Korean J. Chem. Eng., **19**(4), 552-556 (2002)

A Study of the Characteristics of Heat Transfer for an Ammonia-Water Bubble Mode Absorber in Absorption Heat Pump Systems

Jae-Cheol Lee, Ki-Bong Lee, Byung-Hee Chun, Chan Ho Lee, Jong Joo Ha and Sung Hyun Kim†

Department of Chemical Engineering, Korea University Seoul 136-701, Korea
(*Received 4 February 2002 • accepted 30 May 2002*)

Abstract−An absorber is a major component in absorption refrigeration systems and its performance greatly affects the overall system performance. In this study, experimental analyses of the characteristics of heat transfer for removal of absorption heat in an ammonia-water bubble mode absorber were performed. The heat transfer coefficient was estimated as a function of the input gas flow rate, solution flow rate, temperature, concentration, absorber diameter and height, and input flow direction. The increase of gas and solution flow rate affects positively in heat transfer. However, the increase of solution temperature and concentration affects negatively. Moreover, under the same Reynolds number, countercurrent flow is superior to cocurrent flow in heat transfer performance. In addition, from these experimental data, empirical correlations that can explain easily the characteristics of heat transfer are derived.

Key words: Absorption Process, Absorption Heat Pump, Heat Transfer, Bubble Mode, Ammonia-Water

INTRODUCTION

Due to the ozone depletion problem associated with the use of CFC and HCFC refrigerants, absorption heat pumps and refrigeration systems have received increasing interest in 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. In heat pump systems, the absorber is one of major components from the viewpoint of size and performance. It is the largest component and has a complicated heat and mass transfer mechanism which influences the system performance significantly. Therefore, it is required to analyze combined heat and mass transfer mechanisms in the absorption process. In general, falling film modes and bubble modes have been recommended to enhance heat and mass transfer performance in ammonia-water absorption systems [Christensen et al., 1996].

Over the last ten years, ammonia-water falling film absorption has been extensively investigated both numerically and experimentally [Kang et al., 1999, 2000; Sung et al., 2000; Sujatha et al., 1999; Tsutsumi et al., 1999; Yamashita, 1999]. Especially, the characteristics of heat and mass transfer for each factor have been investigated experimentally, and empirical correlations for heat and mass transfer were derived [Kang et al., 1999]. However, few papers have been found for bubble mode absorption, and there is no paper for the characteristics of heat transfer, although Sujatha et al. investigated the characteristics of mass transfer for bubble mode absorber working with R22 and five organic absorbents experimentally.

In the present study, researches for a bubble mode absorber are performed. In particular, mass transfer of absorption solution and heat transfer to cooling water in the absorber of absorption heat pump systems are essential. Lower level of solution temperature by the effective absorption heat removal improves mass transfer between ammonia gas and solution. Heat transfer coefficients are measured as function of the input gas flow rate, input solution flow rate, temperature, concentration, flow direction between gas and solution, absorber length, and absorber diameter in these experiments. Then, the characteristics of heat transfer for each factor were investigated.

EXPERIMENTAL APPARATUS AND PROCEDURE

The schematic diagrams of the experimental absorption systems for characteristics of heat transfer and the cylindrical bubble mode

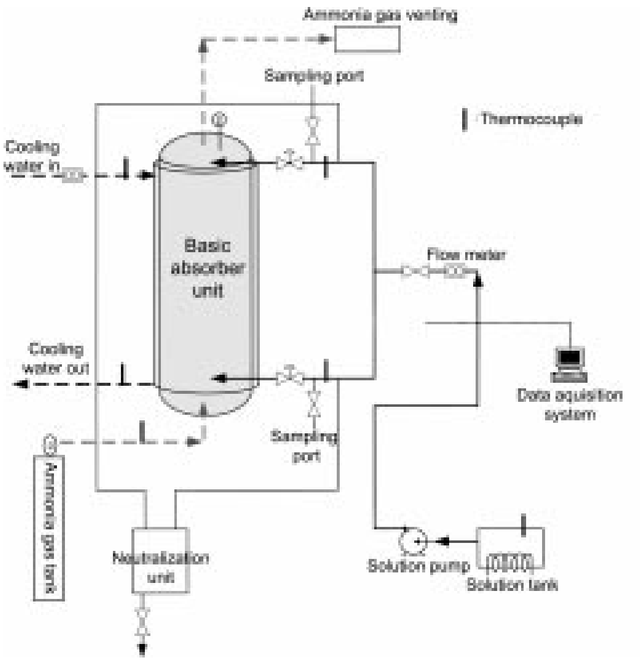

Fig. 1. Experimental bubble mode absorber system for heat transfer experiments.

†To whom correspondence should be addressed.
E-mail: kimsh@korea.ac.kr
‡This paper is dedicated to Professor Wha Young Lee on the occasion of his retirement from Seoul National University.

absorber are given in Fig. 1. Four kinds of absorbers were made; the diameters and heights of the absorbers are 3 cm/70 cm, 3 cm/40 cm, 2 cm/70 cm and 4 cm/70 cm, respectively. For the flow of cooling water, each absorber has double jackets. The 3 mm inner diameter gas injection orifice is equipped at the bottom of the absorber. Ammonia gas flowed up while ammonia solution flowed both up and down. Six thermocouples were equipped in the input and output lines of cooling water, input and output lines of solution, solution tank, and gas input line. Input solution was preheated in the solution tank where three 500 W-cartridge heaters were equipped. An embedded type cartridge heater of 500 W was set in the input line to control more accurate temperature. The flow rate of ammonia gas and solution was controlled by the metering valve equipped in the input line and was measured by mass flow meter. Each temperature measured by thermocouples (K-type) was stored by data acquisition systems. In the experiments, heat transfer coefficients were estimated according to various experimental factors. The concentration of aqueous ammonia solution (0-28%), temperature of solution (15-60 °C), flow rate of solution (0.2-0.8 kg/min), flow direction and flow rate of pure ammonia gas (1-9 L/min) were varied at normal pressure. The heat transfer coefficient can be estimated by measuring the temperature variation of cooling water and the temperature difference between the absorber and cooling water.

ANALYSIS METHODS FOR EXPERIMENTAL RESULTS

1. Calculation Method for Overall Heat Transfer Coefficient

The enthalpy variation of cooling water is equal to the heat transfer rate from the absorber to cooling water. It can be expressed as the relation with the average local temperature difference, overall heat transfer coefficient, and heat transfer area. Therefore, the overall heat transfer coefficient can be expressed as follows:

$$U_o \cdot A \cdot \Delta T_{LMTD} = m_c \cdot C_{p,c} \cdot \Delta T_{c,w} \tag{1}$$

$$U_o = (m_c \cdot C_{p,c} \cdot \Delta T_{c,w})/(A \cdot \Delta T_{LMTD}) \tag{2}$$

From the measured temperatures of input and output cooling water, the heat transfer rate from solution to cooling water can be easily calculated. Also, the overall heat transfer coefficient can be obtained by calculating the log mean temperature difference, LMTD (ΔT) from input and output solution and cooling water temperatures [McCabe et al., 1993].

2. Estimation Method for Heat Transfer Coefficient (h_i) of Absorber Inside Surface

Consider the local overall heat transfer coefficient at a specific point in a double-pipe exchanger. When the warm solution flows through the inside pipe and the cooling water flows through the annular space, the relation of overall heat transfer coefficient and surface heat transfer coefficient can be approximated as follows:

$$1/U_o = 1/h_i + 1/h_o + \delta_w/k_w \tag{3}$$

$$1/h_i = 1/U_o - \delta_w/k_w - 1/h_o \tag{4}$$

To understand heat transfer phenomena in the absorber, estimation of the heat transfer coefficient in the inside surface is the most important thing. However, it is very difficult to estimate the inside heat transfer coefficient (h_i) directly. Moreover, even though Eq. (4) is used to estimate, data of heat transfer coefficient (h_o) of cooling water surface are necessary. As several absorbers were used for these experiments, the value of outside heat transfer coefficient (h_o) of each absorber must be different, in spite of the same flow rate of input cooling water for each absorber. Therefore, h_o for each absorber must be determined for the estimation of h_i.

In this study, the following numerical method was used to determine h_o. From the empirical Eq. (5) for the heat transfer coefficient of inside pipe, the relation for the heat transfer coefficient and the Reynolds number can be derived. When the solution flow through the inside pipe is laminar, the Nusselt number is proportioned to an exponential function of the Graetz number:

$$Nu \propto Gz^{1/3} \tag{5}$$

$$\begin{aligned} Gz &= (mC_p)/(kL) = (\pi\rho VD^2C_p)/(4kL) \\ &= ((\rho DV)/\mu)\,((\pi C_p D\mu)/(4kL)) = Re((\pi C_p D\mu)/(4kL)) \end{aligned} \tag{6}$$

$$h_i = aRe^{\beta} \tag{7}$$

$$1/U_o - \delta_w/k_w = 1/h_i + 1/h_o \tag{8}$$

$$Y(=1/U_o - \delta_w/k_w) = a'Re^{-\beta} + y_0(=1/h_o) \tag{9}$$

As can be seen in the above equations, the Nusselt number (Nu) which is proportional to an exponential function of the Graetz number (Gz) can be expressed as a function of the Reynolds number (Re). Therefore, experiments were performed to measure the overall heat transfer coefficient as a function of the solution Reynolds number. In all experiments, cooling water flow rate was maintained constant. From experimental data, $Y(=1/U_o - \delta_w/k_w)$ and Re can be obtained, and a, β, and y_0 can be easily estimated by a plot of Y versus $Re^{-\beta}$. Finally, h_o can be presented as the reciprocal of y_0. The h_o of each absorber in these experiments was obtained by this estimating method. The results for h_o are as follows:

- In the case of height 70 cm and diameter 3 cm absorber
  $Y(=1/U_o - \delta_w/k_w) = 9.17873 \times 10^{-3}\, Re^{0.26} + 9.49908 \times 10^{-4} (=1/h_o)$
  $h_o = 1052.734$ [J/s·K·m²]

- In the case of height 70 cm and diameter 2 cm absorber
  $Y(=1/U_o - \delta_w/k_w) = 0.01122\, Re^{0.26} + 1.60228 \times 10^{-3} (=1/h_o)$
  $h_o = 624.1099$ [J/s·K·m²]

Consequently, after the overall heat transfer coefficient (U_o) and heat transfer coefficient (h_o) are determined by experiments and estimation method, the heat transfer coefficient h_i can be obtained from Eq. (4).

RESULTS AND DISCUSSION

1. Effects of Input Gas Flow Rate

Fig. 2 shows the variation of heat transfer coefficient (h_i) as a function of input gas flow rate under the constant input solution Reynolds number of 184 in diameter absorber of 3 cm. As can be seen in Fig. 2, h_i increases as the input gas flow rate increases. This can be explained as that turbulence and eddies are generated by ammonia gas injected into laminar solution flow, and turbulence breaks

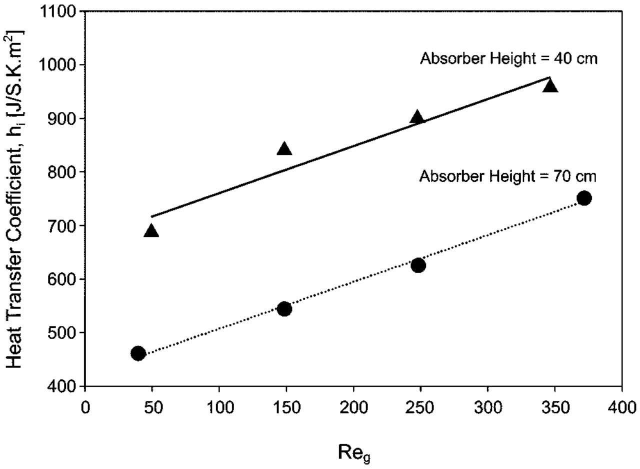

Fig. 2. Effect of gas flow rate on heat transfer coefficient for Re_{sol} =184.

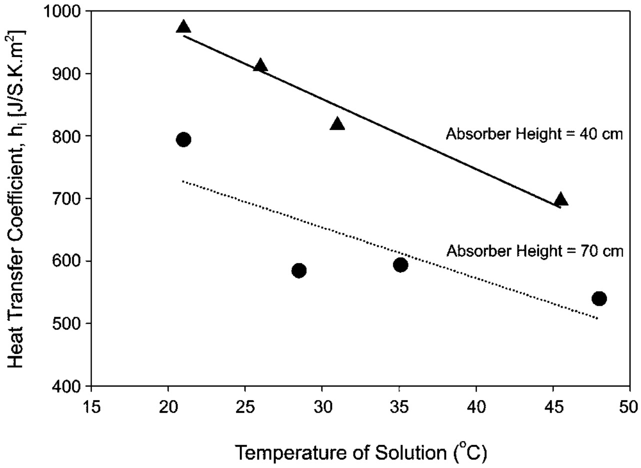

Fig. 4. Effect of temperature on heat transfer coefficient for Re_g= 248 and Re_{sol}=184.

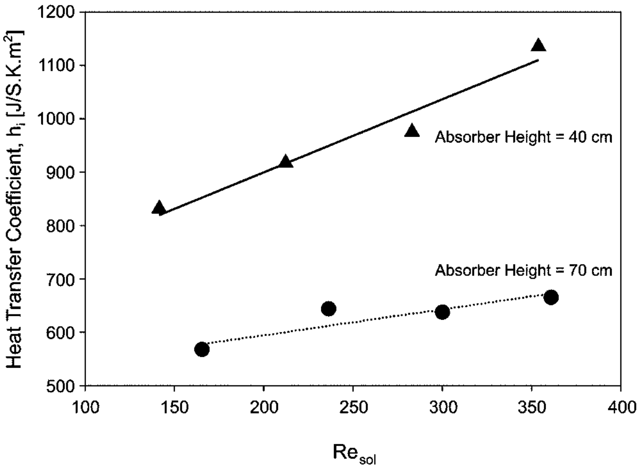

Fig. 3. Effect of solution flow rate on heat transfer coefficient for Re_g=248.

the thermal boundary layer formed along wall boundary.

2. Effects of Input Solution Flow Rate

Fig. 3 shows the variation of heat transfer coefficient (h_i) as a function of the input solution flow rate under the constant input gas Reynolds number of 248 in diameter absorber of 3 cm. As can be seen in Fig. 3, h_i increases as the input solution flow rate increases. In general, the Nusselt number of newtonian laminar flow through the inside pipe is proportional to (Graetz number)$^{1/3}$. In other words, as the flow rate of solution increases, the thermal boundary layer is formed thinly. The improvement of heat transfer performance can be explained as follows: the increase of the solution flow rate makes thin thermal boundary layer and some eddies.

3. Effects of Temperature Difference Between Gas and Solution

Fig. 4 shows the effects of the temperature difference between gas and solution, when the Reynolds number of gas and solution is 248 and 184, respectively, and input gas temperature is maintained at constant. Fig. 4 shows that h_i decreases as the input solution temperature increases. In general, the effect of temperature on the heat transfer coefficient appears clearly in falling film absorption process. The reason is that two interfaces are formed similarly in falling film absorption. One is the interface of heat transfer between the liquid film and the wall boundary; the other is that of mass transfer between gas flow and liquid film. As the temperature of gas increases, the sensible heat from the gas to the liquid increases, and this phenomenon affects positively heat transfer to cooling water. However, as liquid temperature increases, the sensible heat from the liquid to the gas increases, and causes a lower heat transfer coefficient. From these bubble mode experiments, the same results as falling film mode are obtained. Finally, it is confirmed experimentally that the same phenomenon occurs like the falling film mode absorption in mass and heat transfer interfaces, although mass transfer interface between gas and liquid is formed irregularly in the bubble mode absorption.

4. Effects of Concentration Difference Between Gas and Solution

In bubble mode absorption, the absorber can be divided into two regions. One is the mixing zone; the bottom region of absorber where ammonia gas is ejected from a nozzle plunges into solution flow,

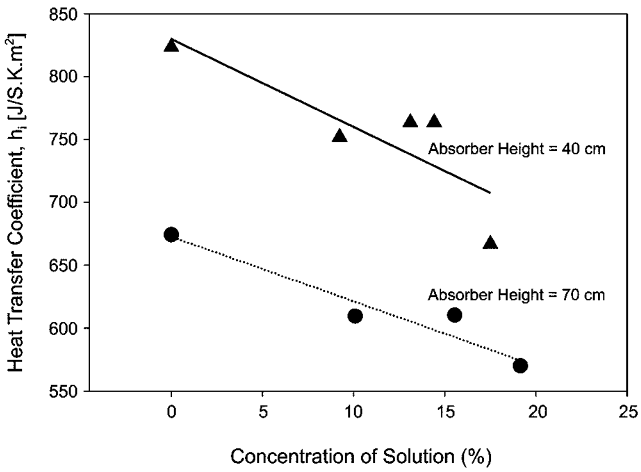

Fig. 5. Effect of solution concentration on heat transfer coefficient for Re_g=248 and Re_{sol}=184.

and turbulence and eddy is generated by injected ammonia gas. The other is the pipe flow zone. It is the upper stable region of the absorber. In general, an increase of the input solution concentration means an increase of the gas absorption region and bubble existence height, but an increase of the input gas flow means an expansion of the mixing zone and the development of turbulence. In other words, the same amount of input gas generates similar turbulences and eddies in the mixing zone, although the solutions of different concentration are supplied into the absorber. However, gas holdup increases in the pipe flow zone with increasing of input solution concentration. In the experiments for solution concentration, it can be determined whether the reason for the positive effects of bubble on heat transfer is the development of mixing turbulence zone or the expansion of absorption region itself. Fig. 5 shows the effects of the concentration difference between gas and solution, when the Reynolds number of the gas and that of solution is 248 and 184, respectively and temperature of input gas and solution is maintained constant. As can be seen in Fig. 5, the effect of increase of ammonia solution concentration does not appear clearly. Therefore, it is confirmed experimentally that the expansion of the bubble absorption region does not affect the improvement of heat transfer performance. On the contrary, a little decrease of the heat transfer coefficient with increasing ammonia solution concentration is observed. This unexpected result can be explained: as the concentration of ammonia solution increases, the rectification of ammonia occurs in ammonia solution, and ammonia solution loses latent heat of ammonia evaporation. Therefore, this phenomenon can negatively affect heat transfer from solution to cooling water.

5. Effects of Absorber Length

Although the absorber must have enough absorption height to absorb ammonia bubbles perfectly, the necessity of surplus absorber height over the bubble absorption region for heat transfer must be confirmed. In these experiments, the 70 cm absorber, which has enough height to absorb bubbles and the 40 cm absorber which does not have surplus absorber height within the limits of these experiments, are compared. Figs. 2 to 5 show the effect of absorber height on the heat transfer coefficient. The heat transfer coefficient of the 40 cm absorber is superior to that of 70 cm absorber. This result indicates that most improvement of heat transfer performance by injected bubbles occurs in the mixing zone at the bottom of the absorber, so surplus absorber height over the bubble absorption region is not necessary for improvement of heat transfer performance.

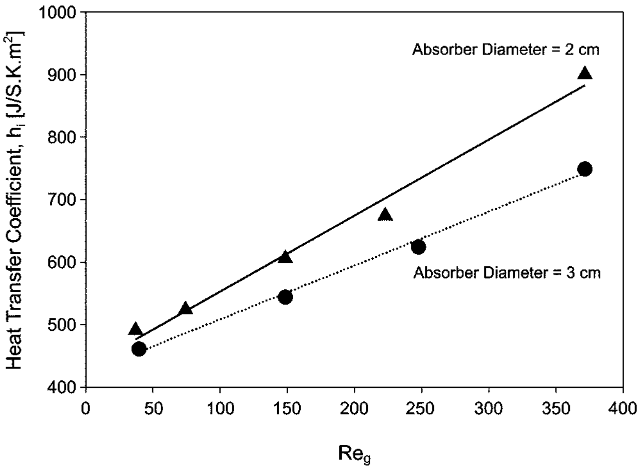

Fig. 6. Effect of absorber diameter on heat transfer coefficient for Re_{sol}=184, Absorber Height=70 cm.

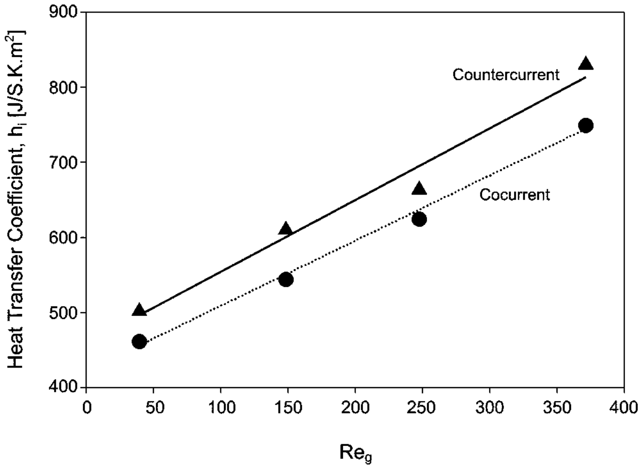

Fig. 7. Effect of flow direction on heat transfer coefficient for Re_{sol} =184, Absorber Height=70 cm.

6. Effects of Absorber Diameter

Fig. 6 shows the effect of absorber diameter on the heat transfer coefficient. As can be seen, the heat transfer coefficient of the 2 cm diameter absorber is superior to that of the 3 cm absorber, under the same conditions for gas and solution Reynolds numbers of both absorbers. The effects of eddy and turbulence near the absorber wall increase with decrease of absorber diameter. These results indicate that the shape of the absorber can affect heat transfer performance.

7. Effects of Flow Direction Between Gas and Solution

Fig. 7 shows the comparison of heat transfer coefficient between cocurrent and countercurrent flows. As can be seen, the heat transfer coefficient of countercurrent flow is superior to that of cocurrent flow. The phenomena of flow direction between gas and solution can be explained as follows: unabsorbed bubbles in the cocurrent flow can exist to higher position of absorber than those of countercurrent, but mixing and turbulence effects of countercurrent are superior to those of cocurrent. Therefore, these experimental results indicate that the development of the mixing zone near to the gas injector is more important than the expansion of the absorption region for the improvement of heat transfer performance.

8. Derivation of Correlation

From twenty-one experimental data, empirical correlations that can easily explain the characteristics of heat transfer are derived as follows. The error between measured and calculated Nusselt number (Nu) by Eq. (10) was within ±15%.

$$Nu=1.487(Re_g)^{0.1866}(Re_{sol})^{0.1760}(\Delta T/T_{gas})^{-0.1146}(\Delta X/X_{gas})^{0.6013}(L/d)^{0.2662} \quad (10)$$

As can be seen in the above correlation, the increase of gas and solution flow affects heat transfer positively. However, the increase of solution temperature and concentration affects negatively. Moreover, under the same Reynolds number, the decrease of absorber diameter affects heat transfer positively. These empirical correlations can be useful to estimate the heat transfer coefficients at the condition of high temperature and pressure at which it is difficult to conduct experiments.

CONCLUSIONS

Mass transfer of absorption solution and heat transfer to cooling water in the absorber of absorption heat pump systems are essential. For the further understanding of heat transfer from ammonia solution to cooling water, heat transfer coefficients are measured as the many operation variables. The following conclusions were drawn from the present experimental studies:

1. The operation variables of experiments for heat transfer performance are the input gas flow rate, input solution flow rate, temperature, concentration, flow direction between gas and solution, absorber length, and absorber diameter.
2. The increase of gas and solution flow rate affects heat transfer performance positively. However, the increase of solution temperature and concentration affects negatively. Moreover, under the same Reynolds number, the decrease of absorber diameter affects positively.
3. The heat transfer performance of countercurrent flow is superior to that of cocurrent flow.
4. The key factor for improvement of heat transfer performance is the development of mixing zone in the bottom of an absorber where gas is injected.
5. These experimental results can be useful to estimate the heat transfer coefficients at the condition of high temperature and pressure at which it is difficult to conduct experiments.

ACKNOWLEDGEMENTS

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.

NOMENCLATURE

A : area [m^2]
C_p : specific heat of fluid [J/K·kg]
$C_{p,c}$: specific heat of cooling water [J/K·kg]
d : absorber diameter [m]
Gz : Graetz number
h_i : absorber inside surface heat transfer coefficient [$W/m^2 \cdot K$]
h_o : cooling water surface heat transfer coefficient [$W/m^2 \cdot K$]
k : thermal conductivity of fluid [W/m·K]
k_w : thermal conductivity of wall [W/m·K]
L : absorber length [m]
m : mass flow rate of fluid [kg/s]
m_c : mass flow rate of cooling water [kg/s]
Nu : Nusselt number
Re : Reynolds number
Re_g : Reynolds number of gas
Re_{sol} : Reynolds number of solution
T : temperature [K]
ΔT_{LMTD} : log mean temperature difference between solution and cooling water [K]
$\Delta T_{c,w}$: temperature variation of cooling water [K]
ΔT : temperature difference between solution and gas temperature [K]
U_o : overall heat transfer coefficient [$W/m^2 \cdot K$]
V : fluid velocity [m/s]
ΔX : difference between ammonia weight fraction of gas and solution
ρ : density [kg/m^3]
δ_w : tube-wall thickness [m]
μ : viscosity [kg/m·s]

REFERENCES

Christensen, R. N., Kang, Y. T., Garimella, S. and Priedeman, D., "Generator Absorber Heat Exchanger (GAX) Cycle Modeling, Component Design and Tests," Final Report to LG Electronics, Contract number: 862805-01/062805 (1996).

Kang, Y. T., Akisawa, A. and Kashiwagi, T., "Analytical Investigation of Two Different Absorption Modes: Falling Film and Bubble Types," *International Journal of Refrigeration*, **23**, 430 (2000).

Kang, Y. T., Akisawa, A. and Kashiwagi, T., "Experimental Correlation of Combined Heat and Mass Transfer for NH_3-H_2O Falling Film Absorption," *International Journal of Refrigeration*, **22**, 250 (1999).

Lee, K. B., Chun, B. H., Lee, J. C., Park, C. J. and Kim, S. H., "Absorption Characteristics of Ammonia-water System in the Cylindrical Absorber," *Korean J. Chem. Eng.*, **19**, 87 (2002).

Lee, K. B., Chun, B. H., Lee, J. C., Park, C. J. and Kim, S. H., "Comparison of Heat and Mass Transfer of Falling Film and Bubble Mode in Ammonia-water," *Experimental Heat Transfer*, In Press (2002).

McCabe, W. L., Smith, J. C. and Harriott, P., "Unit Operations of Chemical Engineering," McGraw-Hill, Singapore, 5th ed., 115 (1993).

Perry, R. H. and Green, D. W., "Perry's Chemical Engineers' Handbook," 6th ed., McGraw-Hill International Editions, Japan (1984).

Reid, R. C., Prausnitz, J. M. and Poling, B. E., "The Properties of Gases & Liquids," McGraw-Hill, Singapore (1986).

Sujatha, K. S., Mani, A. and Srinivasa Murthy, S., "Analysis of a Bubble Absorber Working with R22 and Five Organic Absorbents," *Heat and Mass Transfer*, **32**, 255 (1997).

Sujatha, K. S., Mani, A. and Srinivasa Murthy, S., "Experiments on a Bubble Absorber," *International Community Heat Mass Transfer*, **26**(7), 975 (1999).

Sung, W. M., Huh, D. G. and Ryu, B. J., "Development and Application of Gas Hydrate Reservior Simulation Based on Depressurizing Mechanism," *Korean J. Chem. Eng.*, **17**, 344 (2000).

Tsutsumi, A., Chen, W. and Kim, Y. H., "Classification and Characterization of Hydrodynamic and Transport Behaviors of Three-Phase Reactors," *Korean J. Chem. Eng.*, **16**, 709 (1999).

Yamashita, F., "Effect of Geometrical Parameters of Draft Tubes and Clear Liquid Height on Gas Holdup in a Bubble Column for Gas Dispersion into Tubes," *Korean J. Chem. Eng.*, **16**, 789 (1999).