Noncondensable gas's influence in waster vapor absorption accompanying interfacial disturbance into aqueous solution of LiBr

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ABSTRACT

The aim of this research is to obtain a basic quantitative understanding of the effect of a noncondensable gas on the absorption of water vapor by a H_2O / LiBr combination with n—octanol as the surfactant. Nonflowing aqueous solutions of LiBr (40, 45, 50 mass%) were exposed to saturated water vapor following the addition of an n—octanol surfactant (0.01 and 0.6 mass%). A small amount of a noncondensable gas (air) was allowed into the absorber (0.03 volume%) and its effect was analyzed by measuring the amount of water vapor absorbed. This study will aid to predict the performance of heat pump and safety operating condition when the noncondensable gas is not allowed in the absorber. The results indicate that, in the presence of small amounts of a noncondensable gas, vapor absorption enhancement ratios are less than half of those obtained under the same experimental conditions when a noncondensable gas is not present (1). The presence of a noncondensable gas causes the partial vapor pressure of air to increase at the vapor / liquid interface, which results in an instability of vapor absorption rate and, hence, in an inhibition of interfacial disturbance.

요 약

흡수식 열펌프에서 폭 넓게 사용되고 있는 대표적인 냉매/흡수용액은 H_2O / LiBr 系이다.

그러나, LiBr 수용액의 점성계수는 LiBr의 농도가 커짐에 따라 증가하기 때문에, LiBr 수용액의 농용액 영역에서 물질확산계수가 감소한다.

이 결점을 보완하기 위해 흡수용액에 계면활성제를

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첨가시키므로서 흡수를 촉진시키는 방식을 이용하고 있다. 계면활성제의 첨가에 의한 흡수용액의 열 및 물질이동 촉진에 관한 연구는 계면활성제 첨가농도에 의해 흡수용액의 표면상에서 계면활성제가 액적으로 존재하는 계면활성제 포화용해도 이상의 조건에서 발생하는 마랑고니대류가 효과적이다. 이 흡수촉진효과는 냉매증기의 흡수시 흡수용액표면상의 분포한 계면활성제와 흡수용액사이의 표면장력차에 기인하는 계면교란 현상에 기인한다. 그러나, 이 흡수촉진효과는 냉매증기의 흡수가 일어나는 흡수기 내부의 不안정상태, 즉, 불응축성가스(공기)가 존재하지 않는 조건하에서 이루어지며, 불응축성가스가 흡수촉진저하(열 및 물

질이동의 저하)에 기인하는 연구는 보고된 바 없다.

이러한 불응축성가스가 흡수기 내부에 존재할 때 계면교란의 거동 및 열 및 물질이동저하현상을 파악하기 위하여 계면활성제 농도변화(포화용해도 이상 및 이하의 두 조건)에 따른 증기흡수 실험 및 계면교란가시화 실험을 행하였다. 결과적으로 본실험을 통하여 불응축성가스가 수증기흡수에 끼치는 영향을 파악(계면교란의 악화) 첨가시의 흡수량과 不安定상태(불응축성가스가 존재시)의 증기흡수량의 비교에 의해 급격한 증기흡수저하가 不安定상태하에서 발생함으로서 불응축성가스가 흡수촉진효과(계면교란현상)을 저해시키는 결론을 얻었다.

1. Introduction

In most H_2O / LiBr commercial absorption machines, absorption enhancement is achieved by adding surfactants to the solution. The vapor absorption enhancement mechanism for inducing interfacial disturbance has previously been reported by the authors, who conducted experimental analyses to clarify the basic mechanism involved in the inducement of interfacial turbulence.[1)-3),6)]

By drastically reducing the surface tension of the absorption solution and generating superficial disturbance upon refrigerant vapor absorption, surfactants can improve absorption enhancement by up to 4 times[1)]. Although it is well known that a noncondensable gas can hinder absorption considerably, its actual effect on vapor absorption has not yet been reported. Hence, there is a need to understand and quantify the influence of such a gas on the phenomenon of water vapor absorption enhancement in LiBr aqueous solutions with interfacial disturbance generated by n-octanol addition.

The authors have thus carried out experiments to understand the absorption behavior when a noncon-

densable gas is present in the absorber during the absorption of water vapor by LiBr aqueous solutions (40, 45, 50 mass%) with n-octanol added as a surfactant (0.01, 0.6 mass%). Interfacial disturbance behavior was visualized by real-time holographic interferometry. Furthermore, both the temperature distribution and the vapor absorption rate were calculated numerically, assuming the existence of a noncondensable gas in the LiBr aqueous solution with surfactant addition. The effect of the noncondensable gas was estimated by comparing the experimental and numerical results for surfactant concentrations of 0.01 and 0.6 mass%.

2. Experimental Apparatus and Procedure

2.1 Experimental setup

Aqueous solutions of LiBr (40, 45, 50 mass%) were used as absorbents, with a surfactant added in concentrations of 0.01 and 0.6 mass%. The experimental apparatus is schematically illustrated in Fig.1. A vapor absorption test section of 15×50mm was used, with four solution depths : 50, 35, 25 and 15mm. Both side walls were made of optical flat acrylic plates, transpa-
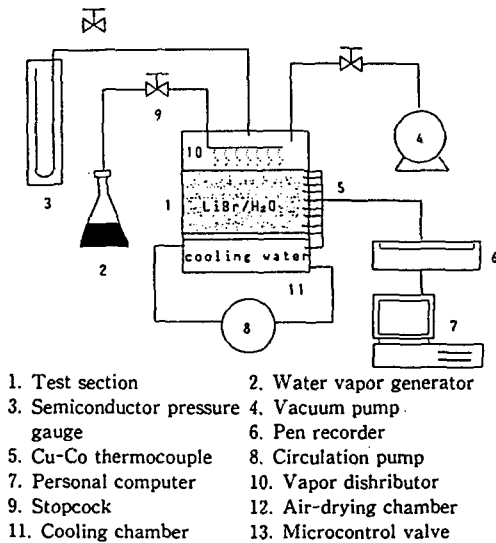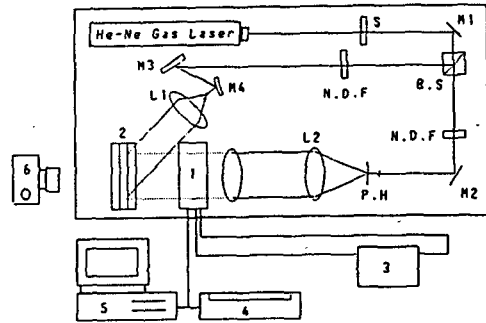
1. Test section
3. Semiconductor pressure gauge
5. Cu-Co thermocouple
7. Personal computer
9. Stopcock
11. Cooling chamber

2. Water vapor generator
4. Vacuum pump
6. Pen recorder
8. Circulation pump
10. Vapor dishributor
12. Air-drying chamber
13. Microcontrol valve

Fig. 1. Test section of the steam absorption experiment

rent to the laser beam. The bottom of the test section had a cooling chamber to ensure efficient removal of the absorption heat from the absorbent to the cooling water ; a bronze plate was installed between the absorbent and cooling chamber. Distilled water, used as a refrigerant, was kept in a water vapor generator connected to the absorbent chamber. Exposure of the LiBr solution to saturated vapor (and, hence, the start of absorption) was controlled by operating a stopcock. The water temperature in the evaporator was kept constant during the absorption experiment, at the initial LiBr aqueous solution temperature, by an electric mantle heater with constant temperature control. The air in the absorbent chamber and water vapor generator was completely evacuated, to below $0.666+0.133$ kPa, by a vacuum pump. A stainless steel tube was used to connect the test section with the vacuum pump and a rubber tube was used for the connection between the water vapor generator and absorbent chamber. The vertical temperature distribution on the side wall was measured by 24 Cu−Co thermocouples. Temperature distribution data, collected every ten

seconds, were plotted by a penrecorder and subsequently stored in a personal computer. A 30mW He−Ne gas laser (wavelength w=632.8nm) was used as the laser light source for the observation of unsteady state phase change inside the solution, in the setup shown in Fig.2.

1. Test section
3. Thermoregulator
5. Personal computer

2. Hologram
4. Pen recorder
6. Camera

Fig. 2. Optical setup of real-time holographic interferometry

2.2 Experimental methods

The experiments were performed by changing the AR (aspect ratio, given by the ratio of absorbent solution depth to solution vessel length), as well as the H_2O / LiBr and surfactant concentrations. Experiments were performed using the methods described below.

(1) Initially, the noncondensable gas effect was eliminated by reducing the pressure in the test vessel and boiler to below the saturated vapor pressure of the refrigerant water at room temperature by using a vacuum pump. After filling the vessel with steam, the LiBr aqueous solution was introduced up to the specified height.

(2) A hologram was taken after the vacuum pump was turned off and the solution became static (constant

at room temperature, 294K, and pressure equal to the saturated vapor pressure of the solution at room temperature). Prior to its introduction into the absorber, the noncondensable gas (air) was dried in a chamber. The amount of noncondensable gas introduced was controlled by a semiconductor pressure gage and adjusted by operating a microcontrol valve.

(3) When the steam boiler valve was opened (time t =0), the pressure level in the vessel immediately increased to that of the saturated·water vapor at room temperature, and steam absorption began on the stationary solution surface. Temperature measurement by thermocouples and filming of the interferograms were started at this time.

(4) After the steam boiler valve was closed (t=300), the amount of water vapor absorbed was measured by the weight change of the water vapor generator, as compared with its initial weight, by using a digital gravimeter.

2.3 Experimental results

The influence of a noncondensable gas on the heat and mass enhancement process in the absorber was studied by analysis of absorption rates for LiBr aqueous solutions of different concentrations and aspect ratios. Figure 3 shows the amount of water
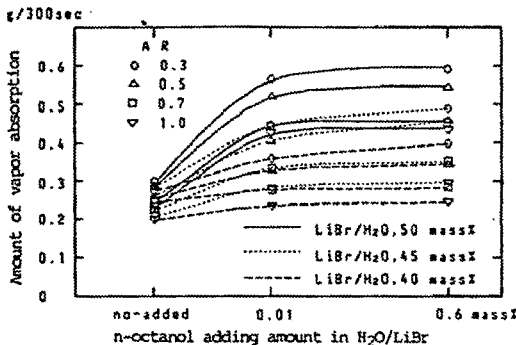
Fig. 3. Amounts of vapor absorption for various AR and LiBr concentrations(with noncondensable gas)

vapor absorbed for each experimental condition at 300 seconds after the start of absorption. The effect of surfactant addition is described in terms of the absorption enhancement rate, which is determined from the experimental results as the ratio between the amounts of vapor absorbed with and without surfactant addition. Figure 4 shows absorption enhancement rates calcu-
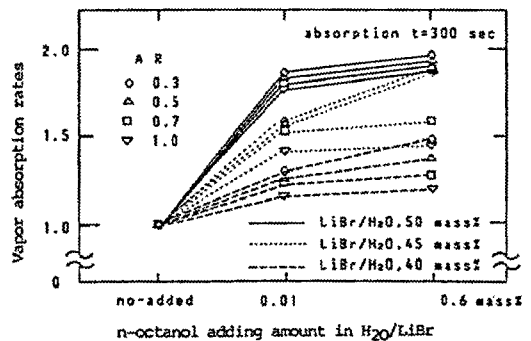
Fig. 4. Vapor absorption rates with noncondensable gas(experimental results)

lated for each aspect ratio in comparison with the basic condition of a LiBr solution without surfactant addition. There is a clear tendency for vapor absorption to increase for higher solution concentrations and lower AR values. In the presence of a noncondensable gas, vapor absorption enhancement rates lay between 1.2 and 1.9 for most of the LiBr aqueous solution concentrations and aspect ratios considered. Water vapor absorption enhancement rates are thus less than half of those obtained under the same experimental conditions when a noncondensable gas is not present (absorption enhancement ratios between 4 and 5 reported)[1].

3. Numerical Analysis

As is well known, the existence of a noncondensable gas has a negative influence upon condensation heat transfer. A noncondensable gas also has the effect

of remarkably decreasing mass transfer in the absorber, for the same reason as in the case of the condensation heat transfer.

Vapor absorption decreases in the presence of a noncondensable gas, which acts by decreasing the surface tension imbalance and inhibiting the occurrence of interfacial disturbance. This, in turn, results in a further decrease in the vapor absorption, producing a vicious circle.

This chapter presents a numerical analysis focusing on the influence of a noncondensable gas upon the absorption enhancement that is obtained by interfacial disturbance generated by the addition of the surfactant additive n—octanol (0.01 and 0.6 mass%).

In the case whereby the surfactant is added at a 0.6 mass% concentration above its solubility, the surface tension between the surfactant (n—octanol) and absorbent solution (H_2O / LiBr) is considered to be constant during the steam absorption (i.e., independent of concentration changes in the absorbent solution). In the absence of a noncondensable gas, the surface tension difference between the surfactant and absorbent solution is reported as $\Delta \sigma = 20 \times 10^{-3}$ N / m[1]. It is assumed that in this surfactant—adding concentration (0.6 mass%) surfactant droplets were present on the absorbent surface. The number of randomly occurring surfactant droplets on the solution surface adopted in the calculations was based on the assumption that interfacial disturbance causes the droplets to move from the surface toward the bottom of the absorbent solution (namely, interfacial disturbacne causes the number of surfactant droplets existing on the absorbent surface to change)[2].

In the case whereby the surfactant is added at a 0.01 mass% concentration (i.e., below its solubility limit in the absorbent solution), we artificially applied weak disturbances to the absorbent solution surface in order to trigger interfacial disturbance, since at the initial stage no droplets were present on the absorbent surface. Surface tension was considered to vary according to the absorbent's concentration changes with time (6). Four governing equations—continuity, laminar momentum, energy and diffusion—were solved numerically in order to obtain the unsteady temperature and concentration profiles during steam absorption with interfacial disturbance in the presence of a noncondensable gas.

In these calculations, the boundary conditions that must be defined in order to obtain a numerical solution of the equations are the surface tension difference and the number of random disturbance points (the places where the interfacial disturbance occurs, with the given value of surface tension).

Since these boundary conditions are not clearly identified in the case of a noncondensable gas existent in the absorber, the values of the surface tension difference and the number of random disturbance points were adjusted so as to yield numerical results (temperature distributions, vapor absorption rate, etc.) similar to the experimental ones.

Numerically calculated temperature distributions were compared with those obtained experimentally, by varying the values of the surface tension difference from 1 to 20×10^{-3} N / m and the number of random disturbance points on the absorbent solution surface from 1 to 20 points.

In this calculation, the following assumptions have been made:

(1) Vapor pressure equilibrium exists between the vapor and liquid at the interface.

(2) The cool wall temperature is constant and equal to the initial solution temperature.

(3) Surface turbulence is time—dependent.

(4) Thermal diffusion in the vapor phase is negligible as compared to that in the liquid phase.

(5) At the condition of a surfactant—adding concen-

tration of w=0.6 mass%:

－The surface tension difference between the surfactant droplet and absorbent solution surface is constant.

－Droplets are formed on the absorbent solution surface because the surfactant is added beyond its solubility limit.

－The surfactant droplet size is negligible.

(6) At the condition of a surfactant－adding concentration of w=0.01 mass%:

－Surface tension differences occur due to variations in the LiBr aqueous solution concentration on the absorbent solution surface, upon absorption of water vapor.

－The addition of the surfactant below its solubility limit results in no droplet formation on the solution surface.

In this study, we adopted the central difference finite difference method for each governing equation and used the Gaussian elimination method for inversion of
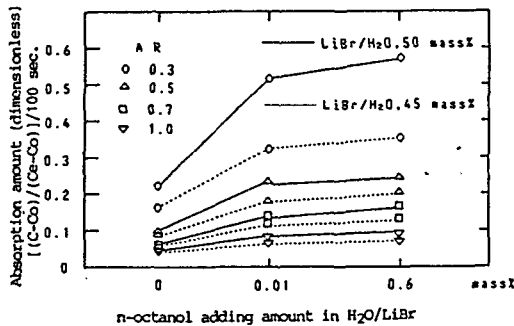
a tridiagonal matrix within the convergence range of 0.1%. We obtained temperature distributions and amounts of vapor absorbed from the start of steam absorption, at dimensionless time intervals of $t=2\times10^{-4}$ for all of the governing equations[7].

3.1 Numerical results－The influence of a noncondensable gas on vapor absorption

Computational results were obtained numerically for dimensionless concentration for various AR and LiBr aqueous solution concentrations of 50 and 45 mass%, with addition of a noncondensable gas.

Figures 5 and 6 show amounts of vapor absorption and vapor absorption rates, respectively. These were calculated for each concentration and AR. The calculation results agreed well with the results obtained from the experiments (Figs.5 and 6), if the boundary
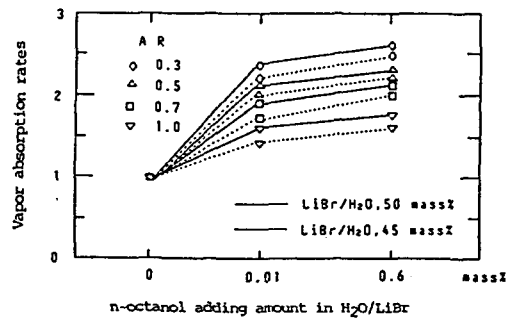

Fig. 5. Amounts of vapor absorption for various AR and LiBr concentrations(numerical analysis, with noncondensable gas)

Fig. 6. Vapor absorption rates for various AR and LiBr concentrations(numerical analysis, with noncondensable gas)

conditions are set as 1 dyne / cm for the surface tension difference and 8 for the number of random disturbance points. Because, in this study, the real three－dimensional space of the experiments is modeled as a two－dimwnsional one, numerically obtained vapor absorption amount and it rates are slightly mismatched with the experimental ones in the vicinity of the absor-

bent surface. For the purpose of this analysis, however, a general understanding of the absorption enhancement process can be considered as satisfactory. The presence of a noncondensable gas causes an increase in the partial vapor pressure of air at the vapor / liquid interface, so that the maximum vapor absorption rate decreases to a value of 2.6 at the surfactant－adding

concentration of 0.6 mass% (the maximum vapor absorption rate is about 4 when the noncondensable gas is absent in the absorber, for the same surfactant— adding concentration). Numerical results obtained with a noncondensable gas (about 0.03 volume%) indicate that decreasing the value of the surface tension difference between the surfactant droplet and absorbent solution has the effect of substantially decreasing the vapor absorption rate in the absorber.

Figure 7 shows representative photos of interference lines with interfacial disturbance caused by the addition of the surfactant above its solubility limit in the absorbent solution, without noncondensable gas. Photo (a) in Fig.7 clearly reveals the generation of a convec-
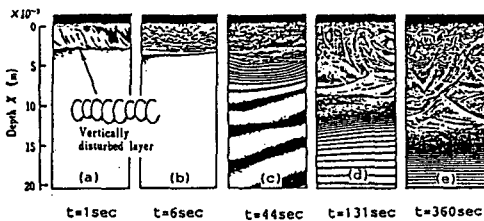

Fig. 7. Representative interference fringes without noncondensable gas

tion layer near the surface immediately after the start of absorption. This strong convection can be observed in all of the photos of Fig.7, with (d) in particular showing convection that flowed in the vertical direction.

Figure 8 shows representative photos of interference lines with interfacial disturbance caused by the addi-
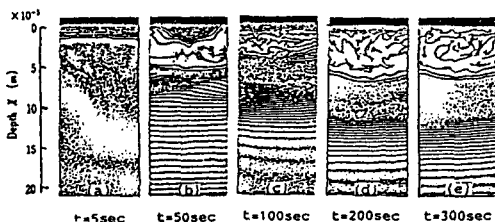

Fig. 8. Representative interference fringes with noncondensable gas(0.03 volume%)

tion of the surfactant above its solubility limit in the absorbent solution, with a noncondensable gas present in the absorber. Photo (a) in Fig.8 does not show a layer of violent convection near the surface after the beginning of absorption. In these photos, no strong vertical convection can be observed. From Fig.8 (e), it can be seen that as time elapses, the interfacial disturbance depth near the absorbent solution surface is less than half of the depth observed in Fig.8 (e), where noncondensable gases are absent. Hence, it can be said that a noncondensable gas acts as an inhibitor of not only vapor absorption, but also of the occurrence of interfacial disturbance.

4. Conclusions

This study is aimed at understanding the effect of a noncondensable gas on the heat and mass transfer characteristics in the absorber. We carried out the study assuming a basic absorption model, where water vapor is absorbed on the surface of a stationary lithium bromide absorbent solution and n—octanol is added in the concentrations of 0.01 and 0.6 mass%. The main results are summarized below:

(1) Water vapor absorption enhancement ratios are less than half of those obtained under the same experimental conditions when a noncondensable gas is not present. In the presence of a noncondensable gas (0.03 volume%) vapor absorption rates lie between 1.2 and 1.9 for LiBr aqueous solutions (40 to 50 mass%).

(2) From the photos of interference lines, it can be seen that, in the presence of a noncondensable gas, the depth of interfacial disturbance near the absorbent solution surface is reduced to less than half of the depth observed when the gas is not present.

(3) Numerical analysis provided further evidence to the experimental observation that the existence of a noncondensable gas reduces surface tension imba-

lances on the absorbent surface.

(4) Experimental and numerical analyses of vapor absorption enhancement rates showed that even small amounts of a noncondensable gas have the effect of hindering mass transfer in the absorber and thus substantially decreasing, but not eliminating, vapor absorption enhancement in the absorber.

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