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Characterization of Marangoni effect in non-isothermal falling liquid films of binary mixtures

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Abstract

The flow characteristics and heat transfer were investigated for the liquid films of water, ethanol aqueous solution, glycerol aqueous solution and aqueous Na_2SO_4 solution. By using a sensitive thermal imaging system, the temperature and liquid distributions of the film could be carefully studied to reveal the influence of Marangoni effect on the heat transfer and flow of the binary mixture films. Since the surface tension gradient and surface tension counteracted on the film, a surface tension factor was presented to describe the surface tension effect in the films and help designing the experiments. It was concluded to be the thermal Marangoni effect that caused the cooled films expanded and the heated films contracted. A novel expansion was found for the heated ethanol aqueous film, due to the concentration variation and so-caused solutal Marangoni flow that overcame the thermal Marangoni flow in the lateral direction of the film. Theoretical analysis also indicated that the solutal Marangoni effect was more effective than the thermal Marangoni effect. Furthermore, viscosity has a complex influence on the Marangoni flow. Larger viscosity generally caused greater temperature gradient, and thus enhanced surface tension gradient (Marangoni flow), meanwhile, all the liquid flow (including Marangoni flow) were retarded due to the more significant viscous resistance.

Keywords: Falling liquid films; Heat transfer; Surface tension gradient; Temperature variations; Marangoni effect

1. Introduction

Falling liquid films are widely employed in the heat and mass transfer processes of the industrial equipments, including vertical condensers, film evaporators, absorption towers and seawater desalinators. The phenomena in the falling film, such as formation of surface waves, breaking of a stream into rivulets, evaporation at a contact line, and liquid maldistribution, are frequently encountered and have significant influence on the transfer processes. Thereby, the good understanding of these phenomena helps to improve the predictions of heat and mass transfer rates in the film devices.

In recent years, the flow characteristics, transfer processes and the interfacial instabilities, especially the Marangoni effect in the non-isothermal film have been widely investigated by using theoretical and experimental methods. The Marangoni flow, which is fluid flow induced by surface tension gradient (due to the variations of concentration or temperature), proceeds from regions of lower surface tension to those of higher surface tension. In 1959, Scriven and Sternling made the linear stability analysis for the solute Marangoni flow [1]. The next year, they [2] reviewed the study of the Marangoni effect. Cazabat et al. [3] also performed excellent work to study the fingering instability of thin spreading films that were driven by temperature gradient. They revealed that lower viscosity and greater temperature gradient reinforced the Marangoni flow. Recently, Aubeterre [4] experimentally investigated the Marangoni effect induced by heat and mass transfer of four aliphatic alcohol (from C1 to C4), exploring that Marangoni number decreased with the increasing carbon number atoms (n), due to the changes of some physical properties (surface tension, diffusivity, viscosity) as heat and mass transfer occurred.

It was reported that the Marangoni effect induced by the temperature gradient or concentration variations was desta-

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Nomenclature

Roman

A	interfacial area of falling film	m^2
B	positive constant	
c	mass fraction	
$C_{Na_2SO_4}$	mass fraction of Na_2SO_4	
C_p	specific heat at constant pressure	$kJ\,kg^{-1}\,K^{-1}$
E	mass fraction of ethanol	
F	parameter	
g	the gravity acceleration	
G	mass fraction of glycerol	
h	heat transfer coefficient	$W\,m^{-2}\,K^{-1}$
F	parameter	
L	length of heating region	m
Ma	Marangoni number	
Nu	Nusselt number	
Q	volume flow rate	$m^3\,s^{-1}$
Re	Reynolds number	
S	surface tension factor	
V	molar volume	

Greek symbols

a	thermal diffusivity	$m^2\,s^{-1}$
ϕ	volume fraction	
θ	contact angle	
γ	surface tension coefficient	
μ	dynamic viscosity	Pa s
ν	kinematics viscosity	$m^2\,s^{-1}$
ρ	density of liquid	$kg\,m^{-3}$
σ	surface tension	$N\,m^{-1}$
λ	liquid thermal conductivity	$W\,m^{-1}\,K^{-1}$
Γ	mass flow rate	$kg\,m\,s^{-1}$

Subscripts

0	initial
A	water
B	organic compound
c	critical
f	average film temperature
T	temperature
h	heat
m	mixture
out	outlet of falling film
s	surface of liquid film
soln	solution
w	wall

bilizing whereas capillarity and evaporation were stabilizing processes [5–7]. Kabov Group [8] discovered that the instabilities of a thin locally heated falling film, which was caused by the Marangoni effect, probably resulted in a decrease of the heat transfer coefficient with the increasing Reynolds number. Joo [9,10] discovered that the thermo-capillary instability was dominant due to the absence of gravity-driven flow in the lateral direction, inducing the spontaneous film rupture. Zhang [11,12] also investigated the heated water films, revealing that the heated water films were evidently contracted in the lateral direction by the transverse surface tension gradient. This is quite similar to the non-isothermal spreading of liquid drops on heated (cooled) horizontal plates. For these drops, Ehrhard and Davis [13] proved that heating (cooling) retarded (augmented) the spreading process by creating surface tension gradient driven flows.

Some researchers [14–16] paid special attentions to the heat and mass transfer enhancement of the LiBr aqueous film by Marangoni effect resulted from adding surfactants into the film. Sun [17] successfully obtained the expressions for the liquid-phase mass and heat transfer rate enhanced by Rayleigh–Benard–Marangoni cellular convection. Furthermore, Hosoi and Bush [7] discovered that the evaporation of ethanol– or methanol–water solution led to concentration variations, causing the surface tension gradients that drove flow up an inclined rigid plate. It was also found that the condensation heat transfer of binary mixture vapor was enhanced by Marangoni effect which produced a disturbed, turbulent banded condensate film [18,19].

The films of binary solutions are more frequently used in the industry and should be further investigated to optimize the operation and designing of the falling film equipments. The thermal imaging research on the falling liquid films is very useful to make clear the inducement and behavior of Marangoni effect. In the present work, the heated/cooled films of water, ethanol aqueous solution (volatile liquid), glycerol aqueous solution (viscous liquid) and aqueous Na_2SO_4 solution (electrolyte aqueous liquid) were investigated. Based on the theoretical analyses of surface tension effect, the experiments were carefully designed. The experimental data allowed analyzing the influences of film flow rate, viscosity, surface tension, liquid concentration and heating conditions on the heat transfer, surface temperature gradient and liquid distributions of the heated/cooled film. Thus the influence of Marangoni effect on the heat transfer and flow of the binary mixture films could be determined. Moreover, the contributions of temperature and concentration variations to the surface tension gradient were compared.

2. Experimental apparatus

The experiment scheme is illustrated in Fig. 1. In each run of the experiment, the liquid in the reservoir was maintained a preset temperature and was pumped to the upper tank. Then it flowed through a rotameter to the liquid distributor, in which the liquid film about 8.5 cm wide was formed. The liquid film then flowed down over the test section (a vertical smooth stainless steel plate about 600 mm wide and 400 mm long) whose backside was heated with water at a scheduled temperature T_h, and