[논문] 한국태양에너지학회 논문집 Vol. 30, No. 4, 2010
Journal of the Korean Solar Energy Society ISSN 1598-6411

Prediction on heat and mass transfer coefficients in a packed layer of a regenerator with a solar desiccant cooling system

Eflita, Yohana* Choi, Kwang-hwan**

*Graduate school, Dept. of Refrigeration and Air Conditioning Engineering, Pukyong National University
**College of Mechanical Engineering, Pukyong National University

태양열제습냉방시스템 중 재생기의 충진층 내 열물질 전달계수에 관한 예측

에프리타 요한나*, 최광환**

*부경대학교 냉동공조공학과 대학원, **부경대학교 공과대학 냉동공조공학과(choikh@pknu.ac.kr)

요약문

본 논문은 태양열이용 냉난방시스템 중에서 실제로 액체흡수제를 재생하는 재생탑 내의 충진층에 있어서의 열 및 물질전달의 실험치와 이론적 해석에 의한 결과치와의 비교를 나타내고 있다. 특히 물질전달의 극대화를 위하여 충진층 내에서 공기와 흡수제의 접촉면적을 크게 할 필요가 있는데, 이를 위해서 본 실험에서는 직경이 3cm인 플라스틱제 충진재를 사용하였으며, 흡수제로는 저농도의 염화리튬 수용액이 사용되었다.

충진층 내에서의 최적 높이를 예측하기 위하여 해석의 모델인 실험장치를 직접 제작하여 실험을 수행하였고,이론 해석에 있어서 체적 열전달을 고려한 정상상태를 모델화하여 해석하였다. 이 결과, 충진층 내에서 실험치와 이론적인 계산치가 잘 일치함을 알 수 있었으며, 충진층의 높이가 2m 이상인 경우에는 높이에 따른 재생량의 차이가 없어서 없음을 알 수 있었다.

Keywords : Desiccant cooling(제습냉방), Solar radiation(태양열), Mass transfer(물질전달), Packed layer(충진층), Dehumidification(제습)

1. Introduction

Desiccant systems can provide an effect of adequate dehumidification and cooling. Liquid desiccant cooling system is useful particularly for hot and humid air caused when latent heat load is larger than sensible heat.

In this research, a strong desiccant is used directly for contacting humid air in

투고일자 : 2010년 6월 1일, 심사일자 : 2010년 6월 15일, 게재확정일자 : 2010년 7월 18일
교신저자 : 최광환(choikh@pknu.ac.kr)

the counter flow packed layer to dehumidify a stream air. To make the process continuous, the weak solution of liquid desiccant, which turns into the diluted solution after the dehumidification process, needs to be reconcentrated. To set up this process, the weak desiccant was pumped to the regenerator in which a total heat exchanging part is already installed.

A total heat exchanging part would be heated by solar collectors. The process air in the regenerator unit is induced from the bottom of the packing layer while lithium chloride solution is sprayed at the top of the packing layer and flows downward directly, like a countercurrent flow type. The regeneration process works from 30℃ and above, which is very suitable for the efficient utilization of solar energy for this purpose.

Ahmed Sultan., [1] carried out the analysis of the operation of absorption/regeneration system for water extraction from atmospheric air. The conclusions are the final concentration for the operating desiccant strongly depended on the initial concentration, absorption temperature and regeneration temperature. The system efficiency has peak values depending on the cycle time, regeneration temperature, final concentration and absorption air stream velocity.

Choi et al., [2] have studied a solar operated liquid desiccant system. They made it clear that regenerating speed can be rapid when the solution temperature is above 50℃.

Fumo and Goswami., [4] already developed a lithium chloride desiccant system for dehumidification. The influence of the design variable studied on the water condensation rate from the air and evaporation rate from the desiccant can be assumed as linear.

Furthermore Y. Yin., et al., [7] have also published papers about sorption dehumidification by the liquid desiccant. The average mass transfer coefficient in the packing layer of regenerator is $4 g/m^2 \cdot s$.

In this paper, a method predicting the suitable height of the packed layer in the regenerator is described from the base of volumetric heat and mass transfer coefficient which were presented from the point of countercurrent flow view between air and liquid desiccant passing through the packed layer with plastic at random.

2. Experiment set-up and methods

The experimental apparatus was designed for keeping the flow rate constant during the experiment. The flow rate of air and liquid desiccant are $110 m^3/h$ and $5 kg/m^2 s$ respectively. The main packed layer was constructed with an acrylic and the volume was 35cm(in height) x 35cm(in width) x 30cm(in length).

In the experiment, the porous plastic was used as a packing material because it allowed the flow of the desiccant to be wide and uniform along with downward. Many plastic packing materials were stuffed inside the packed layer at random and each one has a height of 3cm and a diameter of 3cm. On the other hand, a regenerator consists of a fan, a heat exchanger, and a pump. The liquid desiccant is normally heated by hot water which was generated by solar thermal energy. The temperature of air stream and humidity entering and leaving the packed layer were measured just before around entrance and exit respectively. Lithium chloride with about 28(w.t.)% of concentration was used as liquid desiccant. The loop of liquid desiccant regenerating process is shown in Figure 1.

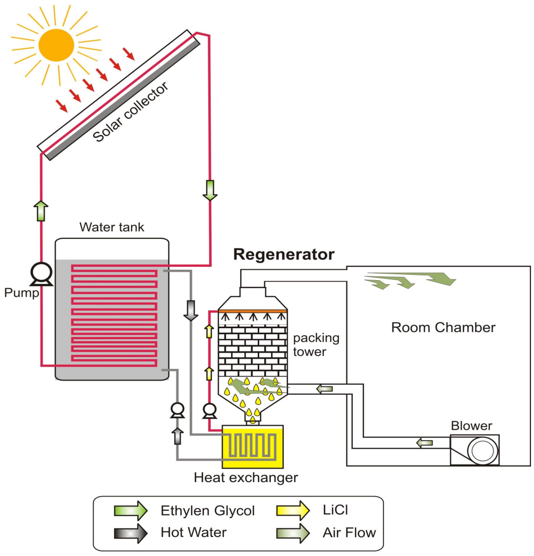

Fig 1. Configuration of experimental system

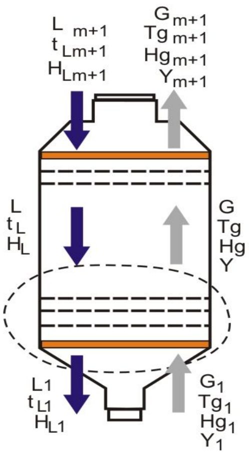

Fig 2. Continuous counter current adiabatic gas-liquid desiccant

3. Theoretical analysis

A packed layer is filled with lots of packing materials. Desiccant trickles down from the top wetting the surface of the packing materials, while air is induced from the bottom as shown in Figure 2. The driving force for regenerations is the difference at between equilibrium vapor pressure of the desiccant and the partial pressure of vapor in the air. As long as the partial pressure of the desiccant is higher than that of the air, mass transfer can take place from the solution to the air.

The theoretical analysis of the heat and mass transfer in a packed column was derived from Treybal's work[8] on adiabatic gas absorption. In accordance with references[2, 3, 5], the assumptions in this study are:

1. The system is adiabatic.
2. The thermal resistance in the liquid phase could be ignored in comparison with the gas phase.
3. The change of sensible heat is smaller than that of the latent heat so that it is negligible.
4. The interfacial surface area for heat and mass transfer is same and equal to the specific surface area of the packing materials.
5. The thermal resistance in the liquid phase could be ignored.
6. The temperature gradient takes place only along with the flow direction.

A mass balance for the liquid side is over the lower part of the packed layer.

$$L - L_1 = G(Y - Y_1) \tag{1}$$

This relationship is fairly complex and will be developed in manner of Olander. Referring to Figure 3 represents a section of layer of differential height, dZ, and aspects of liquid and gas, separated by the gas-liquid interface. The changes of temperature and humidity are all differential over section.

The mass transfer rate per tower cross sectional area and the mass transfer resistance in the liquid phase is negligible.

$$N_v M_v adZ = -GdY \tag{2}$$

Sensible heat at gas side, as energy rate per tower cross sectional area, is the following.

$$q_G adZ = h_G' a(t_G - t_i)dZ \tag{3}$$

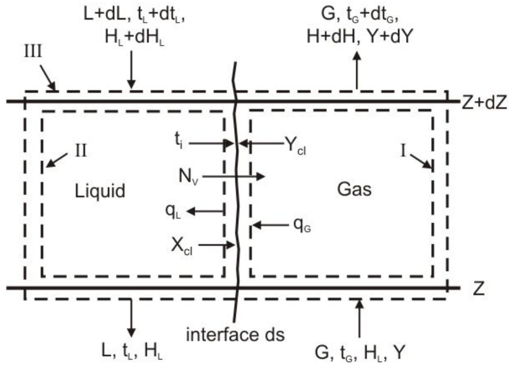

Fig 3. Differential control volume of a regenerating surface layer

Enthalpy balance base on the envelope I sketch in Figure 3.

$$GH - \{G(H + dH) - GdY[C_v(t_G - t_0) + \lambda_o]\} = q_G adZ \tag{4}$$

The mass transfer rate can be written as

$$G' dY = k_G a\ (Y_i - Y)dZ \tag{5}$$

Humidity gradient in this expression is obtained from equation (2).

$$\frac{dY}{dZ} = -\frac{M_v k_G a}{G}(P_{v,G} - P_{v,i}) \approx -\frac{k_G a}{G}(Y - Y') \tag{6}$$

By integrating equation (6), a new relationship would be as following.

$$k_G\ a = \frac{G}{Z}\ln\left(\frac{Y_1 - Y_i}{Y_2 - Y_i}\right) \tag{7}$$

A stepwise heat balance across the tower is normally performed to evaluate the tower performance. Hence the heat transfer coefficient must be calculated at every step instead of assuming that it is constant throughout the layer. Air temperature variation across over all segments could be obtained by heat transfer gradient.

$$\frac{dt_G}{dZ} = -\frac{h_G' a(t_G - t_i)}{Gc_p} \tag{8}$$

By integrating equation (8), it was found as following.

$$h_G' a = \frac{Gc_p}{Z}\ln\left(\frac{t_{G,1} - t_i}{t_{G,2} - t_i}\right) \tag{9}$$

On the other hand, mass transfer coefficient changes in the air side are also given by Treybal (8) and it eventually turned into equation (10).

$$\frac{F_G Sc_G^{2/3}}{G} = 1.195\left[\frac{d_s G'}{\mu_G(1 - \varepsilon_{Lo})}\right]^{-0.36} \tag{10}$$

ds is a diameter of sphere of the same surface as a single packing particle.

In the absence of applicable data, heat and mass transfer coefficient by convection are estimated by adopting an analogy of heat and mass transfer. On assuming *jD=jH*, equation (8) can be transferred as following:

$$j_H = \frac{h_G}{c_p G} \Pr^{2/3} = j_D = \frac{F_G M_v}{G} Sc^{2/3} \qquad (11)$$

The heat transfer coefficient for gas side can be calculated by applying the analogy so that it can be transformed as next equation.

$$h_G = \frac{1.195\, G' c_p \left[\dfrac{d_s G'}{\mu_G (1 - \varepsilon_{Lo})} \right]^{-0.36}}{\Pr_G^{0.667}} \qquad (12)$$

Table 1. Liquid holdup in the packed layer

packing	Nominal size		ds	Aqueous liquid or water at ordinary temperature	ε
	mm	in			
Plastic Pall rings	25	1	0.0356	$\beta = 1.508\ d_s^{0.376}$	0.73
	38	1.5	0.053	$\phi_{LS} = \dfrac{5.014 \times 10^{-5}}{d_s^{1.56}}$	0.87
	50	2	0.0725	$\phi_{Lt} = \dfrac{(2.32 \times 10^{-6})(737.5 L')^{\beta}}{d_s^{2}}$	0.74

By using the Chilton-Colburn analogy for the vapor phase and assuming a penetration theory mechanism for the liquid phase, we obtained followings related to heat transfer coefficient.

$$\frac{h_G' a}{F_G a} = \left[\frac{Sc_G}{\Pr_G} \right]^{2/3} \left[\rho_G c_p \right] \qquad (13)$$

4. Results and discussions

Experimental ratios of heat and mass transfer coefficient usually show a considerable variation, even in case of pure liquid in the packed columns. A vapor transfer can take place at the bottom and top of the column where air and liquid contacts inside the packed layer. If dry areas are left in the packing due to poor liquid distribution or low liquid flow rate, these areas are available for heat transfer, not mass transfer.

To improve heat and mass transfer in the packed layer, one device is adopted for liquid distribution to be more efficient. In the regenerator, a spray system was designed for goal to distribute the solution uniformly over the packing layer.

Heat and mass transfer coefficient were calculated along with each locations of the packed layer. Based on these calculated results, the analysis was done by the same fashion as the case of the maximum height of the packed layer.

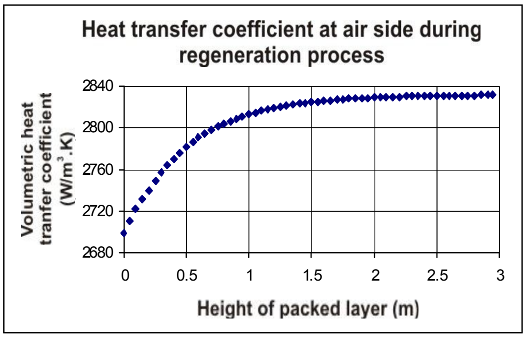

Fig 4. Heat transfer coefficient during regeneration process

Figure 4 shows variations of the heat transfer coefficient at each location height of the packed layer. Heat and mass transfer coefficient started to increase, by 2m of the height of packed layer, after the both values became constant.

Figure 4 and Figure 5 show the information of maximum height for proper performance in the packed layer and its height is approximately 2m.

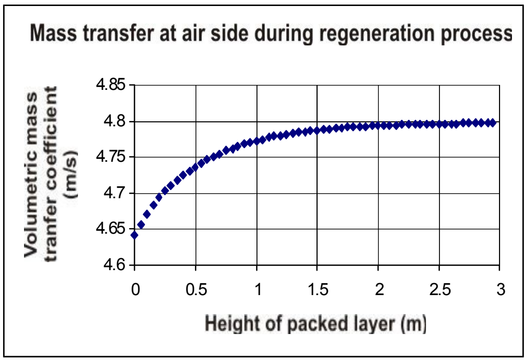

Fig 5. Mass transfer coefficient during regeneration process

Figure 6 yields the air absorption rate per volume as a function of the height of regenerator packed layer, after 2m of height in the packed layer, there is no more absorption rate and the value keeps it constant. This is due to the fact that the weak desiccant has high vapor pressure and the potential for being generated could be increased.

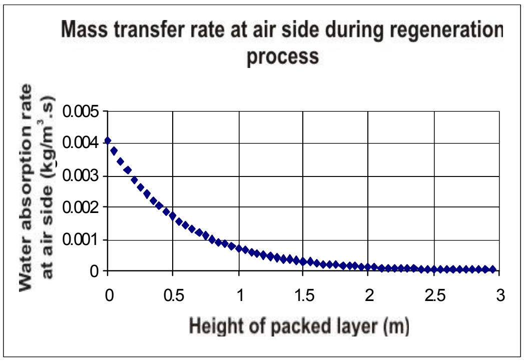

Fig 6. Mass transfer rate during regeneration process

5. Conclusions

The theoretical model of a regenerator has been verified based on the actual experiment data from air side. In this paper, it is indicated that a method is to calculate volumetric heat and mass transfer coefficient for liquid-air contacting in the packed layer, for the air and liquid desiccant flow rates are 110㎥/h and 5kg/㎡s respectively.

This analysis was adopted as the same fashion to figure out the most suitable height for regeneration in the packed layer and conclusions are as follows;

(1) Heat transfer coefficient was slightly low at the bottom of the packed layer, but it finally showed almost same coefficient as 2,820W/㎥K from around 2m in height.

(2) Mass transfer has also almost same variation as heat transfer in performance. The mass transfer coefficient was approximately 4.8m/s at maximum after outlet of the packed layer.

(3) In variations of water evaporation, humidity changes had no more difference between air side and liquid after 2m of the height in the packed layer.

Acknowledgement

This work was supported by the Pukyong National University Research Fund in 2008 (P3-2006-018).

References

1. Ahmed Sultan, Absorption/Regeneration non-conventional system for water extraction from atmospheric air. Renewable Energy 29, 2004
2. Choi, K.H. et al., Development of solar/air

conditioning system using hot water from solar collectors. Refrigeration and Air Conditioning Seminar, Pukyong National University, 70-78, 2004
3. Eflita Yohana. et al., Research on Heat and Mass transfer Coefficient in the Packing Layer with a Solar Desiccant Heating/Cooling System, KSES, 2005
4. Fumo, N and Goswami, D.Y., Study of an Aqueous Lithium Chloride Desiccant System: Air Dehumidification and Desiccant Regeneration. Solar Energy 72, 4, 351-361, 2002
5. Gandhidasan, P and Al-Farayedhi, A. A., Solar Regeneration of Liquid Desiccant Suitable For Humid Climates. Energy 19, 8, 831-836, 1994
6. Longo, G. A. and Gasparella, A., Experimental and Theoretical Analysis of Heat and Mass Transfer in a Packed Column Dehumidifier/Regenerator with Liquid Desiccant. Heat and Mass Transfer , 2005
7. Yin, Y., et al., Experimental Study on Dehumidifier and Regenerator of Liquid Desiccant Cooling Air Conditioning System. Building and Environment, 2006
8. Treybal, R.E., Mass-transfer operations, McGraw-Hill, 3 rd Ed., 1980

Nomenclature

a	Specific internal surface for contact of gas with liquid, (m^2/m^3)
a_m	Specific interfacial surface for desorption, (m^2/m^3)
c_G	Heat capacity of dry air, (J/kmol.K)
c_p	Heat capacity of moist air, (J/kmol.K)
c_v	Heat capacity of vapor water, (J/kmol.K)
d_s	Diameter of sphere of the same surface as single packing particle,m
F_G	Mass transfer coefficient for air ,(kmol/m^2.s)
$F_G\, a$	Volumetric mass transfer coefficient for air, (kmol/m^3.s)
G	Mass flux or flow rate per unit cross-section area, (kg/m^2s)
$\dot{G}$	Superficial gas mass velocity, (kg dry air/m^2.s)
H	Molar enthalpy of air, (kJ/kmol)
M_v	Mol air side, (kg/mole)
N_v	Mass transfer flux, mole/m^2.s
h_G,	Heat transfer coefficient for air, (W/m^2 K)
$h_G\, a$	Volumetric heat transfer coefficient for air, (W/m^3 K)
$h_G\, 'a$	Heat transfer coefficient corrected for mass transfer, (W/m^3 K)
k_G,	Mass transfer for gas, (kg/m^2.s)
$\dot{L}$	Superficial liquid mass velocity, (kg/ m^2.s)
$\Pr_G$	Prandtl number of air
P_t	Vapor pressure, (kg/m^2)
P_v	Partial pressure
$P_{B,\,M}$	Mean pressure of nondiffusing gas, (kg/m^2)
q_G	Sensible heat transfer flux, W/m^2
t_G	Air Temperature,^{0}C
t_i	Interface temperature, ^{0}C
Sc_G	Schmidt number for air
Z	Tower height, m

Greek symbols

ε	Void fraction volume in dry packed tower
ε_{Lo}	Void operation space in packing
λ_o	Latent heat of vaporization, (J/kg)
μ_G	Viscosity of air (kg/m.s)
ρ_G,	Density of air (kg/m^3)
$\phi_{Lo}, \phi_{Ls}, \phi_{Lt}$	Liquid operation, static, and total holdup, respectively

Subscript

G	of air side
i	of interface