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Fluid flow and heat transfer on a falling liquid film with surfactant from a heated vertical surface

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Abstract

The addition of surface active agent to a falling liquid film affects the flow characteristics of the falling film. In this study, the flow and heat transfer characteristics for a falling liquid film have been investigated by addition of the surfactant. The falling liquid film was formed on a vertical flat plate. Contact angle of a liquid droplet above a plate surface can be substantially reduced with an increase in the surfactant concentration. The results obtained indicate that not only the wetted area of falling liquid film is increased but also the film thickness is decreased as the surfactant concentration is increased. It is also found that heat transfer rate is significantly increased while the heat transfer coefficient is almost constant value with an increase in the surfactant concentration at a given mass flow rate.

Keywords: Falling film; Surfactant solution; Heat transfer rate; Contact angle

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1. Introduction

Falling liquid film plays a role in a wide variety of naturally occurring phenomena as well as in the operation of industrial process equipment where heat and mass transfer take place. Heat and mass transfer from or to the falling liquid film can be found in various applications, such as evaporative coolers, cooling towers, and absorption chillers, etc. In such cases, it is required that the falling film spreads widely on the surface forming thin liquid film to enlarge contact surface and to reduce the thermal resistance across the film and/or the flow resistance to the air stream flowing over the film [1, 2].

The flow pattern of the falling liquid film over the vertical surface develops in various ways according to the liquid flow rate, the surface tension of the liquid and the contact angle between the surface and the liquid droplet. Even though the surface wettedness can be increased simply by increasing the liquid flow rate, it is usually undesirable because it causes unwanted increases in the circulation energy consumption and the thickness of the falling liquid film [3].

In this respect, a significant effort has been devoted to developing adequate techniques to increase the surface wettedness to enhanocement of the heat and mass transfer from a falling film over many years. Drosos et al.[4] investigated the developing characteristics of a falling film in a vertical rectangular channel with smooth inlet condition. Wang et al. [5] studied the effects of the surface wettability on the cooling performance of an indirect evaporative cooling system. Kim and Kang [6] employed hydrophilic surface treatment and noticed an increase in the evaporation heat transfer from the horizontal tube bundles simulating the evaporator of an absorption chiller.

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The effect of the addition of surfactant on a falling liquid film was investigated experimentally and theoretically by Pierson and Whitaker[7]. They showed that the wave formation can be controlled by small amounts of surfactant addition. Ji[8] studied the effects of a surfactant on the linear stability of falling liquid films. Chang[9] and Ambrosini[10] has also derived analytical expressions relating film thickness and wave velocity with liquid pro-perties. Experiments have shown that the addition of wetting agents reduces the rippling in the falling film by Emmert and Pigford[11]. Nordgen and Stterwall[12] showed that surfactant concentrations under the saturation limit stabilize the falling film when surfactant is added to a falling film and surfactant concentration play a important roll in formation of falling film. And also, Zheng and Worek[13] studied a method of heat and mass transfer enhancement in film evaporation and evaporation of a heated falling liquid film into a laminar gas stream was investigated by Tsay and Lin[14].

The addition of surfactant to a falling liquid may change the physical properties of the film and decreases the contact angle between the liquid droplet and solid surface. Even though many studies have been done on falling liquid film with surfactant, not much attention has been given to the wettability and transport process from heated wall to the falling film. The present study is directed at the effect of surfactant materials on the wetted area and film thickness of falling liquid film as well as on heat transfer rate from the heated plate to falling liquid.

2. Experimental system

An experimental system has been designed and built to investigate falling film flow and heat transfer characteristics over a vertical plate, as shown in Fig. 1. The dimension of vertical plate has 225 mm height, 270 mm width and 3 mm thickness.

Film flow may be formed by flooding over a vertical flat plate. An electrical heater (Silicon rubber heater) is located on the back side of the plate to provide heat which is controlled by DC power supply. The back of the flat plate was insulated to minimize heat loss. There are 9 holes with 2 mm in depth from the back of the plate. Thermocouples are embedded into these holes and filled with high thermal conductivity thermal grease to measure the variation of the plate temperature. The temperature was measured at nine points of plate surface and the surface temperature was identical to within ±0.2°C.

The liquid flow rate was measured by a calibrated flow meter(Blue White Co., F-50376LN) covering the range of the present experiments. Flowmeter calibration was achieved by means of flow rate that was measured during 60 seconds with a stopwatch, beaker and measuring cylinder. The measurement error of flow meter is shown to be within ±3%. The fallen liquid was recycled by using a DC pump. The flow patterns of falling liquid film were detected by high-speed video system (Photron Fastam 1K).

Flow rate was varied for 0.028~0.062 kg/s and surfactant concentrations were controlled at 0~1000 ppm. Triton X-100[$C_8H_{17}C_6H_4(OCH_2CH_2)OH$] with saturation limit of 1000 ppm was used as surfactant. T-type thermocouples were used to measure the temperatures and all the thermocouples were calibrated in a constant temperature bath to ensure reliable temperature measurements. The measurement error in temperature was ±0.2°C.

The same volume of solution was doped by an injector above the horizontal plate to measure the contact angle of a droplet. The contact angle of droplet with solid surface was measured by a protractor for various surfactant concentrations. The measurement of each contact angle was obtained 10 times, which corresponds to an error in contact angle average of ±1.25°. Average film thickness δ of falling film is estimated as follows:

$$V_p = (\dot{m}/\rho) \times t \tag{1}$$

$$\delta = V_p/A \tag{2}$$

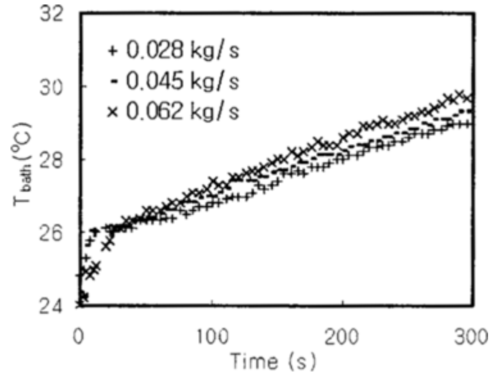
where t is traveling time of falling film from top to bottom of plate, V_P volume of existed solution over the vertical plate, $\dot{m}$ mass flow rate supplied by pump and A the area of wetted plate. The falling film thickness, δ, means the average thickness of wetted area of vertical flat plate. Furthermore, the time that it takes while falling film flows from top of the plate to the bottom of the plate, t, was measured with small particles after they were acquired by high-speed camera. Because the shape of falling film is a trapezoid by the effect of gravity, the wetted area is calculated by trapezoid integral formulation.

3. Results and discussion

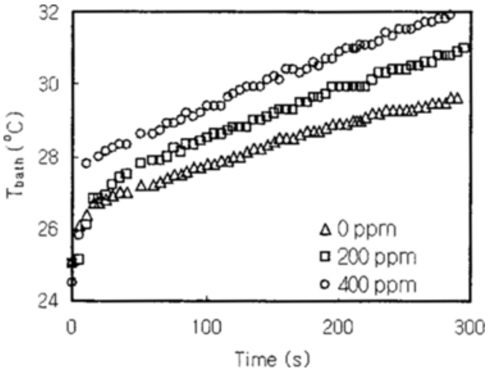
Transient variations of bath temperature are shown in Fig. 2. The variation of bath temperature for circulating flow rate by using pure water in Fig. 2(a) and Fig. 2(b) shows the variation of bath temperature for surfactant concentration for a given flow rate of 0.06 kg/s. It is found that the temperature gradient is almost linear after approximately 40 sec even though it is steep in the beginning. Heat transfer rate in water bath can be estimated by using this temperature in the bath as Eq. (3). Here m is the total mass of liquid solution in bath.

$$\dot{Q}_{bath}=mC_p dT/dt \tag{3}$$

The heat transfer rate in the water bath corresponds to the heat transfer rate from the heated plate to the falling film, neglecting heat loss to ambient air from falling film. To evaluate the heat transfer coefficient

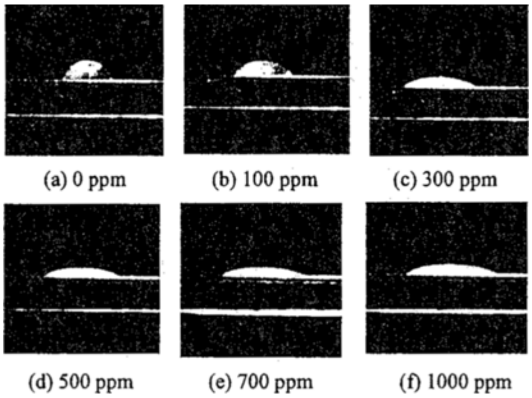


(a) Pure water



(b) Pure water with surfactant

Fig. 2. Transient variation of bath temperature (a) for pure water and (b) at given mass flow rate $\dot{m}$ =0.06 kg/s.



(a) 0 ppm (b) 100 ppm (c) 300 ppm

(d) 500 ppm (e) 700 ppm (f) 1000 ppm

Fig. 3. Photographs of droplet for surfactant solutions.

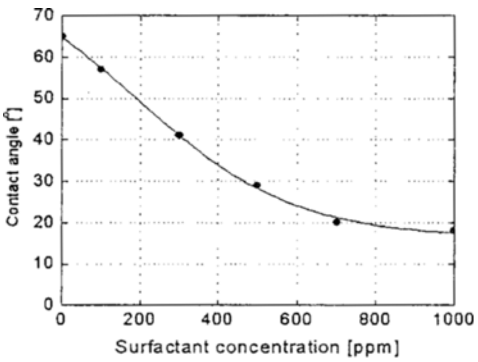
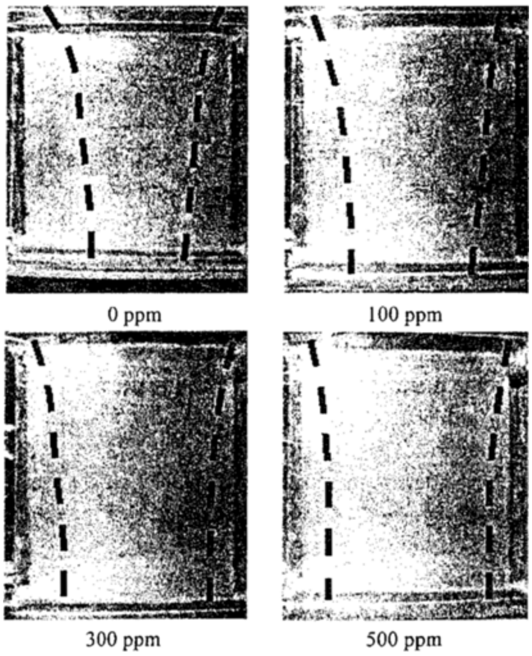


Fig. 4. The change of contact angle by surfactant concentration.



0 ppm 100 ppm

300 ppm 500 ppm

Fig. 5. Effect of surfactant concentration on flow pattern.

from the heated plate to the falling film, the measured heat transfer rate in a bath is employed as Eq. (4).

The bath temperature is measured during the test time and then the thermal energy transfer from the flat plate to the liquid solution is determined by the convection heat transfer rate equation on falling film. The energy input to the falling liquid film from the heated plate is given by Eq. (4). Here $\dot{Q}$ is the heat transfer rate of liquid solution in the bath.

$$\dot{Q}=hA\Delta T_{lm} \tag{4}$$

$$\Delta T_{lm} = \ln\frac{(T_{w,in}-T_{w,out})}{(T_s-T_{w,out})/(T_s-T_{w,in})} \tag{5}$$

The contact angle between a liquid droplet and the plate surface was measured in the range of surfactant concentration 0 to 1000 ppm. Fig. 3 shows the photographs of contact angle of droplet for the same volume of surfactant solutions. It is found that the droplets spread out as surfactant concentration is increased. The contact angle can be used as a measure of wettability of the surface. While a low contact angle indicates good wettability, a high contact angle indicates weak wettability. The effect of surfactant concentration on the contact angle is shown in Fig. 4. As surfactant concentration increases, the contact angle is gradually decreased. However, when the concentration of surfactant is over 700 ppm, the contact angle becomes 18~20°. The contact angle is limited by the saturation concentration in which further addition of surfactant does not change the surface energy[11].

The shape of falling film on the vertical flat plate shows a trapezoidal shape whose width of fluid flow becomes narrow gradually downward by the effect of gravity. The wetted area can be estimated by the images of the flow pattern. The images of flow pattern are illustrated in Fig. 5 at a given flow rate 0.06 kg/s. Dotted lines indicates the boundary between wetted and dry area of the plate. It is found that the wetted area of the film flow without the surfactant covers 0.041 m^2. However, as surfactant concentration is increased up to 100 ppm, 300 ppm, and 500 ppm, the wetted area is also gradually increased to 0.046 m^2, 0.051 m^2, and 0.054 m^2, respectively. The wetted area is increased by about 34% with 500ppm surfactant concentration than that without the surfactant.

Fig. 6 shows the wetted area and the film thickness as a function of the mass flow rate. Wetted area as well as film thickness is substantially in-creased as mass flow rate increases. The effect of mass flow rate on the heat transfer rate and heat transfer coefficient is indicated in Fig. 7 for the pure water without the surfactant. As the mass flow rate of falling liquid film is increased, both the heat transfer rate and heat transfer coefficient are significantly increased, as

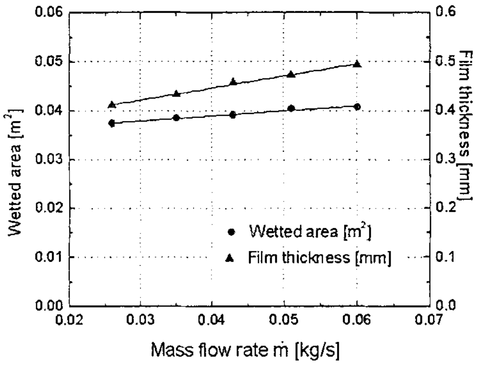


Fig. 6. Effect of mass flow rate on wetted area and film thickness for pure water.

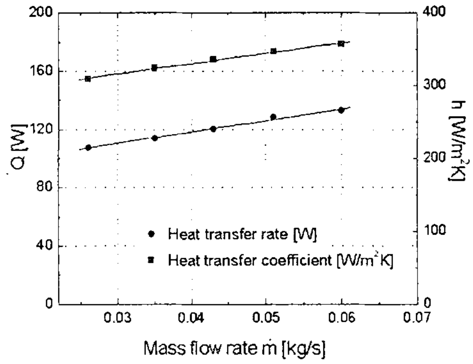


Fig. 7. Effect of mass flow rate on heat transfer rate and heat transfer coefficient fort pure water.

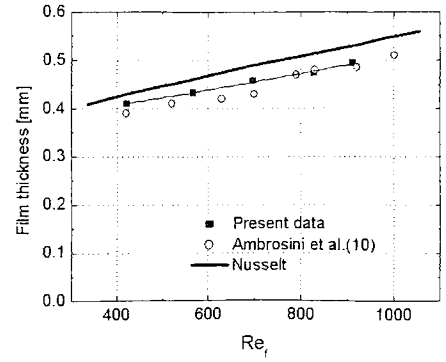


Fig. 8. Comparison between present experimental results and previous empirical formulas for Aluminum surface.

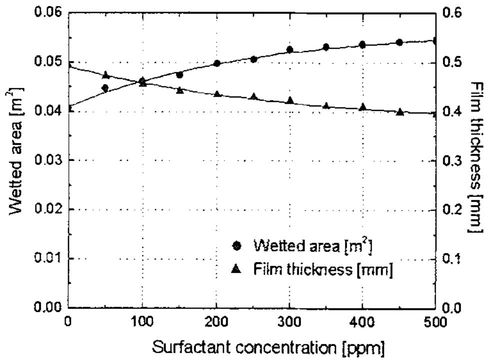


Fig. 9. Effect of surfactant concentration on wetted area and film thickness.

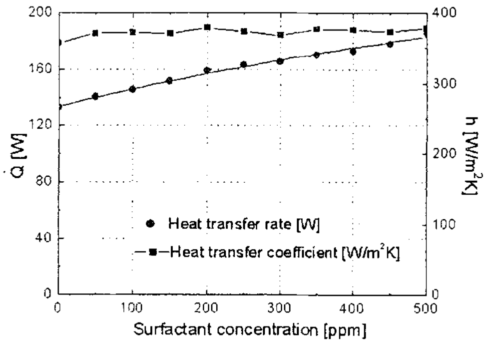


Fig. 10. Effect of surfactant concentration on heat transfer rate and heat transfer coefficient.

expected.

The measured average film thickness is compared with previous empirical formulas in Fig. 8. Ambrosini et al. [10] carried out an experiment with similar test conditions for a vertical flat plate which mainly consisted of stainless steel. The well-known Nusselt expression for laminar flow, which is a prediction of generally accepted formulas, is as follows[15]

$$\delta = \left(\frac{3\Gamma\mu}{g\rho^2}\right)^{1/3} \quad \text{for } \mathrm{Re}_f < 2000 \qquad (6)$$

where Γ is the liquid mass flow rate per unit width of wetted perimeter, μ and ρ are the liquid viscosity and density. The film thickness in the present study showed a similar tendency on the whole and the present experimental results for the average film thickness show good agreement with the previous empirical formulas even though the results show a little higher than the result of Ambrosini et al. and lower than Nusselt's empirical formula.

The effect of surfactant concentration on the wetted area and film thickness is shown in Fig. 9 at a given mass flow rate, 0.06 kg/s. It is seen that wetted area is substantially increased while film thickness is gradually decreased as the surfactant concentration is increased. The result indicates that wetted area is increased by about 34% and film thickness is decreased by about 20% with 500 ppm surfactant concentration than that without the surfactant.

Fig. 10 shows the effect of surfactant concentration on heat transfer rate and heat transfer coefficient. It is found that the heat transfer rate is substantially increased by 23% with a surfactant concentration of 500 ppm. However, the heat transfer coefficient is not affected by surfactant concentration. This means that heat transfer rate enhancement with surfactant is attributed to an increase in the wetted area while heat transfer coefficient is not changed much.

4. Conclusions

Experiments were carried out to investigate the flow and heat transfer characteristics on a falling liquid film with surfactant along a vertical plate. The addition of surfactant to liquid changes the fluid physical property of falling liquid film. This decreases the contact angle between liquid droplets and the solid surface. The wetted area is increased while film thickness is decreased with an increase in the surfactant concentration.

As flow rate of liquid is increased, both heat transfer rate and heat transfer coefficient are increased while wetted area is little affected. However, both heat transfer rate and the wetted area are increased while the heat transfer coefficient is not affected much as surfactant concentration is increased. These results indicate that heat transfer rate enhancement with surfactant is attributed to an increase in the wetted area while heat transfer coefficient is not changed much. Thus, it is expected that thermal transport from a heated plate to falling film can be substantially enhanced with surfactant materials due to an increase in the wettability.

Nomenclature

A : Wetted area, m^2
C_P : Specific heat, J/kgK
δ : Average film thickness, mm
h : Heat transfer coefficient, W/m^2K
L : Film width, m

m : Total solution mass in the bath, kg
$\dot{m}$: Mass flow rate, kg/s
$\dot{Q}$: Heat transfer rate, W
T : Temperature, K
t : Traveling time of falling film from top to bottom of plate, sec
V_p : Volume of solution on the plate, m^3
Γ : Mass flow rate per unit perimeter, kg/m·s
μ : Viscosity, $N \cdot s/m^2$
ρ : Density, kg/m^3

Subscripts

bath : Bath
in : Inlet
out : Outlet
s : Plate surface
w : Fluid

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