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Enhancement of Heat and Mass Transfer by Insert Spring in a Vertical Absorber with Surfactant

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Abstract : This research was concerned with the enhancement of heat transfer by surfactant added to the aqueous solution of LiBr. Different vertical tubes were tested with and without an additive of normal octyl alcohol. The test tubes are a bare inner surface, a groove inner surface, a corrugated inner surface and a spring inserted inner surface tubes. The additive concentration was about 0.08 mass%. The heat transfer coefficient was measured as a function of the film Reynolds number in the range of 20~200. Experiments were carried out at higher cooling water temperature of 35℃ to simulate an air cooling condition for several kinds of absorber testing tubes. The experimental results were compared with and without surfactant. The enhancement of heat transfer by Marangoni convection effect which was generated by addition of the surfactant is observed in each test tube. Especially, it is clarified that the tube with an inserted spring has the highest enhancement effect.

Key words : Absorption chiller/heater, Enhancement of heat transfer, Air-cooled absorber, Surfactant, Marangoni convection

Nomenclature

A : Heat transfer area [m^2]
C_P : Specific heat at constant pressure [J/kg · K]
d_a : Inner diameter of an outer absorber tube [m]
d_i : Inner diameter of an absorber [m]
d_o : Outer diameter of an absorber [m]
g : Gravity acceleration [m/s^2]
G : Mass flow rate [kg/s]
G_R : Absorption rate of a refrigerant vapor [kg/s]
h : Heat transfer coefficient [$W/m^2 \cdot K$]
U : Overall heat transfer coefficient [$W/m^2 \cdot K$]
L : Tube length of an absorber [m]
Ls : Characteristic length of an absorption solution [m]
Nu : Nusselt number

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P : Pressure [mmHg]
Pr : Prandtl number
Q : Heat transfer rate [W]
Re : Reynolds number
Re_f : Film Reynolds number
Sh : Sherwood number
T : Temperature [℃]
ΔT_{lm} : Log mean temperature difference [℃]

Greek symbols

λ : Thermal conductivity [W/m · K]
ρ : Density [kg/m^3]
μ : Viscosity [Pa · s]
β : Mass transfer coefficient [m/s]
δ : Falling film thickness of solution [m]
Γ : Solution flow rate per unit length [kg/m · s]
ξ : Concentration [wt%]

Subscripts

A : Absorber
E : Evaporator
I : Inlet
CL : Chilled water
CO : Cooling water
m : Mean
o : Outlet
R : Refrigerant
s : Absorption solution

1. Introduction

Recently the electric load during the summer has been increasing rapidly. Thus, the cooling system, which is not using electric power, is on demand for development. One of these demands can be met by an absorption chiller/heater. But, only the large capacity water-cooled absorption chiller/heater is being used. Large capacity, which is over 50 RT using H_20/LiBr as working fluid, is mainly produced for commercial purposes. The air-cooled absorption chiller/heater has been studied. However, a small sized air-cooled absorption chiller/heater has not yet been developed. Among the studies, many researches have actively focus on the high efficiency of the air-cooled absorption machine on these days. While the water-cooled absorption heater/chiller is taking of a falling film type with horizontal tubes, the air-cooled type absorber is using falling film type absorber in which solutions flow down along vertical tubes inside.

Yoon et al[1]. analyzed the experimental results on the characteristics of heat and mass transfer and pressure drop caused by the vapor flow in an absorber. They investigated the shape of an absorber with a spring-inserted tube. They focused on the inner diameter, the length of heat transfer tube and the shape of the inner tube. William et al[2]. evaluated performance of heat and mass transfer of vertical absorber using bare tube, pin-fin tube, fluted tube, grooved tube, and twisted tube. Yoon et al[3]. experimented performance of heat and mass transfer of horizontal bundle absorber using bare tube, bumping bare tube, floral tube, and twisted floral tube. Also, Yoon et al[4]. experimentally tested the enhancement of the heat transfer by using three kinds of tubes namely, a bare, a floral, and a hydrophilic tubes adding surfactant.

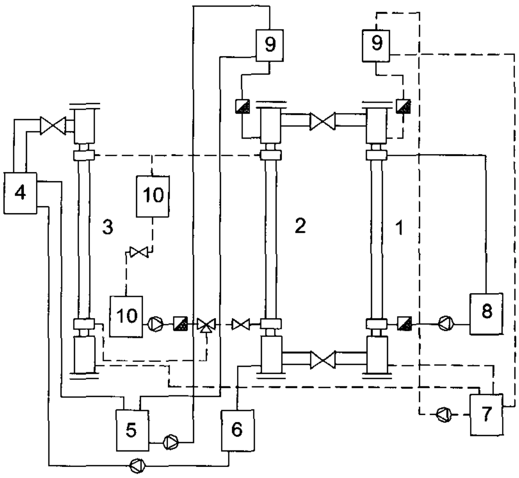
Hoffmann[5] reported that both the cases enhance the heat and mass transfer and improve the performance of the absorber. Cosenza and Vliet[6] investigated falling film absorption for smooth horizontal tubular surfaces. They obtained experimental data for absorption of water vapor into an aqueous LiBr solution flowing over internally cooled horizontal tubes.

Kim et al[7]. measured the absorption rate in a vertical tube for LiBr solution film of 50-63 wt%. When 3-6 ppm of 2-etyl-1-hexano is added as surfactant, absorption rate starts to increase. When 20-30 ppm is supplied, the increasing rate of absorption is maximized. The performance enhancement by adding the surfactant is due to a decrease of the surface tension of the absorption solution and the surface tension of the absorption solution and the surface distribution by the Marangoni convection[8, 9].

However, on the whole, fundamental phenomena are not well understood. Especially, a study on the vertical absorber with enhanced tubes is sparse, that is, enhanching the heat transfering area in the vertical type absorber followed by adding the surfactant as an additive in order for increasing the heat tarsfer performance has not been reported on the relevent litarature. Also, the understanding of the underlying mechanisms of the heat and mass transfer in a falling film type absorber does not seem to be well established. The purpose of this study is to examine experimentally the characteristics of absorption heat transfer using LiBr solution in an air-cooled insert spring vertical tube. Also, the effect of heat transfer performance with and without surfactant will be investigated systematically.

2. Experimental apparatus and procedure

This study is carried out to investigate the heat transfer characteristics on an absorber with the additive to absorption solution. The inner diameters and the surface configurations of heat exchanger tubes were varied to search the physical backgrounds of absorption process. The working fluids for the absorption experiment are lithium bromide and water. Lithium bromide is the absorbent



1. Evaporator
2. Absorber
3. Condenser
4. Generator
5. Strong solution tank
6. Weak solution tank
7. Refrigerant tank
8. Chilled water tank
9. Constant pressure tank
10. Cooling water tank
Pump
Flow meter

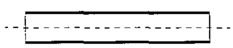
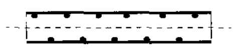
Fig. 1 Schematic diagram of experimental apparatus

and water is the absorbate. Aqueous solution of lithium bromide flows inside vertical tubes with absorption of water vapor. As latent heat of vaporization of solution is transferred to the spring tubes, cooling water due to the continuous absorption cools the solution. The surfactant used in this study is n-octanol. The concentration of surfactant is approximately 0.08 wt%.

The experimental equipment used in this study is shown in Fig. 1. Test apparatus with batch mode operation is designed to test vertical absorbers. The absorbent flows down inside the inner tubes. The absorption of water vapor takes place at the inner wetted surfaces of the inner tubes and the heat of absorption is removed by the upward flow of cooling water at the annular gap between the inner and the outer tubes. A and well insulated tank is connected to a heat exchanger with pipes. And, all major components are constructed with stainless steel. Tubes of an absorber used for this experiment are bare tubes, spring inserted tubes, corrugated tubes, and grooved tubes. Specifications of absorber tubes are shown in Table 1. The experiment is carried out with a commercially sized machine. It is also carried out with bare tubes having inner diameters of 14.35 mm and 23.80 mm to predict the effect of inner diameter. The experimental results of bare tubes have a nominal value compared to absorption abilities with various kinds of absorption heat exchanger tubes. In order to find the effects of a surface configuration, corrugated tubes, grooved tubes and spring inserted tubes, having inner diameter 14.35 mm were experimented. The inner diameter of a spring inserted tube was 17.6 mm, and is made up with a pitch of 1.0 mm. Spring diameters are of two types, 1.0 mm, and 0.5 mm. Material for a heat exchanger tube and a spring is made of copper and stainless steel, respectively.

Surfactant of octyl alcohol (n-octanol) is the most commonly used additive with lithium bromide-water in absorption applications. After adding the surfactant, the surface tension of LiBr solution decreases remarkably at the experimental conditions. These conditions including absorber temperature, the pressure, the concentration and the flow rate are summarized in Table 2. The absorption solution concentration and the pressure

Table 1 Specification of test tubes

Test tube	Inside Diameter	Length	Configurations	
Bare	14.35 [mm]	1,419 [mm]		Smooth Surface
	23.80 [mm]	1,419 [mm]		Smooth Surface
Insert spring	14.35 [mm]	1,419 [mm]		Spring Dia. 1.0 [mm], Pitch 10 [mm]
	17.60 [mm]	1,119 [mm]		Spring Dia. 1.0 [mm], Pitch 10 [mm]
	17.60 [mm]	1,119 [mm]		Spring Dia. 0.5 [mm], Pitch 10 [mm]

responding to saturation temperature of refrigerant vapor evaporation decide the solution temperature of absorber inlet. The flow rate of solution into the absorber is controlled by a needle valve and is measured by a flow meter. Unnecessary absorption solution passes through a bypass pipe to establish the constant pressure inside the tank and it comes back to the strong solution tank. Vapor of absorption process is supplied into the upper header, and flows downward to an absorber tube for complete absorption. The experiment has been conducted in a saturated concentration stage. If the surfactant exceeds saturated concentration level, n-octanol remains at solution surface in a drop condition. The saturation solubility of LiBr solution of 60 wt% (50℃) is approximately 0.01 wt%. The experimental absorption process initiates, inlet temperatures of the absorption solution are adjusted to maintain an equilibrium temperature in the tank.

Table 2 Experimental conditions

Strong solution	Film Reynolds number	20~180[-]
	Temperature	45±0.5[℃]
	Concentration	60±0.5[wt%]
Cooling water	Flow rate	2.8×10^{-5}[m^3/s]
	Temperature	35.0±0.5[℃]
Chilled water	Flow rate	3×10^{-5}[m^3/s]
	Temperature	18.0±0.5[℃]
Pressure of absorber		7±1[mmHg]
Concentration of surfactant		0.08[wt%]

3. Calculation of heat and mass transfer coefficient

To evaluate heat transfer characteristics in absorption process, a physical model is shown in Fig. 2. The heat transfer rate can be estimated with chilled water mass flow rate and the temperature difference between the inlet and the outlet of an evaporator as given in equation 1.

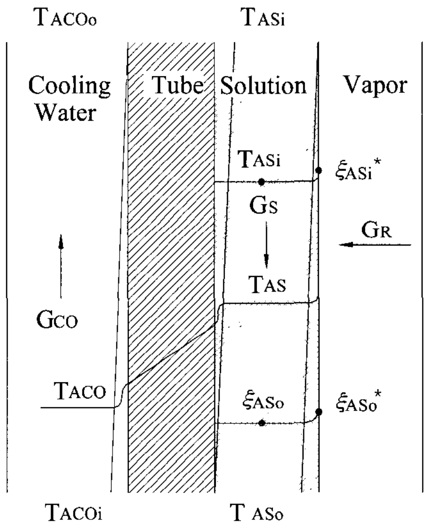


Fig. 2 Physical model of falling film absorption

$$Q_E = G_{CL} \cdot C_{PCL} \cdot (T_{ECLi} - T_{ECLo}) \tag{1}$$

The heat transfer rate of a coolant in absorption process can be estimated with mass flow rate and temperature difference of a coolant between the inlet and the outlet of an absorber as given in equation 2. And the heat balance of the heat transfer rate can be calculated with the absorption rate minus the sensible heat of absorption solution at an absorber as given in equation 3. Here, the differences of the latent heat of evaporation and condensation are very small, so they are neglected.

$$Q_A = G_{CO} \cdot C_{PCO} \cdot (T_{ACOo} - T_{ACOi}) \tag{2}$$

$$Q_A' = Q_A - G_S \cdot C_{PS} \cdot (T_{ASi} - T_{ASo}) \tag{3}$$

From the latent heat of vapor in an evaporator (Eq. 1) and the latent heat of condensation in an absorber(Eq. 3), equilibrium heat transfer of experimental apparatus is obtained. The logarithmic mean temperature difference, ΔT_{lm}(℃), is defined as equation 4, and overall heat transfer coefficient was calculated by the following equation 5.

$$\Delta T_{lm} = \frac{\{(T_{ASi} - T_{ACOo}) - (T_{ASo} - T_{ACOi})\}}{\ln\{(T_{ASi} - T_{ACOo})/(T_{ASo} - T_{ACOi})\}} \tag{4}$$

$$U = Q / \{\Delta T_{lm} \cdot A\} \tag{5}$$

where T_{ACOo} and T_{ACOi} are the bulk temperatures of the cooling water at the top and the bottom, respectively. T_{ASi} and T_{ASo} are equilibrium temperatures at absorber pressure for the inlet and the outlet solution, respectively. A and U are the area of a tube surface and overall heat transfer coefficient, respectively.

The heat transfer coefficient on the cooled side of a tube surface, h_o, can be obtained in the following.

$$Nu_{co} = \frac{h_o \cdot d_h}{\lambda} \tag{6}$$

where, $d_h = d_a - d_i$

$$Nu_1 = 3.66 + 1.2(d_i/d_a)^{-0.8} \tag{7}$$

$$Nu_2 = f_g[Re \cdot \mathrm{Pr} \cdot d_h/L]^{0.33} \tag{8}$$

where, $f_g = 1.615[1 + 0.14(d_i/d_a)^{-0.5}]$

$$Nu_3 = [2/(1+22\,\mathrm{Pr})]^{0.166}(Re \cdot \mathrm{Pr} \cdot d_h/L)^{0.5} \tag{9}$$

$$Nu_{co} = (Nu_1^{\ 3} + Nu_2^{\ 3} + Nu_3^{\ 3})^{0.33} \tag{10}$$

The heat transfer coefficient in the falling aqueous film along a vertical tube, h_i, is calculated by neglecting thermal resistances of the wall of a heat transfer area as equation (11). And, Nusselt number is defined as following equation (12).

$$h_i = 1/\ \{\ 1/U - d_i/(d_o \cdot h_o)\ \} \tag{11}$$

$$Nu = h_i \cdot L_s / \lambda \tag{12}$$

$$L_s = \{(\mu_s/\rho_s)^2/g\}^{0.33} \tag{13}$$

The film Reynolds number, Re_f, is defined as follows.

$$Re_f = 4 \cdot \Gamma_s/\mu_s \tag{14}$$

Mass transfer resistance of the refrigerant vapor in the absorption process is considered to exist only between the liquid-vapor interface and absorption solution, assuming the resistance between the liquid-vapor interface and the bulk vapor is negligibly small. Also, assuming the vapor pressure at the liquid-vapor interface is equal to the vapor pressure in the falling film, the LMCD, $\Delta\xi_{lm}$, is defined as Eq.(15) in terms of equilibrium concentration ξ^* and concentration ξ of falling film. On the basis of these assumptions, the mass transfer coefficient, β, is derived as Eq.(16).

$$\Delta\xi_{lm} = \frac{\{(\xi_{ASi}^{*} - \xi_{ASi}) - (\xi_{ASo}^{*} - \xi_{ASo})\}}{\ln\{(\xi_{ASi}^{*} - \xi_{ASi})/(\xi_{ASo}^{*} - \xi_{ASo})\}} \quad (15)$$

$$\beta = G_R / \{ \rho_m \cdot \Delta\xi_{lm} (\pi \cdot d_i \cdot L) \} \quad (16)$$

Here, G_R is the refrigerant vapor absorption rate and the equilibrium solution density, ρ_m is defined as

$$\rho_m = (\rho_{ASi} + \rho_{ASo}) / 2 \quad (17)$$

where, ρ_{Asi} is the solution concentration of the absorber inlet, and ρ_{Aso} is the solution concentration of the absorber outlet.

Sherwood number is defined as following equation (18).

$$Sh = \beta \cdot L_s / D_s \quad (18)$$

In the present experiment, Properties and datas of LiBr solution defined in McNeely[10] has been used.

4. Experimental results and discussion

Fig. 3 presents the heat balance at an evaporator and an absorber. In other words, the figure shows the ratio of equation 1 which is the latent heat of vapor per hour in an evaporator, and equation 3 the latent heat of condensation per hour in an absorber. From this figure it can be claim that the heat balance results agree within 20% approximately.

Fig. 4 presents the experimental results as a function of the film Reynolds number for a bare tube. Solution flow rate varies in the range of the film Reynolds number from 20 to 200. In this range, flow is characterized as laminar or wavy laminar. Experiments are done with two kinds of bare heat exchanger tubes with inner diameters 14.35 mm and 23.8 mm and length 1,419 mm. The figure shows that as the inner diameters of a heat exchanger tube increases from 14.35 mm to 23.8 mm, Nusselt number increases, too.

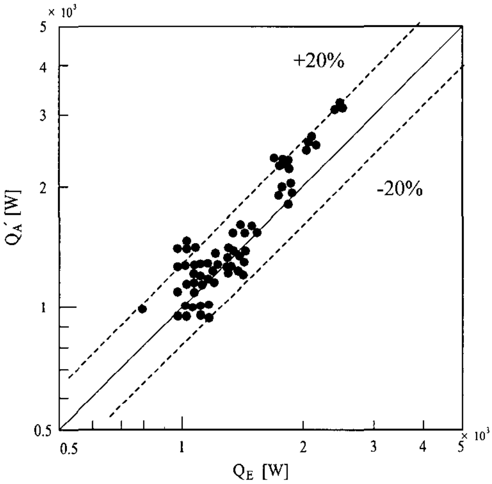


Fig. 3 Heat balance of the test section

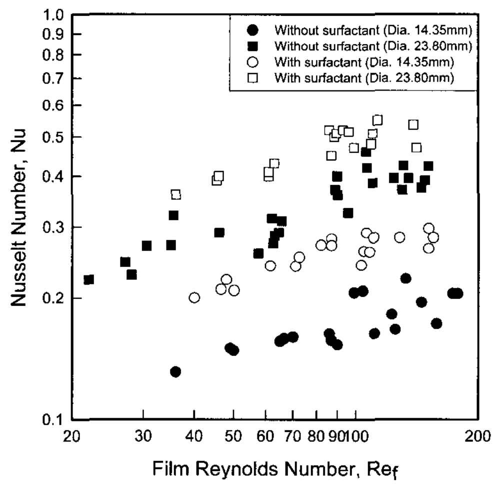


Fig. 4 Effect of film Reynolds number on the Nusselt number with bare tubes

The decrease of the film thickness by increasing the diameter and the pressure loss by the refrigerant vapor enhances the heat transfer. And at the small film Reynolds number, Nusselt number is small. This is due to the fact that the formation of liquid film was not well constructed. At the high film Reynolds number, the resistance of the heat transfer decreases Nusselt number. In this experiment, this situation did not occur to the film Reynolds number of 180. As the film Reynolds number increases above that figure, the film wave motion and the disturbance around the solution surface increase. Therefore, the absorption of the solution and the thermal movement is enhanced.

Nusselt number increases as the film Reynolds number increases irrespective of the addition of surfactant. This phenomena arises due to the sufficient liquid film near the surface caused by the increased film Reynolds number. As a result, the heat transfer rate is enhanced. With surfactant, the heat transfer rate is increased nearly by 30%~50%. This enhancement is due to the effects of Marangoni convention, which develops disturbance on the liquid film by decreasing the surface tension of the absorption solution when refrigerant vapor is absorbed. It may be mention here that there are some points in this figure look like outlier, this could have happened due to the experimental error and the experiment was done with a heat balance of 20%.

Mass transfer characteristics in bare tube is shown in Fig. 5. Even though it is different from the case of heat transfer characteristics, film Reynolds number increases regardless of inner diameter. Improvement rate of Sherwood number for bare tube after surfactant addition were maximum, the increase was approximately 45%.

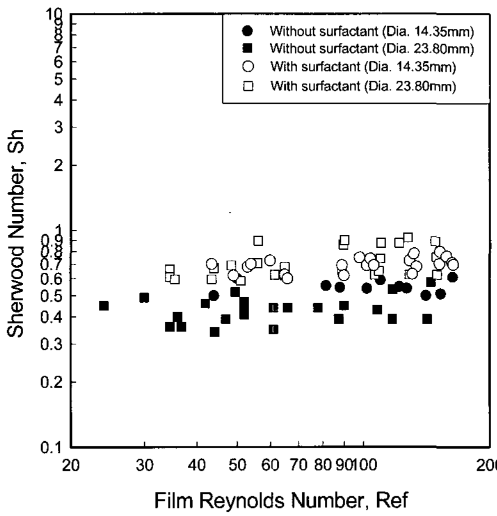


Fig. 5 Effect of film Reynolds number on the Sherwood number with bare tubes

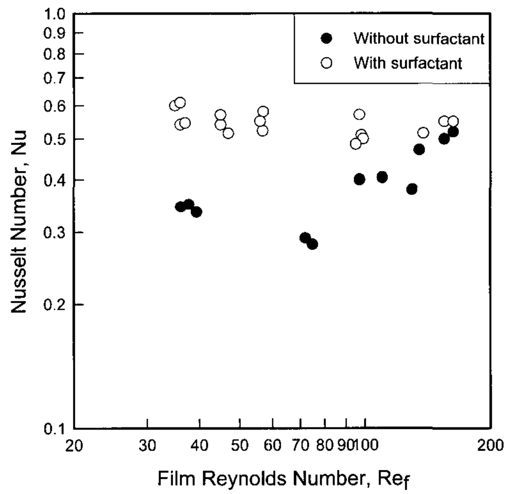


Fig. 6 Effect of film Reynolds number on the Nusselt number with insert spring tubes

Heat transfer of a spring inserted tube is shown in Fig. 6. The inner diameter of the insert tube is 14.35 mm and length is 1,419 mm. The pitch and the diameter of the spring is 10 mm and 1.0 mm, respectively. The heat transfer rate in a spring inserted tube is higher than that of a bare tube, especially in low solution flow rate. It results from the increased heat transfer area between the liquid film and the tube wall caused by easy formulation of the liquid film in enhanced tubes. The spring effects in the spring inserted tube drives the flow to turbulence. As the result, heat transfer rate of the spring inserted tube is 2.5 times higher than that of the bare tube. Without surfactant, the film Reynolds number decreases slightly down to a certain film Reynolds number, and beyond the corresponding Nusselt number, the film Reynolds number increases regardless of the tubes type. The critical film Reynolds number is approximately 110 for an insert spring tube. However, with surfactant the critical film Reynolds number does not exist. As a result, the film Reynolds number increases while the Nusselt number decreases. If the film Reynolds number increases below the critical film Reynolds number, the improvement rate of Nusselt number for a spring inserted tube increases. And above the critical film Reynolds number, Nusselt number decreases. Improvement rate of Nusselt number decreases as the film Reynolds number increases compared to a bare tube.

Mass transfer characteristics in insert spring tube is shown in Fig. 7. After the addition of surfactant, the mass transfer rate has improved dramatically. Sherwood number at the inner side of the spring tube is larger than that of bare tube and it decreases slightly with the increase of the film Reynolds number. Mass transfer characteristics found to be superior to bare tube that of the inserting spring.

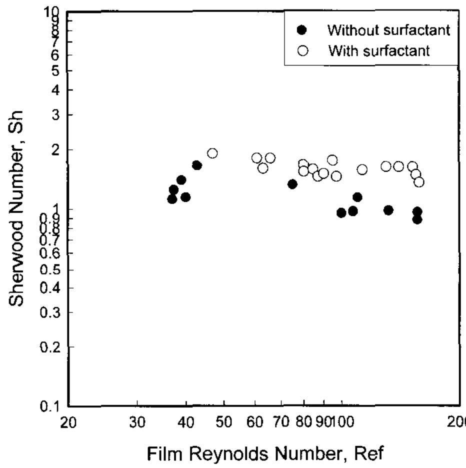


Fig. 7 Effect of film Reynolds number on the Sherwood number with insert spring tubes

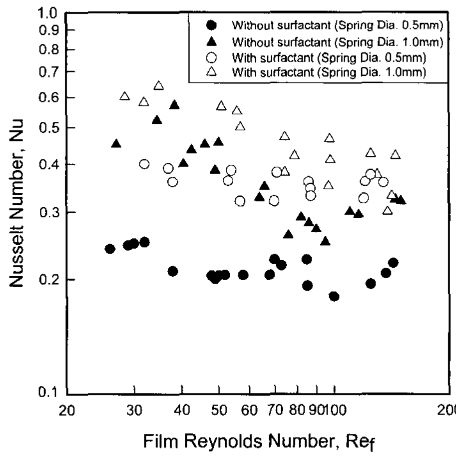


Fig. 8 Effect of film Reynolds number on the Nusselt number at different insert spring tubes.

Since a spring inserted tube showed the best heat transfer performance among various tubes, it is selected for further investigations. Fig. 8 shows the effects of the film Reynolds number on the Nusselt number for different diameters. The inner diameter of the tube is 17.6 mm, length is 1,119 mm, and pitch is 10mm. Two kinds of spring diameters, 0.5 mm and 1.0 mm, are used. In the case of surfactant addition, it is clear that there is acceleration effects of heat transfer regardless of diameters. In the case of spring diameter of 0.5 mm, heat transfer acceleration effect due to surfactant addition is better than that of spring having diameter 1.0 mm. Without surfactant, the disturbance of the falling film by a spring inserted tube is considered to be fully intense in the case of spring with diameter 1.0 mm. It is mainly due to the disturbance improvement effect brought about by the addition of surfactant. In the case of a diameter of 0.5 mm compared to that of a diameter of 1.0 mm, the disturbance effect of a falling film by a spring inserting is smaller, but with surfactant it increased remarkable.

Effect of film Reynolds number on the Sherwood number at different spring diameter has been shown in Fig. 9. Acceleration of mass transfer by surfactant addition is evident regardless of the spring diameters. Both heat transfer and mass transfer rates have been accelerated after surfactant addition and the results found in spring having diameter 0.1mm is higher than that having diameter 0.5mm. As film Reynolds number increases, Sherwood number decreases. The range of the decrease is larger at spring diameter 1.0mm than that of the spring diameter 0.5mm. But, Sherwood number of spring diameter 1.0mm is larger than spring diameter 0.5mm almost in the whole range film Reynolds number. Regardless of surfactant addition, when film Reynolds number is small, the influence of spring diameter to Sherwood number is large, and when film Reynolds number is large, it becomes progressively smaller.

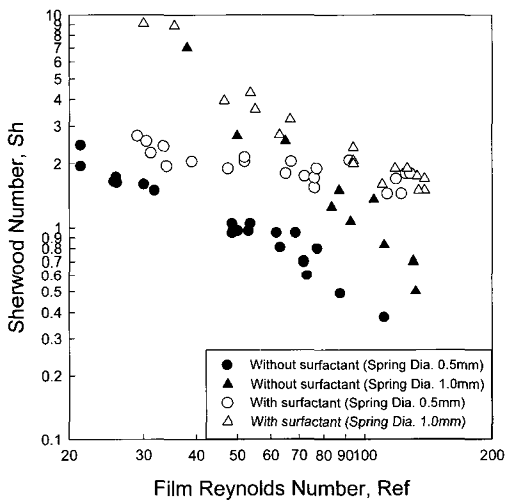


Fig. 9 Effect of film Reynolds number on the Sherwood number at different insert spring tubes.

5. Conclusion

This study provides basic data on absorption of aqueous lithium bromide falling films of vertical tubes. Testing was completed with a smooth tube and absorption tubes for lithium bromide with concentration of 60 wt%. The heat and mass transfer coefficient were measured as a function of the film Reynolds number from 20~200. The result could be summarize as follows:

(1) Heat transfer rate increases when the diameter of a bare tube increased. As the film Reynolds number increases, the Nusselt number increases in the entire range of Reynolds number with surfactant or without surfactant for a bare tube. With surfactant, the heat transfer rate increased significantly.

(2) Without surfactant, the film Reynolds number decreases slightly down to a certain film Reynolds number, and beyound the corresponding Nusselt number, film Reynolds number increases regardless of the kinds of tubes. However, with surfactant, the critical film Reynolds number does not exist. As the film Reynolds number increases Nusselt number decreases.

(3) The heat transfer rate of the spring-inserted tube is 2.5 times higher than that of the bare tube.

(4) In case of the spring having diameter of 1.0 mm, the heat and the mass transfer rates with surfactant are higher than that of the spring with a diameter of 0.5 mm.

Acknowledgement

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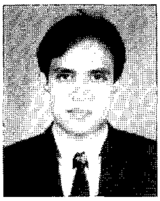

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