Absorption of Water Vapor into a Film of Aqueous Solution of LiBr Falling along a Vertical Pipe*

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The heat transfer surface used in the experiments is a chrome-plated smooth brass pipe of 28 mm diameter and 1 400 mm length. The film Reynolds numbers are varied in the range of 40–400, which includes the range of real machines. The average absorptions mass flux is compared with the numerical results derived from the laminar flow model proposed in the previous paper. The agreement is good up to 100 in Re_f , but the experimental values are far higher above 200. This may be attributed to the wave motions on the film surface. Pictures show that the film is completely smooth only at Re_f below 20. Beyond 20, ring-shaped waves appear, but the surfaces between the waves are relatively smooth at Re_f below 200. The measurements of the film thickness show that its minimum is constant at about 0.38 mm, but its maximum thickness increases for Re_f larger than 60.

Key Words: Absorption Refrigeration, Mass Transfer, Heat Transfer, Absorption Mass Flux, Falling Film, Film Thickness

1. Introduction

Many investigations have been conducted so far^{(1)–(5)} on improvement of the performance of the absorber of an absorption chiller or absorption heat pump. In the absorber, refrigerant vapor coming from the evaporator is absorbed by the absorbent liquid with which the cooling surfaces are irrigated. There are various configurations for these surfaces. At present, horizontal tube bundles are most commonly used in the water-cooled absorber. Vertical pipes are used in the new air-cooled absorber, where air flows outside and the refrigerant flows inside. Vertical pipes are also used in industrial heat pumps for waste heat recovery to save installation space; here absorbent flows outside of the pipes. As such, there are many types of flow, but even in the vertical pipe case, the mass transfer coefficient and heat transfer coefficient are not yet fully established. In this paper, the absorption process of the vertical pipes is studied.

In the previous papers^{(6),(7)}, analysis of the falling film along the vertical wall was conducted and experiments were carried out at a small flow rate. They agreed with each other to some extent. In the analysis, the falling film was assumed to be laminar and have no waves on the surface. But actually, the ideal flow is not realized at the higher flow rate. In actual machines, a small flow rate is desirable so as to make the energy necessary for pumping as small as possible. Hence most of the machines are driven at a flow rate which does not correspond to the laminar nor fully turbulent regime. However, most studies concerning falling films belong to the turbulent flow range, and transient film studies are rare. In this paper the absorption mass flux of steam was measured in the flow rate range used in real machines, and the heat and mass transfer coefficients were also obtained. To obtain knowledge of the film flow, photos were taken and the film thickness was measured.

Nomenclature

Re_f : Film Reynolds number ($Re_f = 4\Gamma/\mu$)
 $\dot{m}$: Average absorption mass flux $\text{kg}/(\text{m}^2 \cdot \text{s})$
 α : Heat transfer coefficient $\text{W}/(\text{m}^2 \cdot \text{K})$

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β : Mass transfer coefficient m/s
 Γ : Mass flow rate of film kg/(m·s)
 μ : Viscosity Pa·s

2. Experimental Setup

Figure 1 shows a schematic diagram of the experimental setup. The system for performing steady-state-type experiments consists of two parts. One is a steam generator which recovers concentration and also generates vapor to be absorbed, and the other is a vessel where the steam is absorbed. The vessel ① is a steam generator, where solution coming from the absorber ② is heated by a heater ③ and flashed for vaporization in ①. The generated steam is passed through baffle plates to eliminate droplets. The enriched solution is directed to the top of the absorber by a gear pump at a constant flow rate, and then it flows down a vertical pipe ④. The falling film is cooled from inside by water. Heat exchangers ⑤ and ⑥ control inlet temperatures of the absorbent and the cooling water, respectively. Flow rates of steam, absorbent and cooling water are measured by rotor meters ⑦-⑨. The concentration of lithium bromide solution entering the absorber is determined from its density, since the density of liquid mixture is a function of composition at a given temperature. The density is measured by a float-type meter. The pressure in the absorber is measured by a manometer which employs dibutyl phthalate as the indicator oil. To make the absorption at the bottom of the pipe as small as possible, the opening area of the liquid receiver is minimized. The absorber pipe consists of smooth brass pipe of O. D. 28 mm and I. D. 20 mm and 1 400 mm effective length. It is chrome plated to prevent

Fig. 1 Experimental setup

rusting. In order to ensure circumferentially uniform flow, a uniform slit is formed, as shown in Fig. 2. Four stainless steel wires are placed between the pipe and the liquid reservoir, which are machined to be parallel with each other. The flow rate of the liquid is determined by the liquid depth and the flow resistance at the slit. The wire diameters are selected between 0.2-0.7 mm, depending on the flow rate.

3. Experimental Results

Experiments are carried out under conditions as near as possible to those of real machines. The inlet conditions of the LiBr solution are kept at a constant concentration of 59 mass% and constant temperature of 38°C. Mass flow rate, cooling water temperature and pressure in the absorber are varied as parameters.

Figure 3 shows the average mass absorption flux $\dot{m}$, which is the total absorption rate divided by the surface area of the pipe. Figures correspond to the cooling water temperatures 26, 30 and 34°C, respectively, from left to right. The horizontal axis is film Reynolds number, which is a nondimensionalized film flow rate. At each temperature of the cooling water, pressures are set at 667 Pa or 933 Pa. Heat input to the generator is regulated to keep the vessel pressure within 13 Pa of the target value. The solid lines in Fig. 3 show the numerical results obtained by the laminar flow model analysis proposed in the previous paper. In the calculations, the boundary condition of the energy equation at the wall is considered to be that the overall coefficient between cooling water and wall surface is known. The heat transfer coefficient of the cooling water is calculated by the Dittus-Boelter's equation. As a whole, experimental plots of absorption mass flux $\dot{m}$ are shifted downwards as the cooling water temperature rises. Analytical results show trends similar to those of experiment. The absorption mass flux is greatly influenced by the small change in pressure from 667 Pa to 933 Pa. It increases considerably with the increase of pressure. Numerical results show about the same increase. Hence, numerical results predict the influence of cooling water and system

Fig. 2 Liquid outlet

Fig. 3 Average absorption mass flux

pressure qualitatively. As for the influence of the flow rate at the cooling water temperature of 26°C, the experimental absorption mass flux increases with Re_f till 200 and then decreases, but the calculated value shows its peak at Re_f of 60. At Re_f larger than 200, the experimental value exceeds the calculated value considerably. Also, at a cooling water temperature of 30°C, the experimental value tends to increase with Re_f till 200 but the calculated value begins to decrease at 70. At 34°C of cooling water, the calculated value decreases slowly with Re_f beyond 60 at 667 Pa, and it is almost constant for Re_f larger than 100 at 933 Pa. The experimental value increases till 200 and then levels off. Thus, at all the cooling water temperatures, the experimental values are lower than the calculated values at Re_f smaller than 100, but exceed them considerably at Re_f beyond 100.

Figure 4 shows the heat transfer coefficient between the falling film and the heat transfer surface at cooling water temperatures of 26, 30 and 34°C from the top. The heat transfer coefficient is calculated from the overall heat transfer coefficient which is obtained from the heat received by the cooling water and the logarithmic mean temperature difference of the bulk of cooling water and the liquid film. The solid lines in Fig. 4 are the results of numerical solution. They have weak dependence on Re_f and their values lie between 1 000–2 200 W/(m²·K), but the experimental values show more variation with Re_f and lie between 1 500–3 000 W/(m²·K). The broken lines in the same figures are the Nusselt's equation for the local heat transfer coefficient of filmwise condensation. They are calculated using the properties of LiBr solution as those of film, and the driving temperature difference is defined as the temperature difference of the bulk mean of the film and wall. These lines slope down on the right at almost the same angles as for the experiment. The one-dot chain lines are the coefficients between the film and the wall when the falling film does not permit absorption or evaporation

Fig. 4 Heat transfer coefficient

from the surface; namely the film is adiabatic at the surface. These are the heat transfer coefficients obtained when heat contained in the film at the inlet as sensible heat is removed. They are obtained by solving

the following differential equation.

$$u \frac{\partial T}{\partial x} + v \frac{\partial T}{\partial y} = a \left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} \right) \quad (1)$$

The coordinate axes are taken as x along the flow and y vertical to it. Boundary conditions are

$$x=0 \quad T=T_0 \quad (2)$$

$$y=0 \quad \lambda \frac{\partial T}{\partial y} = K(T - T_w) \quad (3)$$

$$y=\delta \quad \frac{\partial T}{\partial y} = 0, \quad (4)$$

where a and λ are the thermal diffusivity and thermal conductivity of the liquid, and K is the overall heat transfer coefficient between the wall surface and the cooling water. Velocities used in the equation are determined by the Nusselt's equation for a laminar falling film. The properties of LiBr solution are used in the calculations. The coefficients increase with Re_f till 200. At lower flow rate, the heat transfer is completed by the time it flows down a relatively short length from the inlet and the heat transfer coefficient is decreased. For Re_f over 200, the heat content is large enough to allow large heat transfer after flowing down the same length. Therefore, the heat transfer coefficient becomes maximum at about 200 and then decreases with flow rate. The heat transfer for the steam absorption into the LiBr film may have the characteristics of both sensible heat transfer and latent heat transfer. It approaches the condensation curve at a lower flow rate since the sensible heat transfer is finished very quickly. At larger flow rate, it approaches the adiabatic falling film curve since the sensible heat occupies a larger fraction of the transferred heat.

Figure 5 shows mass transfer coefficient β at 933 Pa (7 mmHg). The driving concentration difference is defined as the logarithmic mean of the difference of bulk mean concentration and the equilibrium concentration corresponding to the bulk mean temperatures at the inlet and the outlet. At 667 Pa, the liquid is in a superheated condition at the inlet, and a mass transfer coefficient cannot be defined since evaporation takes place for some length from the inlet. The solid lines in

Fig. 5 Mass transfer coefficient

Fig. 5 are numerical results obtained by the laminar model. They show that β increases with the lowering of cooling water temperature and tends to decrease slightly with flow rate. As the experimental values do not show much dependence on water temperature, they are not classified in the plot. They are about 4×10^{-5} m/s and increase slightly with flow rate.

4. Waves on the Film Surface

In Fig. 3, it is shown that the experimental value of $\dot{m}$ agree with the theoretical results based on the laminar flow model in the lower flow rate range but exceed them considerably in the higher range. This increase may be due to the waves on the surface of the falling film. There are, however, very few papers which deal with the wave motions in these flow rate ranges. Therefore, photos are first taken of the falling films. Since it was impossible to photograph them through the window of the apparatus due to insufficient light, the vertical pipe was taken out of the absorber. The obtained pictures are shown in Fig. 6. To the naked eye, it seems that the flow does not change whether the pressure is atmospheric or vacuum except at a high absorption rate, where the film near the outlet of the steam is disturbed by the steam flow. The pictures are taken at the angle of 40° from the pipe axis to stress the shadows of the waves, because they are not clearly seen from the front. As the pipe surface is almost mirrorlike due to the nickel plating, the pipe is surrounded by white paper to eliminate the reflections of the things surrounding it, which make it difficult to distinguish waves. The positions of the pictures are about 200–300 mm from the outlet of the liquid. The shutter speed is 1/500 s at Re_f of 203 or less and 1/1 000 s above. At Re_f of 15, the surface is perfectly smooth. At Re_f of 20, ring-shaped waves begin to appear regularly at 200 mm from the inlet. At Re_f of 41, the rings become clearer but they collapse into irregular waves as they flow down. At 61, smaller rings appear in front of the big rings. These waves also collapse as they flow down, but the combination of large and smaller waves persists after collapse. The intervals between the waves grow wider as they flow down. At 142, waves with a check pattern begin to appear where those rings cross other rings. The surface between the rings is smooth at the flow rate. At 203, major disturbances are seen there. At 406, the speed of the waves becomes higher and the waveforms are distorted, but the large waves are still accompanied by many smaller foregoing waves. At 812, the distortion of the surface is increased and the forms are quite different from those at 406. These pictures show that only at $Re_f=15$ is the flow laminar, and at larger Re_f the influence of the

Fig. 6 Pictures of falling films

Fig. 7 Measurements of film thickness

waves must be taken into consideration in the modeling of the absorption process.

Secondly, film thickness δ is measured for the falling film of LiBr solution. A contact needle probe is set at 850 mm from the outlet in the apparatus shown in Fig. 1. The distribution curve of the film existence probability, which is the fraction of time that the liquid film exists at the height of the needle, is determined by the probe. The measurement was done without absorption of steam at a pressure of 270 Pa. From the obtained probability curves, the average film thickness is defined as the height where the probability is 0.5. Also the maximum thickness is defined as the height for 1% probability and the maximum thickness for 99%. The measured results are shown in Fig. 7 against Re_f . In Fig. 7, circles denote average thickness, and a solid line is the Nusselt's equation. Average thickness is very near the Nusselt's value. At $Re_f=43$, the thickness does not vary much, but it tends to vary with increase of Re_f . At Re_f larger than 80, the minimum thickness is almost constant at 0.38 mm, but the maximum thick-

ness increases with Re_f . As the flow rate increases, the amplitude of film variation becomes larger and almost equal to the average thickness. A relatively smooth laminar flow is observed only up to 40 in Re_f and the flow becomes disturbed at the surface at larger Re_f .

5. Conclusions

Experiments on steam absorption were conducted for films flowing down a vertical pipe in the Re_f range of 40–400. The results obtained are summarized as follows.

(1) The value of $\dot{m}$ is considerably greater than the theoretical values based on the laminar flow model at Re_f larger than 100.

(2) The heat transfer coefficients of the film are between 1 500 and 3 000 W/(m²·K) and their variation with flow rate is very similar to that of filmwise condensation.

(3) The mass transfer coefficient is about 4×10^{-5} m/s, and it tends to increase slightly with flow rate.

(4) The waves appearing on the falling film surface look like rings accompanied by preceding smaller rings, and the rings are deformed as they flow down.

(5) According to the photos of the flows, the surface between the rings is fairly smooth at Re_f smaller than 142.

(6) The average film thickness is very close to the laminar film thickness of Nusselt.

(7) At $Re_f=60$, the film thickness begins to vary, but the minimum thickness is almost constant at about 0.38 mm. The maximum thickness increases. These variations may be the cause of the increase of absorption rate over the theoretical predictions.

References

- (1) Kohno, K., Sugimoto, S., Oouti, T., Kurosawa, M.,

- Kannow, S. and Takemoto, S., Study on Absorber with Vertical Tubes, Proceedings of 24th National Heat Transfer Symposium of Japan (in Japanese), p. 495.
- (2) Inoue, N., Performance of Absorber for Absorption Refrigeration Machine, Proceedings of 24th National Heat Transfer Symposium of Japan (in Japanese), p. 498.
 - (3) Kashiwagi, T. and Okajima, J., Mass Diffusion in the Process of Ammonia Vapor Absorption in NH_3 - H_2O -LiBr Ternary System, Proceedings of 24th National Heat Transfer Symposium of Japan (in Japanese), p. 501.
 - (4) Nagaoka, Y., Nishiyama, N., Ajisaka, K., Sawada, A., and Tadaki, T., Study on Heat Transfer Tubes for an Absorber of the Absorption Refrigerator (1st Report; The Evaluation for Heat Transfer Tubes), Proceedings of 24th National Heat Transfer Symposium of Japan (in Japanese), p. 504.
 - (5) Nagaoka, Y., Nishiyama, N., Ajisaka, K., Kawamata, O. and Tadaki, T., Study on Heat Transfer Tubes for an Absorber of the Absorption Refrigerator (2nd Report; The Absorption Characteristics of Various Heat Transfer Tubes), Proceedings of 24th National Heat Transfer Symposium of Japan (in Japanese), p. 507.
 - (6) Urakawa, K., Morioka, I. and Kiyota, M., Absorption of Water Vapor into Lithium Bromide-Water Solution Film Falling along a Vertical Plate, Trans. Jpn. Soc. Mech. Eng., (in Japanese) Vol. 52, No. 476, B (1986), p. 1766.
 - (7) Morioka, I. and Kiyota, M., Absorption Experiments of Water Vapor into a Lithium Bromide Water Solution Film Falling along a Vertical Plate, Trans. Jpn. Soc. Mech. Eng., (in Japanese) Vol. 53, No. 485, B (1987), p. 236.
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