International Journal of Air-Conditioning and Refrigertaion Vol. 8 No. 2 (2000) / pp. 1~10

Heat Transfer Performance of Various Tubes for an Air-cooled Absorber with Surfactant

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

Abstract

This research is 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 tube, a groove tube, a corrugated tube and a spring-inserted tube. The additive concentration is about 0.08 mass%. The heat transfer coefficient is measured as a function of the film Reynolds number in the range of 20~200. Experiments are 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 with and without surfactant are compared. The enhancement of heat transfer by Marangoni convection effect which is generated by addition of the surfactant is observed in each test tube. Especially, it is clarified that the tube with an spring-inserted has the highest enhancement effect.

Nomenclature

A : Heat transfer area [m²]

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/ s²]

G : Mass flow rate [kg/s]

G_R : Absorption rate of a refrigerant vapor [kg/s]

h : Heat transfer coefficient [W/m² · K]

U : Overall heat transfer coefficient

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[W/m² · K]

L : Tube length of an absorber [m]

L_s : Characteristic length of an absorption solution [m]

Nu : Nusselt number

P : Pressure [mmHg]

Pr : Prandtl number

Q : Heat transfer rate [W]

Re : Reynolds number

Re_f : Film Reynolds number

T : Temperature [℃]

ΔT_{lm} : Log mean temperature difference [℃]

Greek symbols

λ : Thermal conductivity [W/m · K]

ρ : Density [kg/m³]

μ : Viscosity [Pa · s]

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

s : Absorption solution

1. Introduction

Recently the electric load during the summer has been increasing rapidly. Thus, the cooling system, which is not using an electric power, has on demand of development. One of these demands can be met by the use of an absorption chiller/ heater. Now, only the large capacity of a water-cooled absorption chiller/heater has been used. Large capacity, which is over 50 RT capacities using working fluid of H_2O/LiBr, is mainly produced as commercial purpose. However, a small sized air-cooled absorption chiller/heater is not developed yet. Many researches have actively focused on the high efficiency of the air-cooled absorption machine on these days. While a water-cooled absorption heater/ chiller takes a falling film type with horizontal tubes, an air-cooled type absorber uses falling film type absorber with vertical tubes.

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 absorber with a spring-inserted tube. They focused on the sizes of inner diameters, the lengths of a heat transfer tube and the shapes of an inner tube. Also Yoon et al.[2] examined a vertical absorber changing diameters, inner surface geometries, and velocities of absorption solutions. Kim et al.[3] obtained experimental data on falling Water/LiBr films in the inner surfaces of vertical tubes. They found the effects of non-absorbable gas in absorption process. Kim et al.[4] also obtained data on the effects of the pressure and temperature of the solution with the range of the film Reynolds number from 30 to 200. They found that the absorption rate has the maximum value when the film Reynolds number is 130. Eum et al.[5,6] examined vapor absorption in the vertical tube when the solution is in the sub-cooled and superheated state proposing the empirical correlations of heat transfer and mass transfer when film Reynolds number varies from 35 to 130. Furthermore, Cho et al.[7] performed an experiment to examine the characteristics of heat and mass transfer for a vertical absorber.

They used $LiBr - CaCl_2$ solution (mole ratio $LiBr : CaCl_2 = 2{:}1$) as an absorbent. Even though this absorbent has a lower heat transfer performance than LiBr solution, high melting point of this solution decreases the danger of crystallization. Kim et al.[8] did a numerical computation for the air-cooled absorption process of refrigerant vapor using LiBr solution. Kim et al.[9] 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. Researcher[10,11] performed experiments on the vertical tubes for air-cooled and enhanced heat transfer applications. However, on the whole, fundamental phenomena are not well understood. Especially, the study on the vertical absorber with enhanced tubes is not complete and a study on the surfactant to enhanced tubes is not reported[12]. Also, the understanding on the 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 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 solutions. The inner diameters and surface configurations of heat exchanger tubes are varied to search the physical backgrounds of absorption process. The working fluids for the absorption experiment are lithium bromide and water. Lithium bromide is an absorbent and water is an absorbate. Aqueous solution of lithium bromide flows along vertical tubes with absorption of water vapor. As latent heat of vaporization and solution is transferred to the cooling water for continuous absorption of the solution. The surfactant in this study is n-octanol (see Table 1). The concentration of the surfactant is approximately 0.08 mass%.

The experimental equipment used in this study is shown in Figure 1. Test apparatus with batch mode operation is designed to test vertical absorbers. The absorbent flows down inside of the tubes. The absorption of water vapor takes place at the inner wetted surfaces of the tubes, and the heat of absorption is removed by the upward flow of cooling water at the annular gap between the inner and outer tubes. A tank is connected to a heat exchanger with pipes and well insulated. And, all major components are constructed with stainless steel. Tubes of an absorber used for this experiment are a bare tube, a spring-inserted tube, a corrugated tube, and a grooved tube. Specifications of absorber tubes are shown in Table 2. The experiment is carried out with a commercial sized machine. It is also carried out with bare tubes of inner diameters, 14.35 mm and 23.80 mm, to predict the effect of inner diameters. 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, a corrugated tube, a grooved tubes and a spring-inserted tube, inner diameter 14.35 mm was experimented. A spring-inserted tube is consisted of inner diameter of 17.6 mm, and is made up pitch of 1.0 mm. A spring diameter has two cases of 1.0 mm, and

Table 1 Property of surfactant

Molecule name	n-octanol (octil alcohol)
Molecule equation	$C_8H_{17}OH$
Characteristics	Molecular weight : 130.23 Colorless solution Boiling range: 190～198℃ Fusing point: -16.7℃ Flash point: 81℃

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. The surface tension of LiBr solution with surfactant decreases remarkably at the saturated concentration. If the surfactant exceeds saturated concentration, n-octanol exists at solution surface in a drop condition. The saturation solubility of LiBr solution of 60 wt% (50℃) is approximately 0.01 mass%. The experimental conditions for the absorber temperature, the pressure, the concentration and the flow rate are summarized in Table 3. The solution concentration and pressure responding to saturation temperature of refrigerant vapor decide the solution temperature at the absorber inlet. The

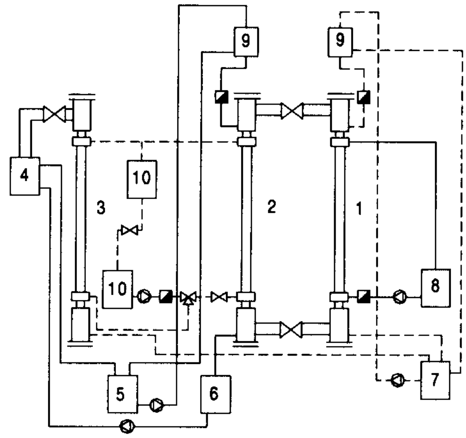

Fig. 1 Schematic diagram of experimental apparatus.

Table 2 Specification of test tubes

Test tube	Diameter	Length	Configurations	
Bare	14.35 [mm]	1,419 [mm]		Smooth Surface
	23.80 [mm]	1,419 [mm]		Smooth Surface
Grooved	14.35 [mm]	1,419 [mm]		Helix angle 18°, 80 Grooves
Corrugated	14.35 [mm]	1,419 [mm]		Pitch 10 [mm], Depth 1.0 [mm]
Inserted 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]

solution flow rate into an 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 at 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. After the experiment for absorption process initiates, inlet temperatures of the absorption solution are adjusted to be an equilibrium temperature in the tank.

3. Calculation of heat transfer coefficient

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

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

Table 3 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%]

The heat transfer rate of a coolant in absorption process can be estimated with the mass flow rate and temperature difference of a coolant between the inlet and outlet of an absorber such 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 difference of the latent heat of evaporation and condensation is very small, so it is neglected.

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

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

From the latent heat of vapor in an evaporator (Eq. 1) and the latent heat of condensation in an absorber (Eq. 3), the 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

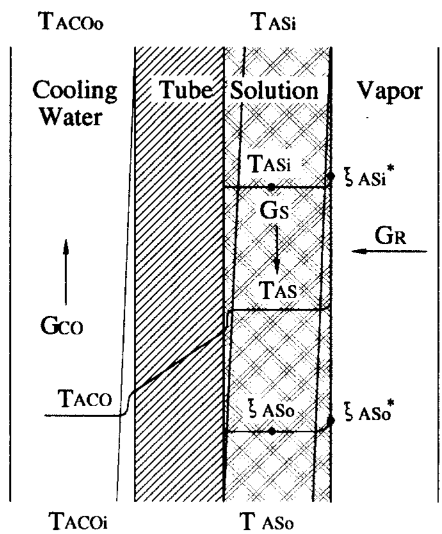

Fig. 2 Physical model of falling film absorption.

by the following equation 5.

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

$$U = Q/\{\Delta T_{lm}\cdot A\} \quad (5)$$

where T_{ACOo} and T_{ACOi} are the bulk temperatures of the cooling water at the top and bottom, respectively. T_{ASi} and T_{ASo} are equilibrium temperatures at absorber pressure for the inlet and 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.

$$Nu_{co}=\frac{h_o\cdot d_h}{\lambda} \quad (6)$$

where $d_h=d_a-d_i$

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

$$Nu_2=f_g[Re\cdot \Pr\cdot d_h/L]^{1/3} \quad (8)$$

$$f_g=1.615[1+0.14(d_i/d_a)^{-1/2}]$$

$$Nu_3=[2/(1+22\Pr)]^{1/6}(Re\cdot \Pr\cdot d_h/L)^{1/2} \quad (9)$$

$$Nu_{co}=(Nu_1{}^3+Nu_2{}^3+Nu_3{}^3)^{1/3} \quad (10)$$

The heat transfer coefficient in a 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 a following equation (12).

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

$$Nu = h_i\cdot L_s/\lambda \quad (12)$$

$$L_s=\{(\mu_s/\rho_s)^2/g\}^{1/3} \quad (13)$$

The film Reynolds number, R_{ef}, is defined as follows.

$$Re_f=4\cdot \Gamma_s/\mu_s \quad (14)$$

Properties of LiBr solution for the present experiment is used the data of McNeely[(13)].

4. Experimental results and discussion

Figure 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. For comparing the heat balance, the results between equation 1 and equation 3 agree within 20% approximately.

Figure 4 presents the experimental results as a function of the film Reynolds number with 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 with 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, the Nusselt number increases.

The decrease of the film thickness by increasing the diameter and the pressure loss by the refrigerant vapor enhance the heat transfer. And at the low film Reynolds number, the Nusselt number is low. This is for the reason that the formation of a liquid film is not well constructed. At the high film Reynolds number, the resistance of the heat transfer decreases the Nusselt number.[14] In this experiment, this situation did not occur to the film Reynolds number of 180. As the film Reynolds number increases over that number, the film wave motion and the disturbance around the solution surface increase. Therefore, the absorption of the solution and the thermal movement are enhanced.

Nusselt number increases as the film Reynolds number increases irrespective of the addition of surfactant. This phenomena dues 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 enhanced about 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.

Heat transfer of a grooved tube, a corrugated tube and a spring-inserted tube is shown in Figs. 5~7. An inner diameter of a tube is 14.35 mm and a length is 1,419 mm. A pitch and a diameter of a spring is 10 mm and 1.0 mm, respectively. The heat transfer rate in all three kinds of enhanced tubes is higher than that of a bear tube, especially in low solution flow rate. It results from the increased heat transfer area between the liquid film and tube wall caused by easy formulation of the liquid film in enhanced tubes. The spring effects in a spring-inserted tube cause the flow to turbulence. As a result, it makes a spring-inserted tube have 2.5 times higher value than a bare tube. Without surfactant, the film Reynolds number decreases slightly down to a certain film Reynolds number, and beyond the number, the film Reynolds number increases regardless of the various tubes. The critical film Reynolds numbers are approximately 70, 80, and 110 for a grooved tube, a corrugated tube, and a spring-insert tube, respectively. 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 in-

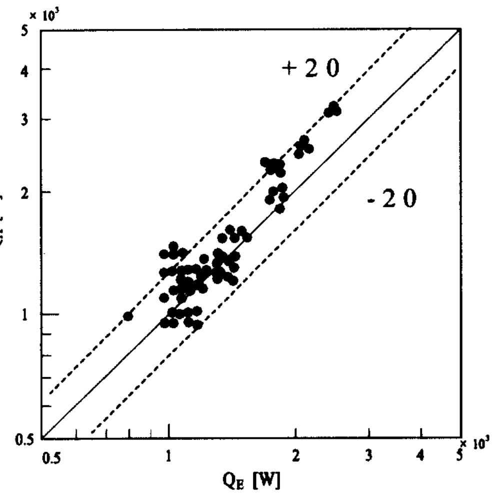

Fig. 3 Heat balance of the test section.

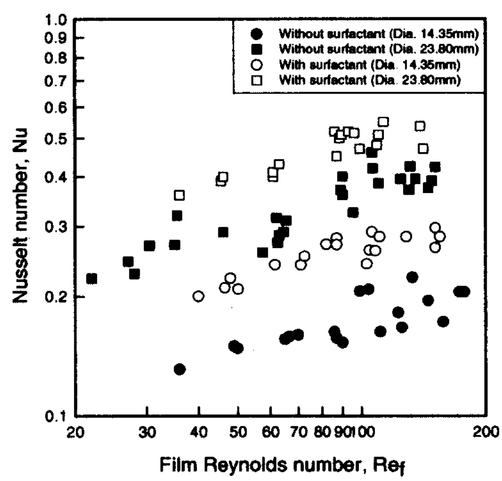

Fig. 4 Effect of film Reynolds number on the Nusselt number with bare tube.

creases below the critical film Reynolds number, the improvement rate of Nusselt number of various kinds of absorption tubes 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. Since a spring-inserted tube shows the greatest heat transfer performance among various tubes, it is selected for further investigations. Figure 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, a length is 1,119 mm, and pitch is 10 mm. 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 effects of heat transfer enhancement regardless of diameters. In the case of spring diameter 0.5 mm, the heat transfer effect of surfactant addition is larger than that of spring 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 diameter 1.0 mm. It is mainly due to the disturbance improvement effect by 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

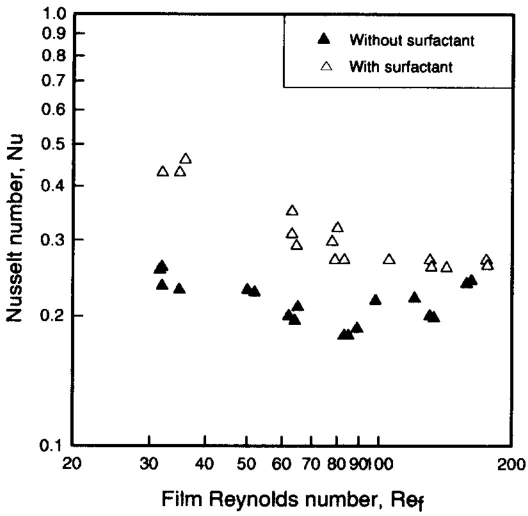

Fig. 5 Effect of film Reynolds number on the Nusselt number with grooved tube.

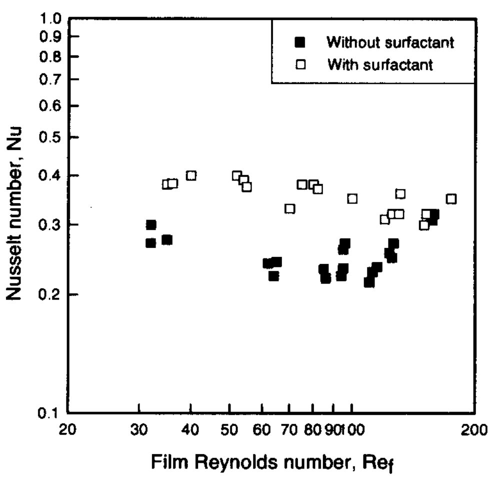

Fig. 6 Effect of film Reynolds number on the Nusselt number with corrugated tube.

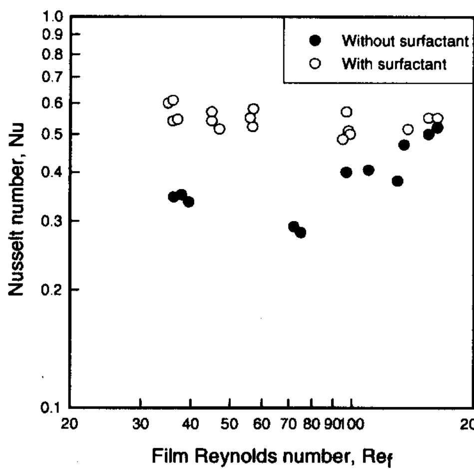

Fig. 7 Effect of film Reynolds number on the Nusselt number with spring-inserted tubes.

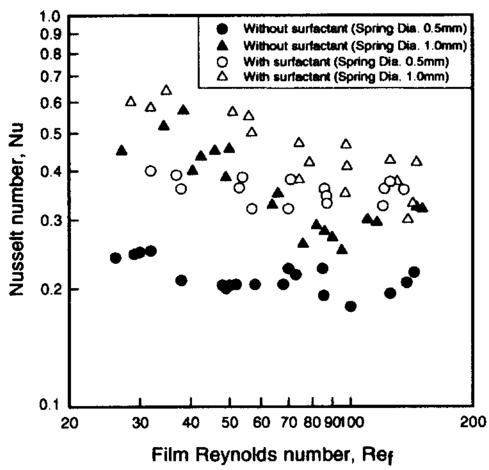

Fig. 8 Effect of film Reynolds number on the Nusselt number at different spring-insert tubes.

effect of a falling film by a spring-inserting is small, but with surfactant it greatly increases.

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 concentration of 60 wt%. The heat transfer coefficient were measured as a function of the film Reynolds number of 20~200.

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

(2) Without surfactant, the film Reynolds number decreases slightly down to a certain film Reynolds number, and beyond that number the Nusselt 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 enhanced tubes with surfactant and without surfactant increase the heat transfer rate in the order of a spring-inserted tube, a corrugated tube, a grooved tube, and a bare tube. The heat transfer rate of a spring-inserted tube is 2.5 times higher than that of a bare tube.

(4) In the case of a spring diameter of 1.0 mm, a heat transfer effect with surfactant is larger than that of a spring diameter of 0.5 mm.

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