on the solution surface in mmHg; t is solution temperature, °C; a and b ere constants depending on the operating solution concentration. Values of a and b with the corresponding concentration are given in table 1

Table 1 Regression constants of equation 15

x % , wt	30	35	40	45	50
A	11.469	11.5963	11.7503	12.0916	12.3388
B	1193.2081	1237.4119	1297.2577	1397.0690	1476.1203

Equation (15) is applicable in a range of water vapour pressure from 6.62 mmHg to 76.2 mmHg with a maximum error of about 6%.

Using equation (8), the maximum value of humidity ratio $w_{out,max}$ of air at tower exit can be evaluated. Then, the tower effectiveness ε can be calculated using the measured data of w_{in} & w_{out} of air. The effectiveness obtained from the experimental data with the help of equation (6) has been plotted versus the air inlet temperature. Figure 5 shows the effect of inlet dbt on effectiveness of the regeneration process for two different opereting conditions of solution flow rate. The regeneration process is shown to be more effective in the group of experiments with lower flow rates. Generally, for a given flow rete of liquid and air, the effectiveness has its minimum value in a given temperature range between the higher and lower dbt.

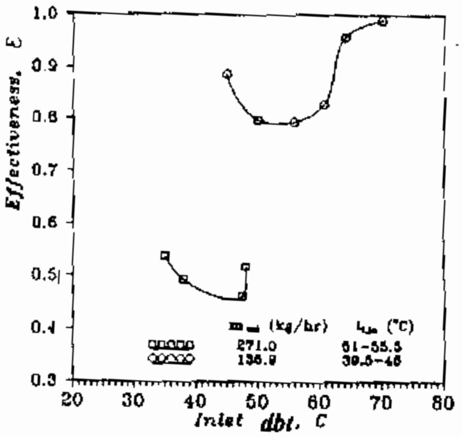


Fig.5 Effect of inlet 'dbt' on the tower effectiveness

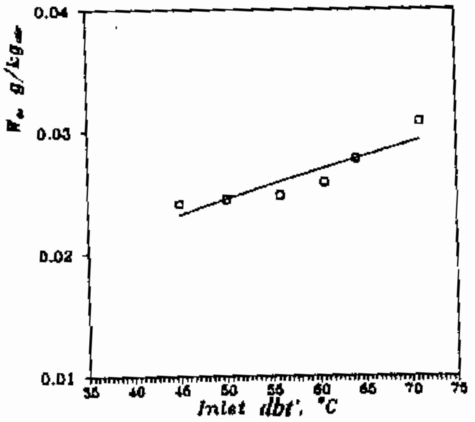


Fig.6 Effect of inlet 'dbt' on exit moisture content

Referring to equation (6), if the air inlet humidity ratio (w_{in}) and liquid inlet temperature have constant values, the effectiveness of the process depends only on humidity ratio of air at outlet of the tower (w_{out}). However, the effect of inlet dbt on the value of w_{out} is plotted as shown in Fig.6. It can be noted that the value of w_{out} increases with increase in inlet dbt.

The dehumidification mode is different from the regeneration mode mainly in the direction of mass transfer. However, the driving force and the controlling parameters are the same in both processes. Theoratical investigation of the process of air dehumidification is presented in [10]. The results of this theoretical investigation show agreement in the trend of the effect of air inlet temparature on the effectiveness with the experimental results of this study.

The influence of inlat liquid temperature on the effectiveness has been presented in Fig.7. As expected, the effectiveness decreases with increase in liquid inlet temperature when inlet air conditions (dbt and W_{in}) are constant.
Values of regenerator coefficient of performance calculated from the experimental data when air is heated to different values of air inlet temperatures are shown in Fig.8 . It can be observed that the trend of the G.C.O.P agrees with that of the effectiveness of regeneration process. The chilled water temperature of the cooling system can be evaluated from the knowledge of water vapour pressure on the solution surface, in the absorber, and the absorber cooling water temperature. For example, if absorber temperature is 25°C and the operating concantration of Ca Cl_2 is 37% then, the evaporator temperature will be 12°C. However, when the solution concentration increases, absorber/ eveporator pressure decreases and condensing temperature can be decreased.

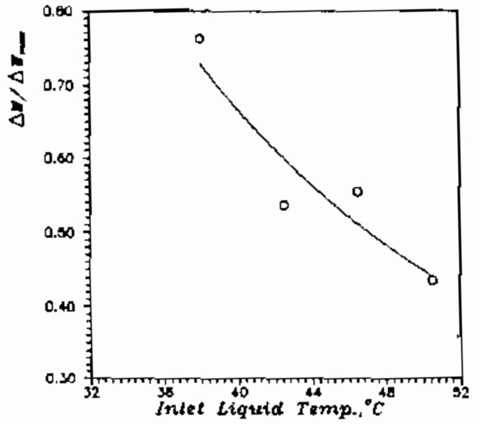


Fig.7 Effect of inlet liquid temperature on the tower effectiveness

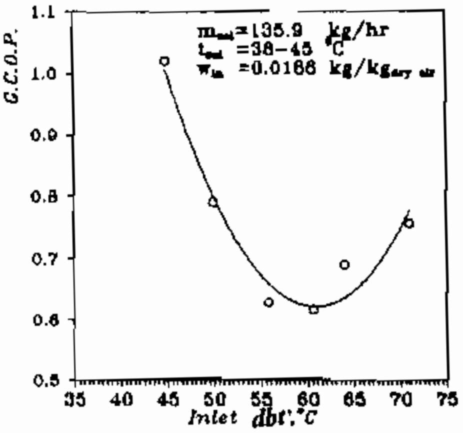


Fig.8 Effect of inlet *dbt* on the generator coefficient of performance (G.C.O.P.)

Typical operating results for runs with air heating are given in table 2. Also, the equivalent cooling capacity can be evaluated for the system. This capacity is the product of mass of evaporated vapour per unit time and latent heat of evaporation of water at the corresponding evaporator pressure. Values of the calculated cooling capacities based on experimental data are also given in Table 2.

Table 2 Sample of results of operation of packed bed regenerator

(Ca Cl_2 37% wt. air inlet 32 °C dbt, W_{in} = 0.0188 $kg/kg_{dry\ air}$)

hot air inlet dbt, °C	air outlet dbt, °C	Air outlet humidity, $kg/kg_{dry\ air}$	liquid inlet temp., °C	liquid outlet temp., °C	max. outlet humidity $kg/kg_{dry\ air}$	effectiveness of regeneration, ε	liquid flow rate kg/hr	Air flow rate kg/hr	equivalent cooling capacity, kW
44.9	39.6	0.0241	39.5	39.8	0.0248	0.887	135.8	110.16	0.41
50.0	41.0	0.0245	40.3	41.0	0.0260	0.797	135.8	109.6	0.44
55.8	43.3	0.0248	42.0	43.3	0.0264	0.794	135.8	109.0	0.458
60.6	45.5	0.0259	43.8	45.0	0.0274	0.829	135.8	108.25	0.535
64.0	46.5	0.0278	45.0	46.0	0.0282	0.958	135.8	107.92	0.673
71.0	48.0	0.0308	46.5	48.0	0.0305	0.990	135.8	103.43	0.855

Although, the experimental data are not sufficient for complete statistical analysis, the effect of air dbt on the value of the humidity ratio, w_o can be expressed as:

$$W_o = 0.0033\ t_{db}^{0.51} \tag{16}$$

The driving force for the regeneration process is a strong function of the difference in potential between absolute humidity of air and the absolute humidity corresponding to the water vapour pressure at the liquid air interface. This fact can be observed in the results of the experimental data shown in Fig.9, where the difference in humidity ratio of air between inlet and exit is plotted against the difference in average values of water vapour pressure in solution and air respectively.

An average value of the overall mass transfer coefficient can be evaluated for each of the three cases, where the air side mass transfer coefficient is given by eqn.(4). For example, the mass transfer coefficient for (c) equals to 0.0367 kg/hr.m^2.mmHg.

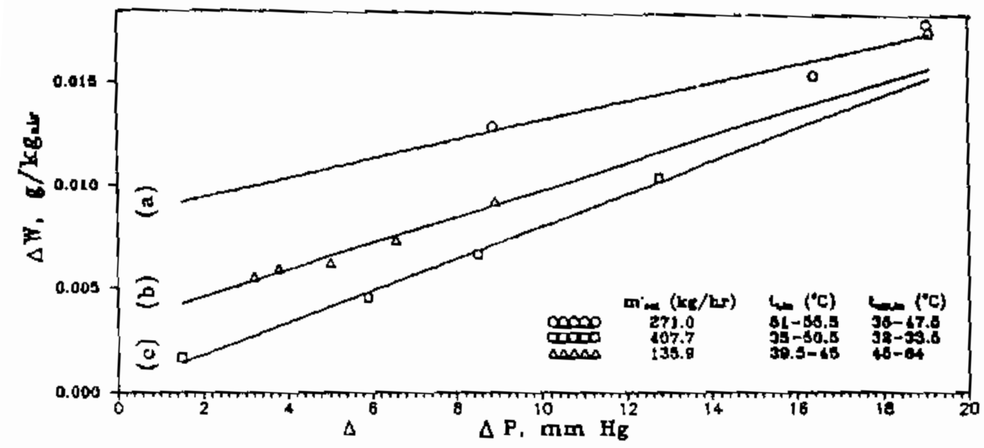


Fig.9 Effect of mean pressure difference on evaporation rate

CONCLUSIONS:

Regeneration of calcium chloride solution in packed column for application with open absorption cooling system is experimentally investigated. Regression constants of the equation describing the most important thermal properties, namely water vapour pressure, concentration and temperature are obtained. Effectiveness of the regeneration process is found to be highly dependent on the air inlet temperature. Experimental results show good agreement with theoretical results of other investigators.

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