Experimental Heat Transfer, 15:191–205, 2002
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0891-6152/02 $12.00 + .00
DOI: 10.1080/0891615029008262 1

COMPARISON OF HEAT AND MASS TRANSFER IN FALLING FILM AND BUBBLE ABSORBERS OF AMMONIA–WATER

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An experimental analysis of ammonia–water absorption process was performed for the falling film and bubble modes in a plate-type absorber. The experiments were made to examine the effects of solution flow rate and gas flow rate on the performance of the absorber. It was found that the bubble mode is superior to the falling film mode for mass transfer performance, and more heat was generated in the bubble mode. Increase of solution flow rate rarely affected the mass transfer, but improved the heat transfer. As the gas flow rate increased, fluidization occurred in the bubble mode and influenced the thermal boundary layer. However, channeling appeared in the falling film mode and decreased the heat transfer area. Increase of the gas flow rate greatly enhanced the performance of heat transfer in the bubble mode but made it worse in the falling film mode. Finally, the results were converted into dimensionless numbers to elucidate physical phenomena and we plotted Sherwood number versus Reynolds number for mass transfer performance and Nusselt number versus Reynolds number for heat transfer performance.

Due to the ozone depletion problem associated with the use of the CFC and HCFC refrigerants, absorption heat pumps and refrigeration systems have taken on increasing interest in the recent years. More and more, they are regarded not only as environmentally friendly alternatives to CFC-based systems, but also as energy efficient heating and cooling technology.

The absorber is a major component in absorption refrigeration systems. The absorber greatly affects the overall system performance. Falling film modes and bubble modes have been recommended to enhance heat and mass transfer performance in ammonia–water absorption systems (Merrill and Perez-Blanco [1]). Falling film modes provide relatively high heat transfer coefficients and are stable during operation. However, falling film modes have wettability problems and need good liquid distributors at the inlet of the liquid flow. Bubble modes provide not only high heat transfer coefficients but also good wettability and mixing between the liquid and the vapor. However, the bubble modes require vapor distribution and a pressure difference on the vapor side to drive the vapor through the pool of liquid. This essentially rules out bubble absorbers

Received 12 September 2001; accepted 6 August 2001.
This Study was supported by research grants from the Korea Science and Engineering Foundation (KOSEF) through the Applied Rheology Center (ARC), an official ERC, at Korea University, Seoul, Korea.
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NOMENCLATURE

A	area, m^2	T	temperature, K
D	diffusivity, m^2/s	U	overall heat transfer coefficient, W/m^2 K
g	gravitational acceleration, m/s^2	V	velocity, m/s
h	heat transfer coefficient, W/m^2 K	W	absorber width, m
k	thermal conductivity, W/m K	x	concentration
K	overall mass transfer coefficient, m/min	γ	kinematic viscosity, m^2/s
		μ	dynamic viscosity, kg/m s
L	length, m	ρ	density, kg/m^3
LMTD	log mean temperature difference		
m	mass flow rate, kg/min	**Super- and Subscripts**	
Nu	Nusselt number	abs	absorption
Q	heat transfer rate, J/s	c	coolant
r_H	hydraulic radius, m	eq	equilibrium
Re	Reynolds number	l	liquid film
Sh	Sherwood number	lm	log mean

for systems employing low pressures (such as water–LiBr systems); in ammonia–water systems the problem is less severe, but the pressure drop must be considered carefully. Recently, bubble modes were recommended strongly for ammonia–water absorption systems because the low wettability in the falling film modes is critical to the performance of the system (Kang et al. [2]). Over the last 10 years, ammonia–water falling film and bubble modes have been extensively investigated both numerically and analytically [2–5]. However, few articles have been found on experimental analysis, and there is no report of an experimental comparison of the falling film and the bubble modes in the same system. Merrill et al. [6] tested three compact bubble absorbers developed for generator–absorber heat exchange absorption cycles (GAX). Results show that enhancement techniques are effective in reducing absorber length and increased tube diameters may increase absorber performance. Kang et al. [7] reported on the ammonia–water falling film absorption process in a plate heat exchanger with enhanced surfaces such as offset strip fins. They found that lower inlet liquid temperature and higher inlet vapor temperature resulted in higher Nusselt and Sherwood numbers.

In the present study the falling film mode and the bubble mode are compared under the same operating conditions. In addition, the results are plotted in dimensionless numbers and correlated.

EXPERIMENTAL APPARATUS AND PROCEDURE

An experimental apparatus was made to examine the heat and mass transfer performance. The size of the plate in the absorber is $11.2 \times 26.4 \times 3.0$ mm, and pre-experiments were performed to retain laminar flow and good wettability even at low solution flow rate. Plates of three types were tested: a smooth plate, a hair-lined plate treated by laser, and a plate treated with sand paper. Laminar flow and good wettability were retained well in the plate treated with sand paper, so the plate treated with sand paper was settled on as the experimental apparatus. Five thermocouples (K-type) were set equidistantly to know the thermal state of the inner absorber, and a transparent window was provided in front of the absorber to identify the solution flow state.

The input solution was preheated in a solution tank equipped with three 500-W cartridge heaters. A 500-W embedded-type cartridge heater was set in the input line to control temperature more accurately. Constant flow rate of the fluids was required to apply the experimental data to the theoretical equations, so the solution flow rate was controlled by a metering valve in the input line and bypass checking of the flowmeter. Each temperature was saved by a data acquisition system, and the concentration of solution sample was analyzed by the measurement of conductivity and comparison with a standard curve that relates conductivity to concentration of ammonia solution.

In the experiments on the effects of solution flow rate, flow rates of ammonia gas were fixed at 1–9 L/min and solution flow rates were varied. To examine the effect of gas flow rate, ammonia solution of 0 to 30 wt% was flowed under the condition of 20°C, 0.3 kg/min, and the ammonia gas flow rate was varied. At each experimental condition, the absorber was operated as the falling film mode and the bubble mode and the results were compared. The experimental data were taken for a certain period of steady-state operation. The steady state was confirmed by test section pressure variation. During the experiments, the maximum measurement errors in temperature, gas flow rate, liquid flow rate, and liquid concentration were ±0.4%, ±0.5%, ±0.8%, and ±0.05%, respectively.

Figure 1 shows the experimental absorption system and Figure 2 shows a schematic diagram of the absorber of two plate types of the falling film and the bubble modes. Ammonia solution flowed down from the top inside the absorber while ammonia vapor flowed up counter to the liquid flow. The coolant flowed up, counter to the solution flow.

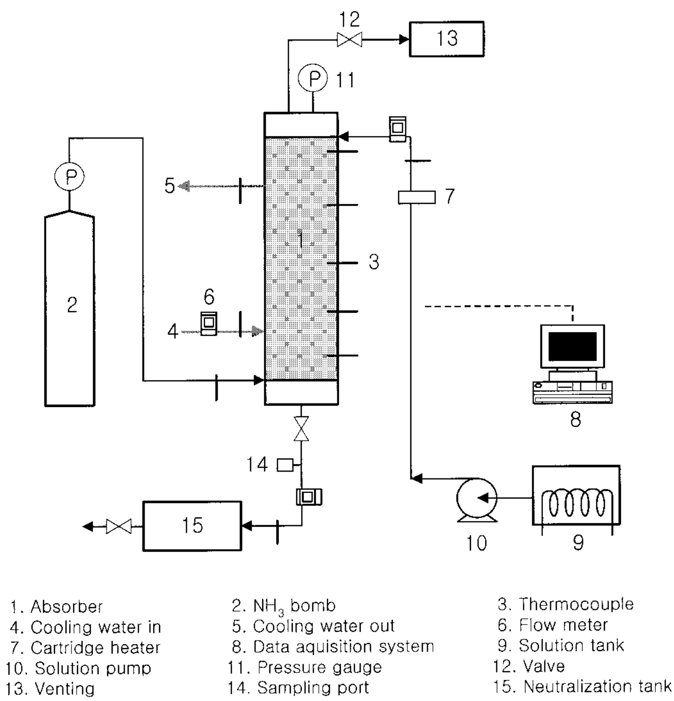

Figure 1. Experimental absorption system.

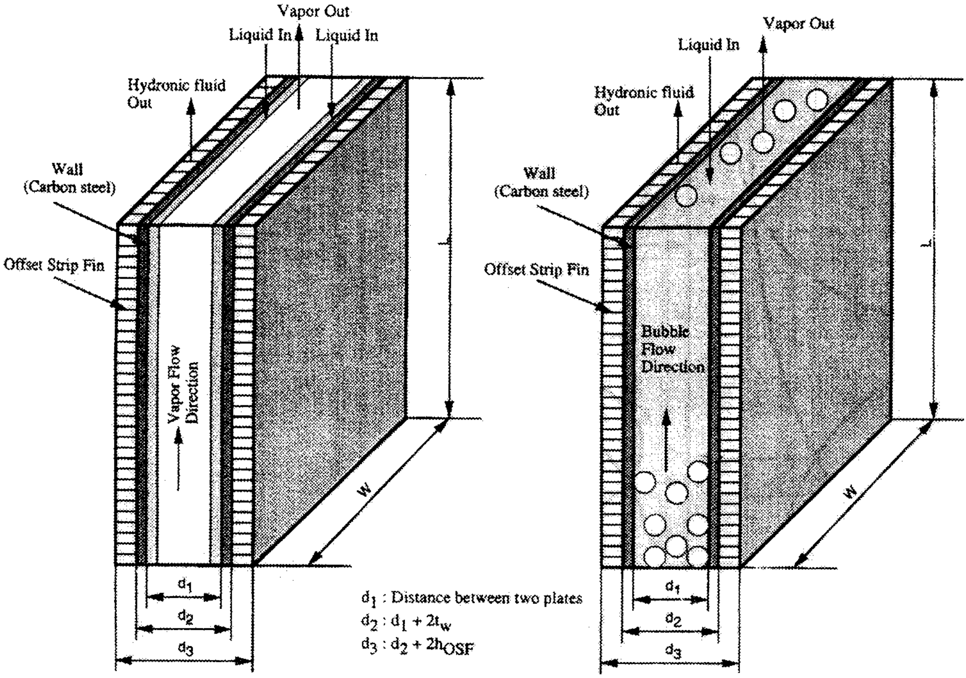

Figure 2. Diagram of falling film and bubble modes.

The input and output temperatures of the coolant were measured to calculate the overall heat transfer coefficients.

ANALYSIS

The heat transferred to the coolant can be expressed as the following heat transfer equations [8]:

$$Q_c = UA\ \Delta T_{\mathrm{lm}} \tag{1}$$

$$\Delta T_{\mathrm{lm}} = \frac{(T_{\mathrm{sol,in}} - T_{c,\mathrm{out}}) - (T_{\mathrm{sol,out}} - T_{c,\mathrm{in}})}{\ln[(T_{\mathrm{sol,in}} - T_{c,\mathrm{out}})/(T_{\mathrm{sol,out}} - T_{c,\mathrm{in}})]} \tag{2}$$

The absorption rate is expressed as the following equations using the overall mass transfer coefficient K [8]. The mass transfer is considered to be mainly in the liquid phase, as usual [4, 5, 7].

$$m_{\mathrm{abs}} = K\rho A_{\mathrm{abs}}\ \Delta x_{\mathrm{lm},l} \tag{3}$$

$$\Delta x_{\mathrm{lm},l} = \frac{(x_{\mathrm{in}}^{\mathrm{eq}} - x_{\mathrm{in}}) - (x_{\mathrm{out}}^{\mathrm{eq}} - x_{\mathrm{out}})}{\ln[(x_{\mathrm{in}}^{\mathrm{eq}} - x_{\mathrm{in}})/(x_{\mathrm{out}}^{\mathrm{eq}} - x_{\mathrm{out}})]} \tag{4}$$

The dimensionless numbers are given in Table 1.

Table 1. Dimensionless numbers

	Falling film mode	Bubble mode
Reynolds no.	$\mathrm{Re} = \dfrac{4m}{W\mu_l}$	$\mathrm{Re} = \dfrac{4r_H V\rho}{\mu_l}$
Sherwood no.	$\mathrm{Sh} = \dfrac{K_l}{D}\left(\dfrac{\gamma_l^2}{g}\right)^{1/3}$	$\mathrm{Sh} = 1.62\left(\dfrac{m}{DL\rho}\right)^{1/3}$
Nusselt no.	$\mathrm{Nu} = \dfrac{h_{abs}}{k_l}\left(\dfrac{\gamma_l^2}{g}\right)^{1/3}$	$\mathrm{Nu} = \dfrac{hL}{k_l}$

RESULTS AND DISCUSSION

Effect of Solution Flow Rate on Heat and Mass Transfer

In this study, heat and mass transfer coefficients were measured by experiments for countercurrent absorption processes in a plate-type absorber that was operated in both falling film and bubble modes. Figure 3 shows the effects of the solution flow rate on mass transfer coefficient. Increase of solution flow rate resulted in a small increase of the mass transfer. More heat was generated as the solution flow rate increased. Figure 4 shows the effects of the solution flow rate on heat generation. In general, the bubble modes were superior to the falling film modes for mass transfer and heat generation.

Figure 5 shows the effects of the solution flow rate on heat transfer coefficient. As can be seen in Figure 5, the heat transfer coefficient increased as the solution flow rate increased for a given gas flow rate. The solution flow rate seriously affected the heat transfer coefficient at low solution flow rate, but its influence became weak as

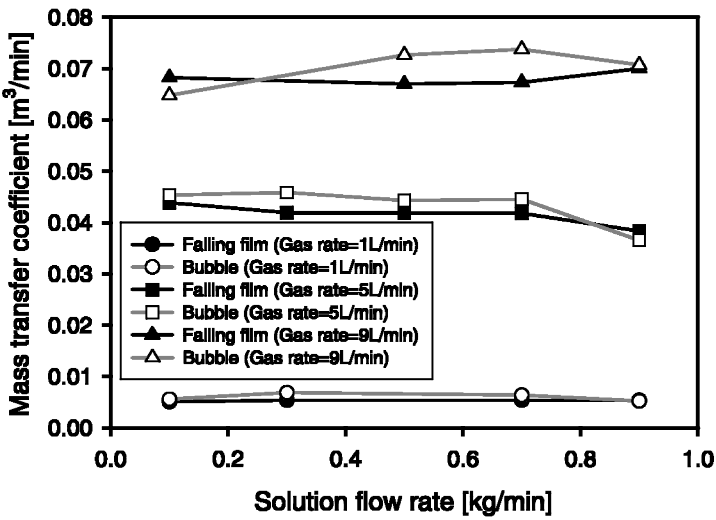

Figure 3. Mass transfer coefficient as a function of the solution flow rate.

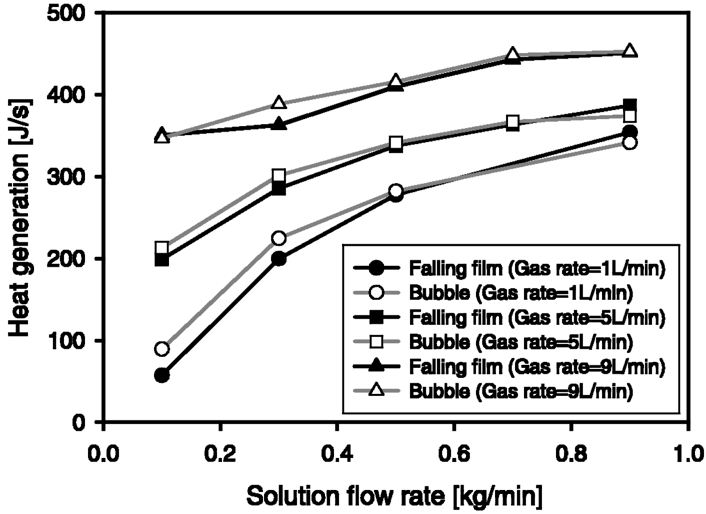

Figure 4. Heat generation as a function of the solution flow rate.

the solution flow rate increased. It was found that at low ammonia gas flow rate the heat transfer coefficients of the falling film mode were larger than those of the bubble mode. However, the difference between the heat transfer coefficients between the falling film and the bubble modes became small at high gas flow. Especially at low solution flow rate, the bubble mode exceeded the falling film mode in terms of heat transfer performance.

Effect of Gas Flow Rate on Heat and Mass Transfer

Figures 6 and 7 show the effects of the ammonia gas flow rate on mass transfer coefficient and heat generation. When the concentration of the input ammonia solution was constant, the amount of absorbed ammonia and generated heat increased as the ammonia gas flow rate increased in both the falling film mode and the bubble mode. Especially, mass transfer performance of the bubble mode was superior to that of the falling film mode. This can be explained by the fact that the contact area of the bubble mode between the ammonia gas and the ammonia solution increased. Because ammonia gas was absorbed more, more absorption heat was generated in the bubble mode, as can be seen in Figure 7.

Figure 8 shows the effect of ammonia gas flow rate on the heat transfer coefficient. At a low ammonia gas flow rate, the falling film mode had better performance than the bubble mode. This is because the plate-type absorber, which has a heat exchanger only at one side, is designed for the falling film mode. The plate-type absorber which has only one-side heat exchange is not adequate for the bubble mode. Though more heat was generated in the bubble mode, the amount of transferred heat in the bubble mode was less than in the falling film mode at low gas flow rate. However, as the gas flow rate increased, the heat transfer performance of the bubble mode exceeded that of the

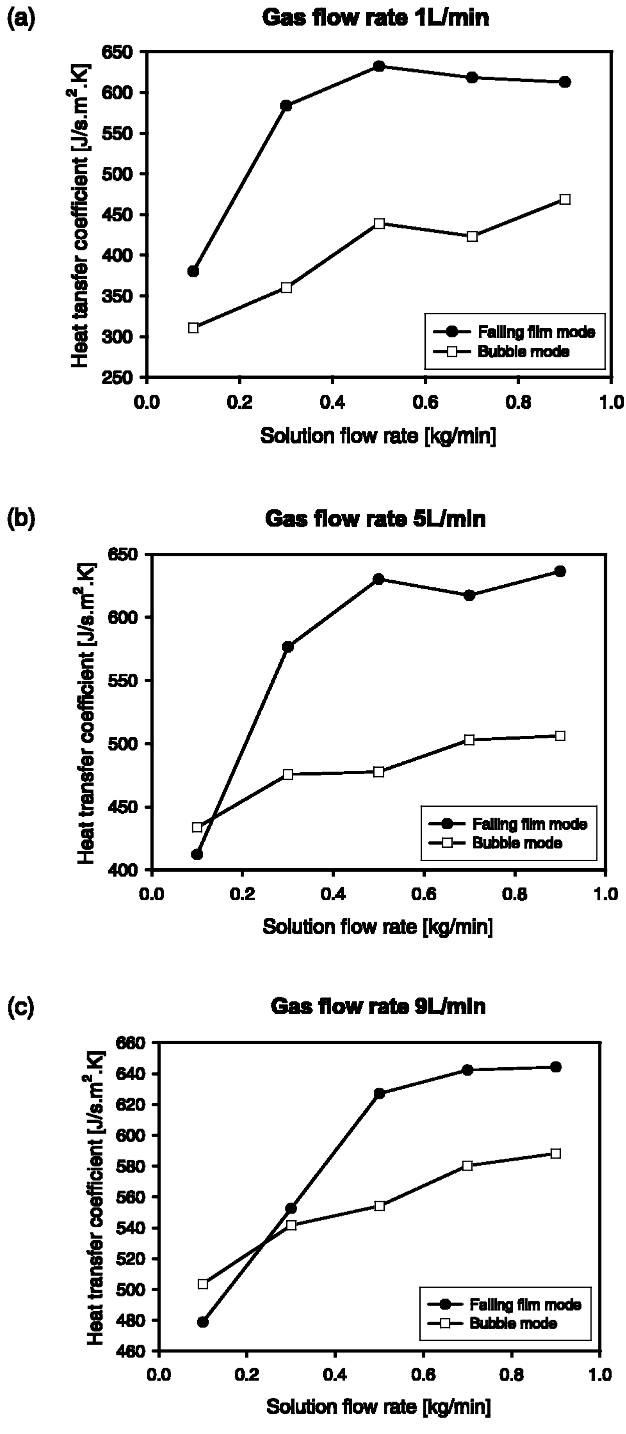

Figure 5. Heat transfer coefficient as a function of the solution flow rate.

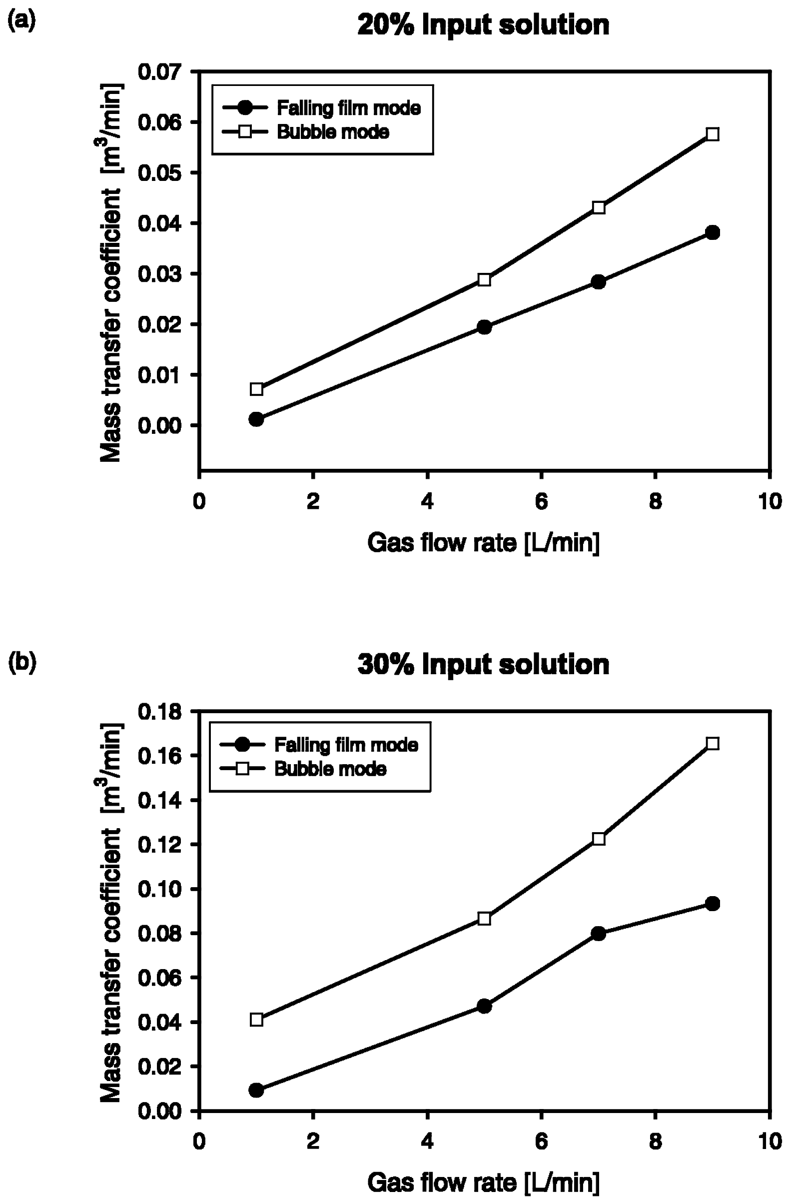

Figure 6. Mass transfer coefficient as a function of the gas flow rate.

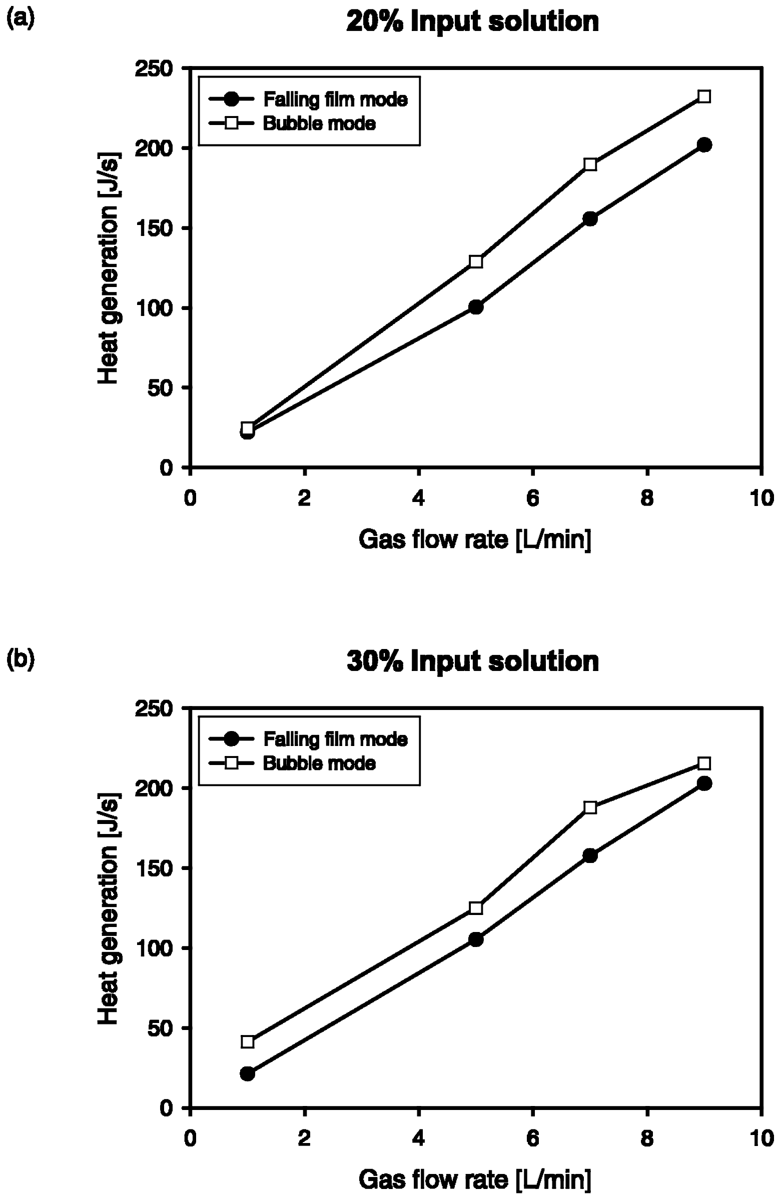

Figure 7. Heat generation as a function of the gas flow rate.

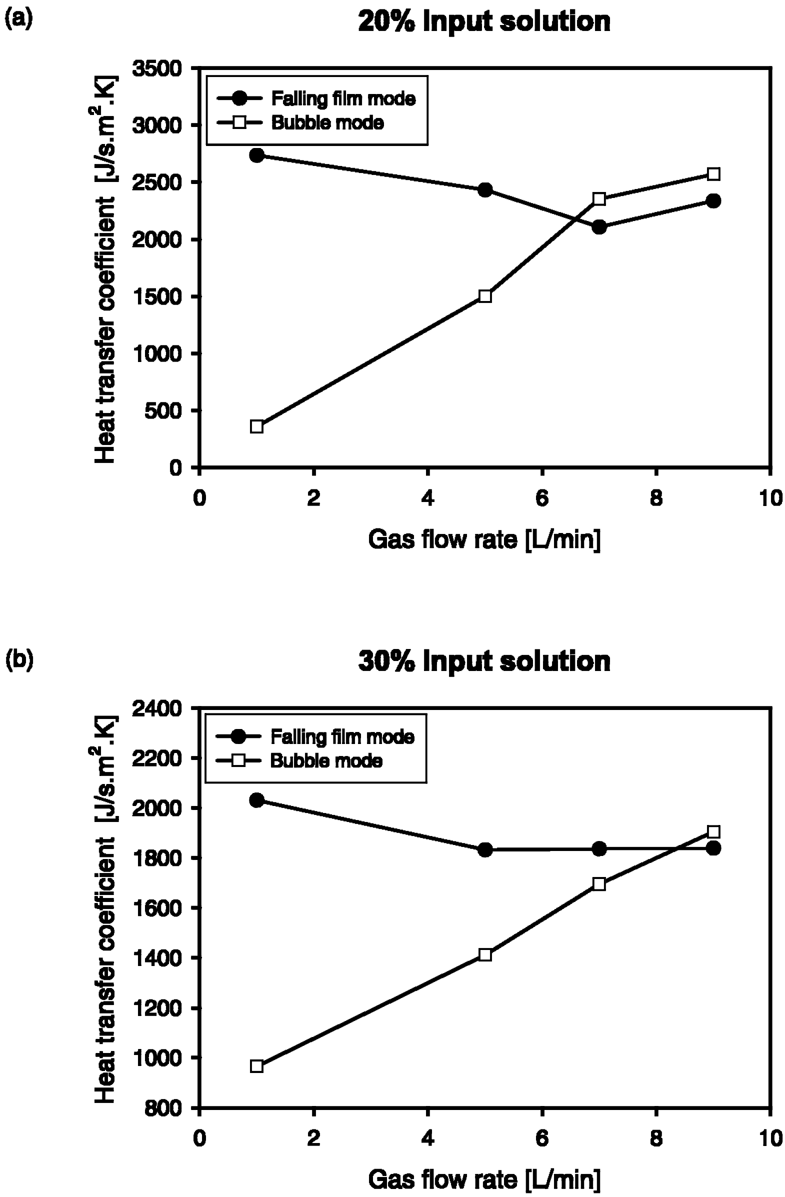

Figure 8. Heat transfer coefficient as a function of the gas flow rate.

falling film mode. This can be explained by the fact that the high gas flow rate caused channeling in the solution flow and the heat transfer area decreased in the falling film mode. Fluidization occurred in the bubble mode and it affected the thermal boundary layer so fairly that the heat transfer performance was improved.

Figure 9 shows the temperature profiles along the length of the absorber. The temperature was higher at the upper side in the falling film mode but at the lower side in the bubble mode. These phenomena were due to the different areas where the absorption mainly occurred and the effect of the coolant.

Relation of Dimensionless Numbers

Figure 10 shows the effects of solution Reynolds number on Nusselt and Sherwood numbers. Solution Reynolds number rarely affected Sherwood number both of the falling film and bubble modes, but Sherwood number increased a little with increase of solution Reynolds number. Nusselt number increased as solution Reynolds number increased.

Figure 11 shows the effects of gas Reynolds number on Nusselt and Sherwood numbers. In the falling film mode, as gas Reynolds number increased, Sherwood number increased; Nusselt number increased at low gas Reynolds number and decreased at high Reynolds number. In the bubble mode, both Sherwood and Nusselt numbers increased as the Reynolds number of the ammonia gas flow increased for a given solution flow rate. These relations of dimensionless numbers corresponded well to the heat and mass transfer results.

In this article, Nusselt and Sherwood numbers were correlated as functions of solution Reynolds and gas Reynolds numbers to evaluate the solution and gas characteristics on the absorption rate as follows:

For the falling film mode,

$$\mathrm{Nu} = 0.01369 \cdot \mathrm{Re}_{\mathrm{sol}}^{0.5103} \cdot \mathrm{Re}_{\mathrm{gas}}^{0.02461} \cdot \left(\frac{\Delta x}{x_{\mathrm{sol}}}\right)^{0.14380} \cdot \left(\frac{\Delta T}{T_{\mathrm{sol}}}\right)^{0.2977} \tag{5}$$

$$\mathrm{Sh} = 658.46 \cdot \mathrm{Re}_{\mathrm{sol}}^{0.0195} \cdot \mathrm{Re}_{\mathrm{gas}}^{0.9571} \cdot \left(\frac{\Delta x}{x_{\mathrm{sol}}}\right)^{-0.0639} \tag{6}$$

For the bubble mode,

$$\mathrm{Nu} = 3.133 \cdot \mathrm{Re}_{\mathrm{sol}}^{0.2519} \cdot \mathrm{Re}_{\mathrm{gas}}^{0.2995} \cdot \left(\frac{\Delta x}{x_{\mathrm{sol}}}\right)^{0.08636} \cdot \left(\frac{\Delta T}{T_{\mathrm{sol}}}\right)^{0.06851} \tag{7}$$

$$\mathrm{Sh} = 43.57 \cdot \mathrm{Re}_{\mathrm{sol}}^{0.0403} \cdot \mathrm{Re}_{\mathrm{gas}}^{0.2865} \cdot \left(\frac{\Delta x}{x_{\mathrm{sol}}}\right)^{0.0462} \tag{8}$$

From Eqs. (5)–(8), $\mathrm{Re}_{\mathrm{sol}}$ and $\mathrm{Re}_{\mathrm{gas}}$ have relatively positive effects on Nu and Sh, but the concentration has no distinct trend in the experimental data.

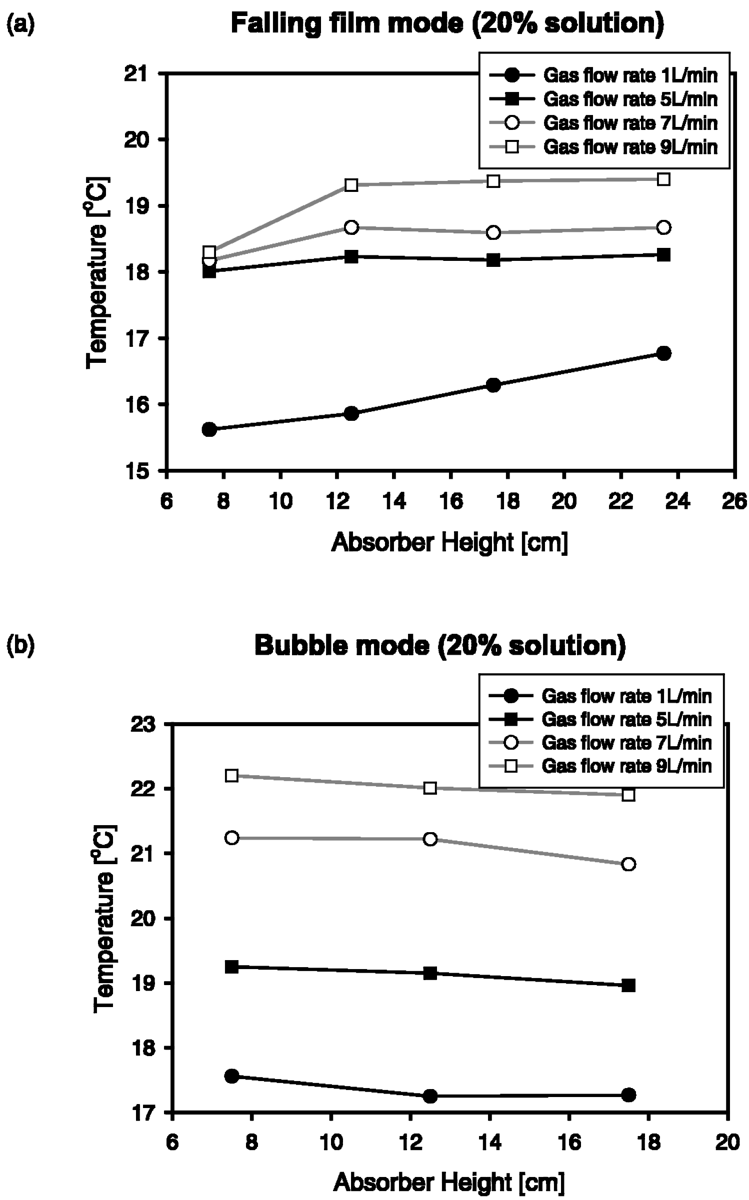

Figure 9. Temperature profile in the absorber.

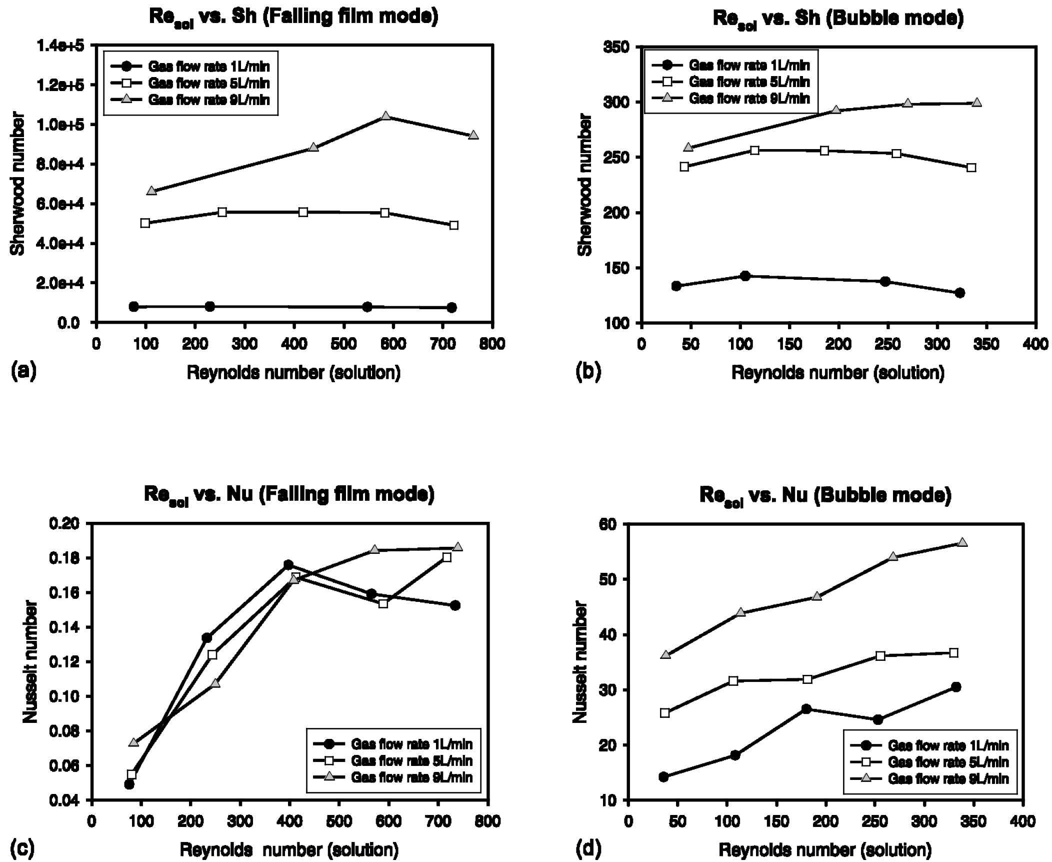

Figure 10. The effect of Re_{sol} on Sh and Nu.

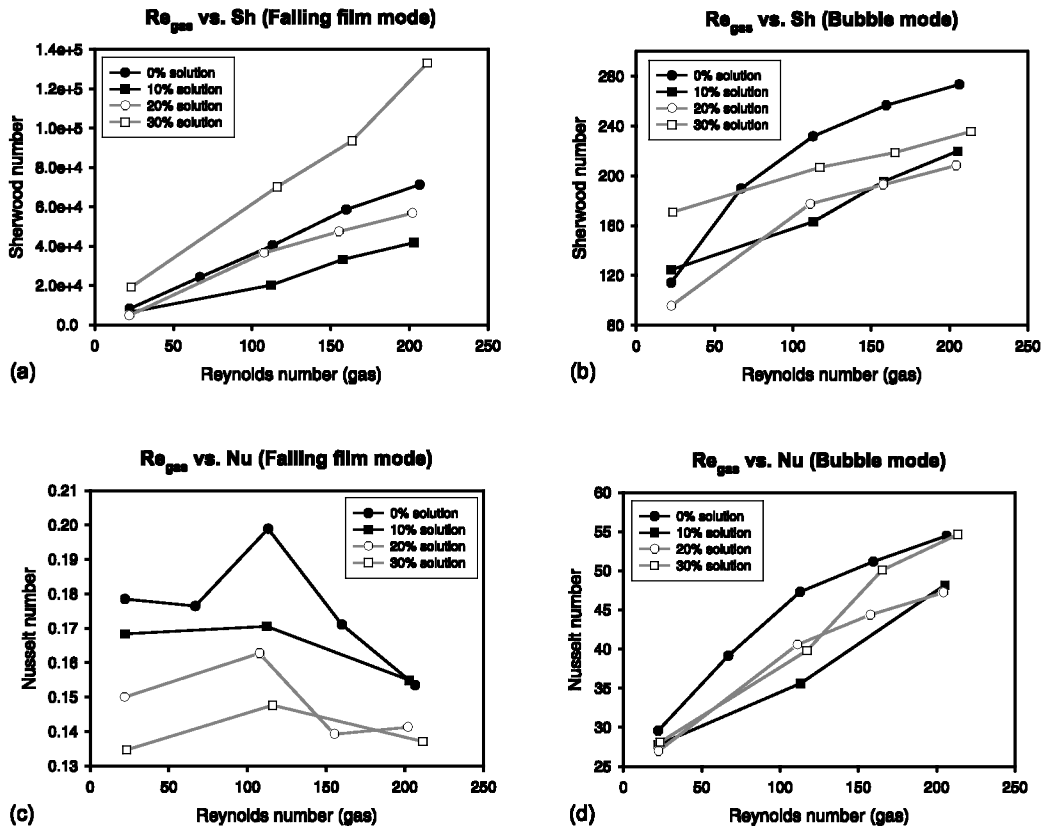

Figure 11. The effect of Re$_{gas}$ on Sh and Nu.

CONCLUSIONS

Falling film and bubble modes for ammonia–water absorption in a plate-type absorber were studied. The following conclusions were drawn from the present experimental studies.

1. As solution flow rate increased, mass transfer performance increased slightly but heat transfer performance increased fairly.
2. As the gas flow rate increased, mass transfer performance increased. For heat transfer performance, bubble mode showed good performance with increase of gas flow rate but the heat transfer in the falling film mode remained or even got worse.
3. In the plate-type absorber, the mass transfer performance of the bubble mode was better than that of the falling film mode.
4. Though more heat was generated in the bubble mode, the amount of transferred heat in the bubble mode was less than that in the falling film mode at high solution flow rate and low gas flow rate. However, as the gas flow rate increased, the heat transfer performance of the bubble mode exceeded that of the falling film mode.
5. In our experiments, bubble modes showed good performances in the plate-type absorber, especially at the low solution flow rate and high gas flow rate.

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