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International Journal of Multiphase Flow 34 (2008) 13–28

International Journal of Multiphase Flow

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An investigation of falling liquid films on a vertical heated/cooled plate

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Received 27 November 2005; received in revised form 9 August 2007

Abstract

The temperature field and flow patterns of a liquid film flowing over a vertical uniformly heated surface have been experimentally investigated. Our experiments show that this film flow is sensitive to the heating conditions. When the film is cooled by the substrate, its surface area increases, and when it is heated its surface area decreases. The analysis attributed the changing properties of the flow to lateral Marangoni effect, i.e. to surface tension gradient transverse to the flow. The influence of the viscosity variations on the non-isothermal liquid film flow was also considered and compared with that of the surface tension variations. It was shown that the contraction or extension of the films was mainly caused by the lateral surface tension gradient that might be determined by the viscosity variations.

Keywords: Marangoni effect; Surface tension gradient; Falling film; Non-isothermal

1. Introduction

Falling films are usually employed as the heat and mass transfer medium in the industrial equipments such as vertical condensers, film evaporators and absorption towers (Yih and Seagrave, 1978). The Marangoni effect, which is induced by surface tension gradients (due to the variations of concentration or temperature), drives the liquid particles toward the direction of the higher surface tension side to eliminate this gradient. The Marangoni effect could strongly influence the flow dynamics and the transfer processes of liquid films (Zuiderweg and Harmens, 1958; Scriven and Sternling, 1960).

Thermocapillary is usually referred to the Marangoni effect induced by the temperature gradient. In recent years, thermocapillary instabilities of falling liquid films such as formation of dry patches, breakage of a stream into rivulets have been observed and theoretically analyzed (Skotheim et al., 2003; Schatz and Neitzel, 2001; Ludviksson and Lightfoot, 1968; Joo et al., 1996). Joo's group (Ramaswamy et al., 1997; Joo et al., 1996) has done very important work in the simulation of the heated films by including the combined

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0301-9322/$ - see front matter
doi:10.1016/j.ijmultiphaseflow.2007.08.003

influence of thermocapillary and surface wave instabilities. In 1996, based on a long-wave evolution equation that governed a drained film on a heated plate, Joo et al. (1996) successfully proposed a possible mechanism for the creation of dry patches and rivulets from continuous films. Then in 1997, they further performed three-dimensional simulation of instabilities in heated falling films and compared it with the long-wave theory (Ramaswamy et al., 1997), drawing the similar conclusions as those obtained in 1996 (Joo et al., 1996). Kabov's Group (Zaitsev et al., 2003; Kabov et al., 2002; Kabov, 2000) has also performed significant work to study the effect of the Marangoni effect in heated falling films by both experimental and theoretical methods. The instabilities of a thin falling film, i.e., the pattern of "regular horseshoe-like structures", caused by the Marangoni effect, were investigated in detail. This pattern of instable flow probably caused a decrease of the heat transfer coefficient with an increase of the Reynolds number (Kabov et al., 2002). In the flow of water films over a medium-sized (150 × 150 mm) heater, the regular jets were caused by thermocapillary forces (Chinnov and Kabov, 2004). Using a fiber optical thickness probe, Zaitsev and Kabov (2005) discovered that the transverse thermocapillary forces led to the formation of periodically flowing rivulets and thin film between them, while no appreciable effect of streamwise thermocapillary forces on the wave amplitudes was detected.

In 2001, using the lubrication approximation, Holland et al. (2001) investigated the flow of a thin liquid rivulet that was assumed to have the surface tension varying linearly with temperature and to flow down on a substrate of slowly varying surface. They found that the variations in surface tension drove a transverse flow and caused the fluid particles to spiral down the rivulet in helical vortices. Later in 2003, they successfully obtained similarity solutions to describe the thermocapillary-driven flow that widened or narrowed the rivulet due to the surface-tension effects on a non-uniformly heated or cooled substrate (Holland et al., 2003).

The influence of viscosity variations on the flow of heated films were also considered by several researchers (Wilson and Duffy, 2003; Kabova and Kuznetsov, 2002; Kabova, 2003; Goussis and Kelly, 1987; Wilson and Duffy, 2002). Wilson and Duffy (2003) theoretically studied the temperature-dependent viscosity effects on a rivulet draining down a uniformly heated or cooled substrate of slowly varying surface. They found that the effect of strong cooling by the atmosphere was to produce a wide rivulet of finite uniform thickness on the upper part of the cylinder, but a deep rivulet of finite semi-width on the lower part of the cylinder. On the other hand, the effect of strong heating by the atmosphere was to produce a narrow and shallow rivulet everywhere except near the top and the bottom of the cylinder. There were other efforts studying the influence of the temperature dependant viscosity on the non-isothermal film flow (Kabova and Kuznetsov, 2002; Kabova, 2003; Goussis and Kelly, 1987; Wilson and Duffy, 2002), showing that variations of viscosity could also induce the similar flow pattern as the Marangoni effect did.

Practically, the physical properties such as surface tension, viscosity of the liquid and surface energy of the plate, usually determine the distribution of the film on a solid surface. The lower surface tension and large surface energy of the plate make the liquid extending better on a solid surface. For the purpose of determining the influence of Marangoni effect on the non-isothermal films, it is quite necessary to discuss the effect of these physical properties on the distribution of the heated/cooled films.

It was mentioned in several works, that for a heated/cooled falling liquid film, the lateral surface tension gradient could influence the film flow effectively and thus the heat transfer (Joo et al., 1996; Kabov et al., 2002; Holland et al., 2001). However, as pointed out by Joo et al. (1996), there have still been no detailed falling-film experiments of low flow rates and heat fluxes with which to compare with their theory. Few attentions were paid on the lateral surface tension gradient for ages. Therefore, it is very necessary to carry out experimental study of heated/cooled films to explore the influence of the transverse Marangoni effect for the purpose of designing or operating falling film devices.

In the present work, the influence of lateral Marangoni effect on the film flow was experimentally investigated. The experimental data allowed to exploring the effect of film flow rate, initial width of the film, surface tension as well as viscosity of the liquid on the film characteristics. It was noted that the transverse surface tension gradient could cause the changes of film flow. The interfacial area that determines the transfer efficiency, and the film-distributing factor, ε that was defined as $\varepsilon = (z_1 - z_0)/2L$ (where z_0 and z_1 denote the film widths at the upper and lower edges of the heater, respectively, and L represents the length of the heater), were both investigated under the different heating conditions to show the influence of the lateral Marangoni effect.

Moreover, the experiments of non-isothermal film flow that contained a surfactant were also performed to compare the influence induced by the surface tension gradient with that caused by the viscosity variations.

2. Experimental apparatus

Specially designed experiments were performed to demonstrate the influence of the lateral Marangoni effect on heated/cooled films (Zhang et al., 2005). As shown in Fig. 1, the liquid from the liquid store tank was transfer to the upper tank and the rotameter, in which the liquid temperature and flow rate were set. Then liquid films (about 85 mm wide) formed through an exit gap located in the upper part of the test section(a vertical stainless steel plate about 600 mm long and 400 mm wide), flowed down over the plate whose surface temperature was maintained by a hot water at a given temperature T_h ($T_h = 0$–70 °C). The temperature field and shape of the film could be accurately recorded and analyzed by a high sensitive infrared camera system—Therma CAM^{TM} SC3000, manufactured by Flir System Company, USA. The thermal sensitivity of the camera is 0.03 °C at 30 °C and the accuracy for temperature is ±2% of measured value. The spatial resolution is 1.1 mrad. Moreover, the Quantun Well Infrared Photon detector with 320×240 pixels is used and the image frequency is 50/60 Hz (capable up to 750/900 Hz). Several Pt-100 thermal resistances were also installed to measure the temperature values of the film and the ambient, respectively. The uncertainty of these temperature values was within ±0.1 °C. In each run of the experiment, a ruler is located on the plate to obtain the ratio of real dimension and dimension measured from the thermal image, thus the width of the film could be calculated from the coordinates of the film rim in the thermal images. The average deviation of the film width was less than 2%. The film interfacial area was calculated from the values of the film widths and the distances down from the upper edge of the heater. Duplicate experiments for each run were done to obtain the average values of film width at different location and the interfacial area. Moreover, an orifice inlet with a diameter of 6 mm was also used as a liquid distributor to examine the effect of the initial film width on the film flow. The operating parameters were described in detail in the reference (Zhang et al., 2005).

Distilled water was used as the working liquid in the experiments, except for 50 ppm *n*-octanol aqueous solution which was used to investigate the influence of the temperature-dependent viscosity on the non-isothermal film flow. Since the film edge was very thin, the temperature at the edge of the film could be regarded as the wall temperature, T_w. The initial temperature of the film T_0 ranges from 0 to 60 °C and is maintained thermostatically. In order to reveal the influence of the Marangoni effect and the physical properties of the liquid on the heated film, the film was set at different values of initial temperature and wall temperature.

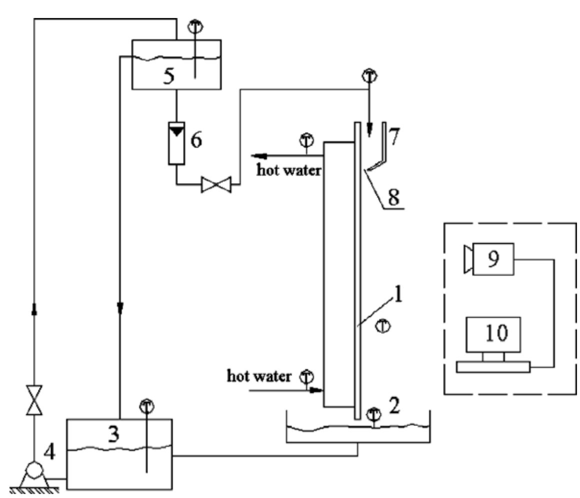


Fig. 1. Sketch of the experimental system. 1, test section; 2, liquid collection vessel; 3, liquid storage tank; 4, pump; 5, upper tank; 6, rotameter; 7, fluid distributor; 8, liquid exit gap; 9, infrared camera; 10, computer; T, thermal resistance.

3. Experimental results

3.1. Experiments on the liquid films formed through a gap-exit

3.1.1. Isothermal falling liquid films

In the present work, the flow of the isothermal falling liquid films ($T_0 = T_h$) was investigated to give prominence to the peculiar flow of the cooled/heated films. A thermal image of the isothermal film is illustrated in Fig. 2. In the thermal images, different colors from deep to light are used to represent different temperature magnitudes from low to high. x and z denote the streamwise and transverse direction. It is shown that the width of the isothermal liquid film keeps almost constant. The profile of the transverse surface temperature of the isothermal film, as indicated by line 1 in Fig. 2, is rectangular. Practically, the surface temperature is almost constant in the streamwise direction of the film (curve 2 in Fig. 2).

The film interfacial area, A, is a very important parameter that usually determines the heat transfer of falling liquid films. Reynolds number is often used to characterize fluid flow pattern. In this work, Reynolds number is defined as follows:

$$Re = \frac{4\Gamma}{\mu} \tag{1}$$

where Γ and μ represent the mass flux per unit perimeter and the liquid viscosity, respectively. The variations of the interfacial area versus the Reynolds number, as illustrated in Fig. 3, indicate that the interfacial area increased slightly with a rise in Reynolds number. It is worthy to note that the interfacial area value of the film with $T_0 = 60$ °C is less than those of the films at temperatures of 25 and 40 °C. This is probably caused by the interfacial evaporation in the location of thin film (especially in the boundaries), i.e., the so-called vapor–thrust effect (Zuber and Staub, 1966) when the film is of high temperature.

Besides the interfacial area, the liquid distributing factor ε is defined to characterize the distribution of the films. As shown in Fig. 4, the liquid distributing factor ε rises quickly with the increasing Re when $Re < 800$, followed by a slight variation when $Re \geqslant 800$. Moreover, for the isothermal films, ε is located between 0 and 0.04, which implies that the isothermal liquid film is slightly extended as it flowing downwards. As will be discussed in the following sections, ε of the isothermal films is larger than that of the heated films, but less than that the interfacial area of the cooled film under the same flow rate.

3.1.2. Heated falling liquid films

The heat transfer and flow characteristics of the heated films have been widely reported in the literatures, covering the deformation of the film (Kabov et al., 2002), different flow patterns (Kabov and Chinnov, 1997),

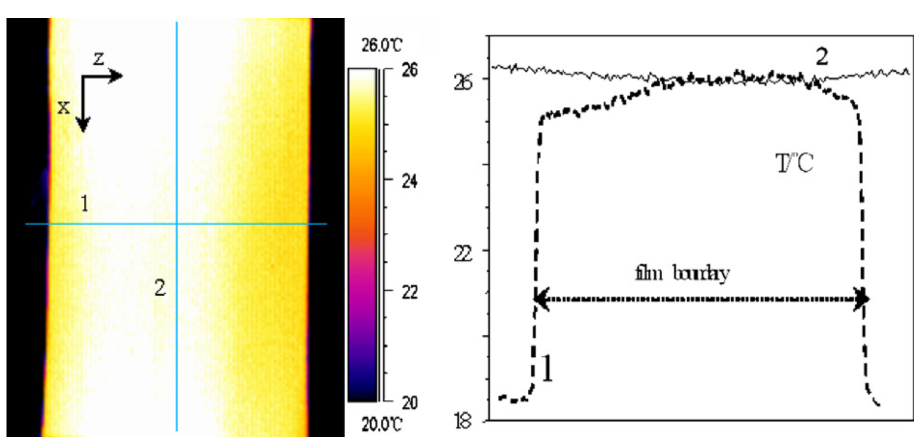


Fig. 2. Temperature distribution of an isothermal film ($\Gamma = 0.18$ kg m^{-1} s^{-1}, $T_0 = 25.5$ °C). x, streamwise direction; z, transverse direction; 1, transverse; 2, streamwise.

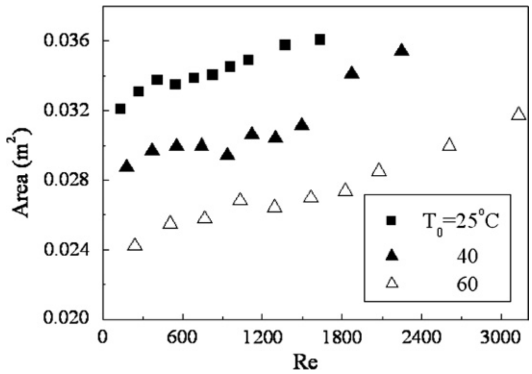


Fig. 3. Variations of the interfacial area versus *Re* for the isothermal films.

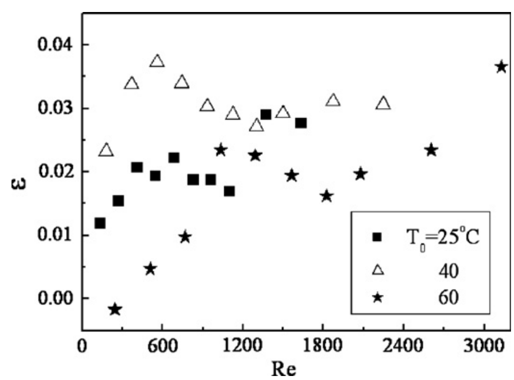


Fig. 4. Variations of ε with *Re* for the isothermal films.

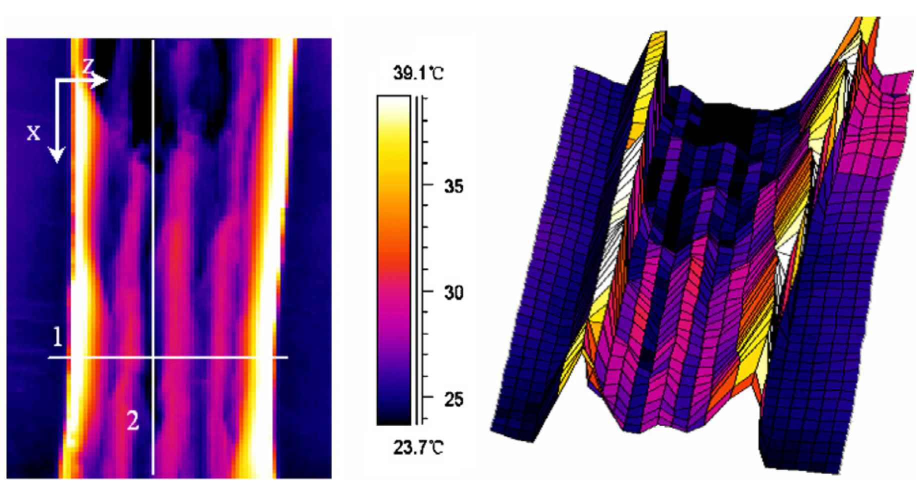


Fig. 5. Thermal images of a heated falling liquid film ($\Gamma = 0.18\ \mathrm{kg\ m^{-1}\ s^{-1}}$, $T_0 = 25\ ^\circ\mathrm{C}$, $T_h = 70\ ^\circ\mathrm{C}$), the right is the 3D view. x, streamwise direction; z, transverse direction.

heat transfer to liquid rivulets or falling films (Ponter and Davis, 1968; Sultanovic et al., 1997), as well as the thermocapillary instabilities (Joo et al., 1991). In this work, the lateral flow patterns of heated falling films were experimentally investigated to discover the peculiar phenomena described by Joo et al. (1996, 1991) and Miller and Neogi (1985).

A thermal image of a heated film is depicted in Fig. 5, where four dark troughs in the center part represent the liquid rivulets. These rivulet formations, described by Zaitsev et al. (2003) as "jets flow", is virtually caused by the Marangoni effect in the lateral direction (Schatz and Neitzel, 2001; Chinnov and Kabov, 2004). Dry spots would be formed in the region of thin film (shown in light or tint) between these flowing jets. This rivulets formation was also found in the distillation of binary mixture (Miller and Neogi, 1985), when the more volatile component was of larger surface tension. In the distillation, since the thin film was prone to approach a higher concentration than the thick film, the surface tension gradient occurred and drove the liquid toward the thicker film, resulting in similar rivulets formations as that in the heated films.

The lateral temperature distribution of line 1 in Fig. 5 is displayed as curve 1 in Fig. 6, showing that the significant surface temperature gradient exists from the boundary to the center of the film and makes the film contracted. Whereas, the streamwise temperature difference is quite small and is consistent with the surface waves of the film (curve 2 in Fig. 6). The surface of the rivulet is covered by a complex array of large and small waves, which are reinforced by the surface tension gradient. Since Marangoni effect in the non-isothermal film flow is dominated by the temperature variations, it is possible that by considering the variations of the interfacial area and the film width of the film versus the heating temperature differences, the influence of the Marangoni effect on the heated film flow could be determined.

The variations of the film interfacial area with the Reynolds number under different heating conditions, as illustrated in Fig. 7, show that the interfacial area A is sensitive to the temperature difference ($T_h - T_0$). The larger the heating temperature difference, the smaller the area A. Meanwhile, the interfacial area increases slightly with a rise in Re. Practically, the influence of the heating temperature difference on A seems to be weakened at large flow rate, i.e., significant differences in A exist at little Reynolds number, and when Re increases the differences in A is lowered. Moreover, by comparing Fig. 7 with Fig. 3, it is shown that the interfacial area of the heated film is much less than those of the isothermal film.

As mentioned above, the parameter ε directly describes the distribution characteristics of the liquid films. There are $0 < \varepsilon < 0.04$ for the isothermal liquid films, and for a heated film, $\varepsilon < 0$ (Fig. 8), indicating the film

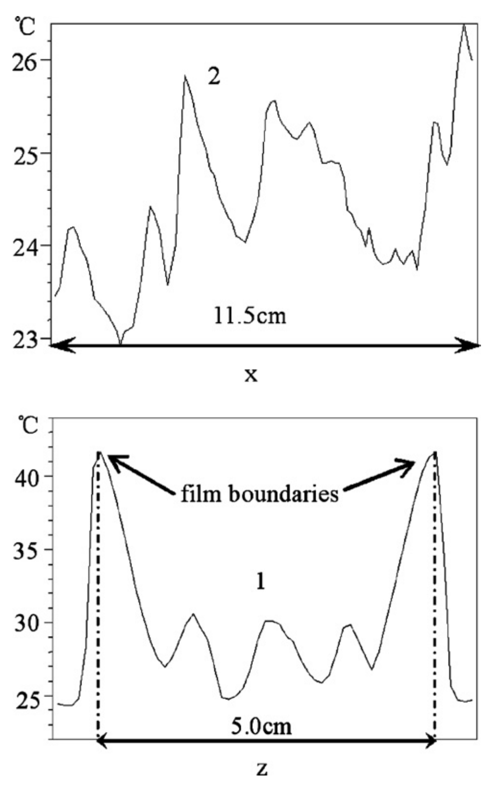


Fig. 6. Temperature distributions of a heated falling liquid film. 1, Transverse; 2, streamwise.

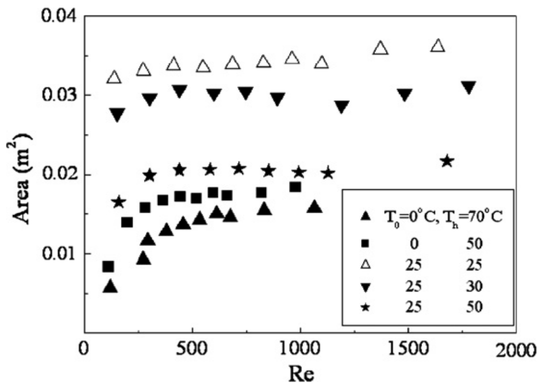


Fig. 7. Variations of the interfacial area with *Re* under different heating conditions for the heated films.

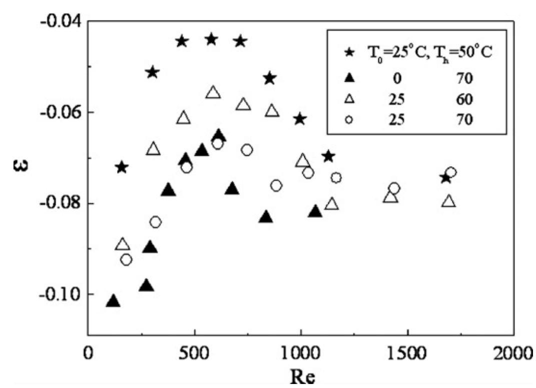


Fig. 8. Variations of ε versus *Re* for the heated films.

contraction caused by the heating. As shown in Fig. 8, ε of a heated film rises sharply with the increasing *Re* till $Re = 700$, then being followed by a distinct reduction to a constant at $Re = 1200$. Besides the Reynolds number, ε is also determined by the heating temperature differences. When *Re* is low, ε drops usually with an increase of the heating temperature difference. When the Reynolds number is large enough, the values of ε are close to each other for all the heating temperature differences, indicating that the Marangoni effect is quite limited when *Re* is large enough.

In a non-isothermal liquid film, a particle of free surface having higher temperature undergoes a stronger interfacial stress than other particles of free surface. Thus it moves from the hotter location to the cooler location, resulting in so-called Marangoni flow. The driving force of the flow is the variation of surface tension that results from the temperature difference. Since the surface tension is usually considered to vary linearly with the temperature, we have $\sigma = \sigma_0 - \gamma(T - T_0)$, where σ and σ_0 are the surface tension at T and T_0, respectively, and the surface tension coefficient, γ, is positive for most liquids. The parameters that stabilize the flow are the viscosity and the thermal diffusivity, since the viscosity tends to slow down particles' velocity and the thermal diffusivity tries to make uniform the temperature profile. The Marangoni number is known as the ratio between the driving force and the resistive force. The influence of the surface tension gradient on the non-isothermal liquid films is characterized by the modified Marangoni number (Kabov and Chinnov, 2001):

$$\mathrm{Ma}^* = \frac{-\gamma \Delta T_\mathrm{F} L}{\mu a}\left(\frac{l_\mathrm{v}}{L}\right)^2 = \frac{-\gamma \Delta T_\mathrm{F} \cdot l_\mathrm{v}(l_\mathrm{v}/L)}{\mu a} \tag{2}$$

where L represents the length of the heater, $\Delta T_\mathrm{F} = T_\mathrm{W} - T_\mathrm{f}$, in which T_f is the average film temperature that is calculated from the initial and outlet temperatures. $\alpha = \lambda/(\rho C_p)$, is known as the coefficient of thermal diffusivity and $l_v = (v^2/g)^{1/3}$ is the viscosity length scale in which v stands for kinematical viscosity and g is the acceleration of gravity.

The modified Marangoni number of the heated film is negative, due to the positive value of ΔT_F. As illustrated in Fig. 9, Ma* increases with a drop of $T_h - T_0$, and is quite small when *Re* is less than 500 and $T_h - T_0$ is higher than 30 °C. This implies that the prominent Marangoni effect exists in the heated films at low flow rates as Joo discovered (Joo et al., 1996). After reaching a local maximum at a certain *Re* (the maximum depended on the $T_h - T_0$ value), Ma* decreases slightly with the increasing *Re* till $Re = 750$. When $Re > 1200$, Ma* becomes substantially high, denoting a possible transition of the film flow from laminar to turbulent as *Re* being within 750–1200.

It can be concluded from Figs. 5–9, that the flow patterns and the film distribution for the heated films are much different from that of the isothermal films. The heated film is contracted by the lateral Marangoni effect as it flowing downwards. Moreover, the Marangoni effect is dominant at low flow rate and becomes weak at the large flow rates.

3.1.3. Cooled falling liquid films

The heated films were frequently studied with experimental and theoretical methods for industrial purposes. The cooling film operations are also very important in the transfer processes. However, the increased area due to cooling has only been theoretically investigated (Holland et al., 2003; Ehrhard and Davis, 1991). Therefore, it is necessary to study the cooled film with thermal imaging technique to experimentally reveal the reason for the increasing area by cooling.

It is found in the heated films that the lateral temperature difference is much larger than that in the streamwise direction. The lateral Marangoni effect caused by the temperature gradient has been considered in some papers (Kabov et al., 1996), while the significance of the transverse Marangoni effect has not been further investigated. In the present work, hot water ($T_0 = 20$–60 °C) films flowing down a plate at a temperature less than T_0 were investigated to show the influence of the heating temperature difference ($T_h - T_0$) and Marangoni effect on the cooled films. For the cooled films, it is shown in Table 1, that the maximum values of the lateral temperature gradients are about 30–260 times of those of the temperature gradient in the streamwise direction. Thus the lateral surface temperature difference of the cooled films is also very effective on the film flow as the case of heated films.

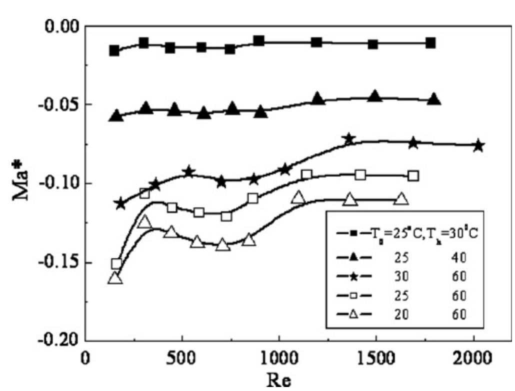


Fig. 9. Variations of Ma* versus *Re* for the heated films.

Table 1
Temperature gradient in cooled films ($T_0 = 35$ °C, $T_h = 2$ °C)

Flow rate (kg m^{-1} s^{-1})	0.06	0.12	0.18	0.24	0.30
LTG (K/m)	769.7	892.76	891.66	971.66	951.8
STG (K/m)	26.0	14.3	7.5	6.5	7.5

LTG: lateral temperature gradient; STG: streamwise temperature gradient.

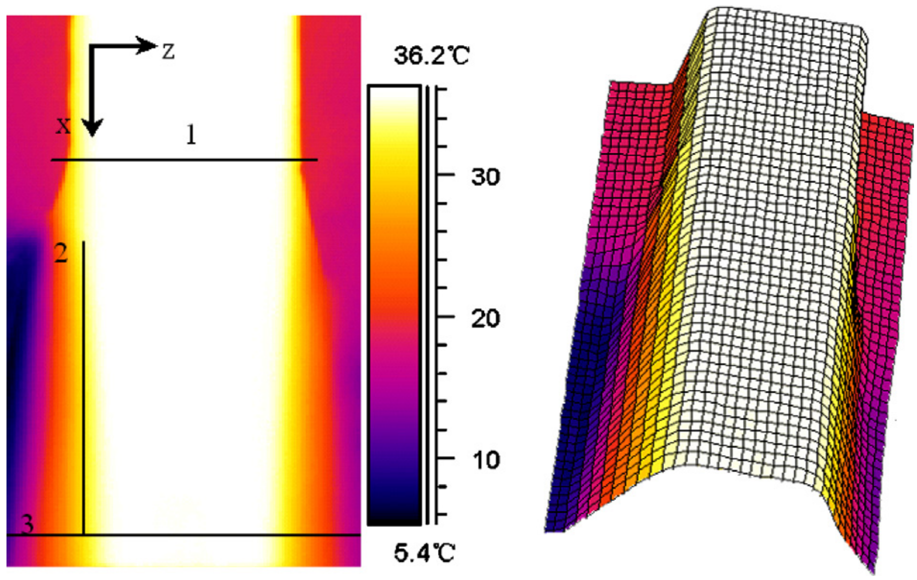


Fig. 10. Thermal images of a cooled film ($\Gamma = 0.24$ kg m^{-1} s^{-1}, $T_0 = 35$ °C, $T_h = 2$ °C), the right is the 3D view. x, streamwise direction; z, transverse direction.

The temperature distribution of a cooled film at the flow rate of 0.24 kg m^{-1} s^{-1} is illustrated Fig. 10, in which the black line 1 indicated the upper edge of the heater. It is shown that the film's area increases as it is cooled. The curves 1–3 in Fig. 11, represent the temperature profiles of the line 1–3 in Fig. 10, respectively. As can be seen, the transverse temperature variation of the cooled film (curve 3) is quite evident. Whereas, the streamwise temperature (curve 2) decreases weakly and fluctuates slightly as the film flowing down. It can be seen in Fig. 11 that the transverse temperature profile changes from rectangular (curve 1) to trapezoid-like (curve 3) when the film is cooled. Since there is much lower temperature in the boundary of the cooled film than that in the center, considerable gradient in surface tension may exist in the rim and drive the hot liquid with low surface tension from the center to the rim, so as to extend the cooled film.

The influences of the heating temperature difference and *Re* on the interfacial area are illustrated in Fig. 12, showing that A is also sensitive to the heating temperature difference as the case of heated films, i.e., A decreases with a rise in $T_h - T_0$. It is found that A varies regularly with Reynolds number: when *Re* is less than 800, A goes up sharply with an increase in *Re*, and then A drops slightly till $Re = 1600$; when *Re* further increases, A rises almost linearly. However, an exception is the film ($T_0 = 20$ °C, $T_h = 2$ °C), in which the variation of A is much different from the other cases when $Re < 800$ and the largest interfacial area in this case is demonstrated at $Re = 114$. This may be caused by the strong condensation of the water in the ambient air adjoining the solid surface at the extreme low temperature. The condensation makes the boundaries of the film undistinguished from the condensed liquid, causing the inevitable error in the measuring of the interfacial area. However, when $T_h > 20$ °C or the flow rate is large enough, the film boundaries are quite definite.

At the same *Re*, the interfacial area of the film ($T_0 = 35$ °C, $T_h = 30$ °C) is a little larger than that of the film ($T_0 = 30$ °C, $T_h = 25$ °C). This can be explained that the higher liquid temperature leads to lower surface tension and thus larger extension of the liquid film. In fact, the surface tension gradient and the surface tension have different effects on the liquid distribution on a solid, i.e., the latter stabilizes the liquid film while the former destabilizes it.

The variations of ε with the heating temperature difference and Reynolds number, as illustrated in Fig. 13, show that for the cooled films, most of the ε are larger than 0.04 except for the case of much low flow rate. Therefore, the extension of the cooled film is greater than that of the isothermal films ($0 < \varepsilon < 0.04$) and the heated films ($\varepsilon < 0$). Practically, the extension is closely related to the heating temperature difference, i.e., the bigger ε responding to the larger absolute value of heating temperature difference. It is found that ε is quite low

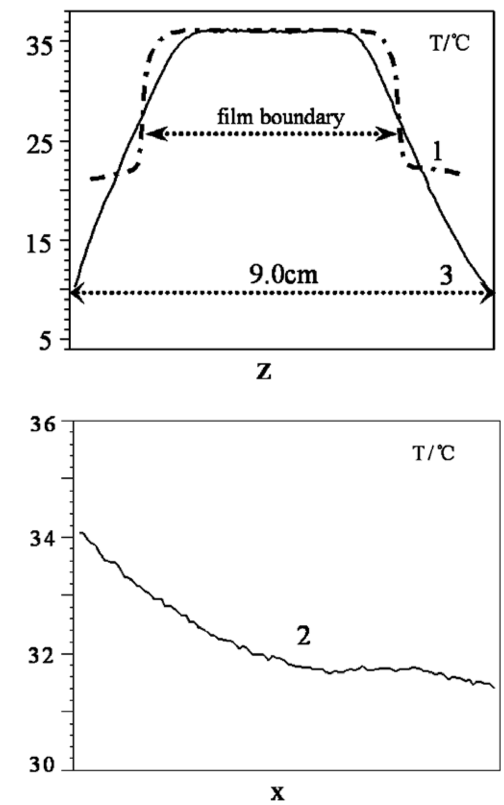


Fig. 11. Surface temperature distributions of the cooled film shown in Fig. 10. 1, Transverse temperature profile of isothermal film; 2, streamwise temperature profile of a cooled film; 3, transverse temperature profile of a cooled film.

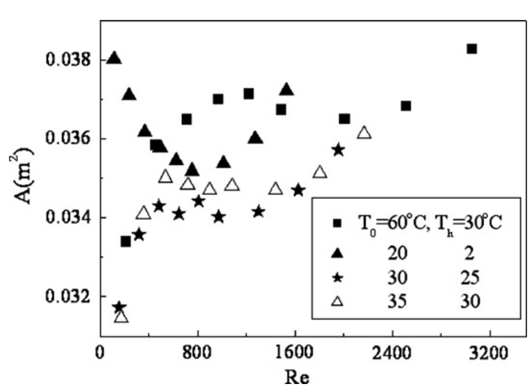


Fig. 12. Variations of the interfacial area versus *Re* for the cooled films.

when *Re* is less than 700. This can be explained that the liquid film is very thin at low flow rate and the surface tension becomes prominent, retarding the extension.

As shown in Fig. 14, the Marangoni number is mainly determined by the heating temperature difference ($T_h - T_0$). Generally, Ma^* increases with a reduction of $T_h - T_0$. An exception is the film at $T_0 = 20$ °C and $T_h = 0$ °C, where Ma^* is higher than those of the films at $T_0 = 60$ °C and $T_h = 30$ °C when *Re* is less than 700. This is because the liquid closing to the plate ($T_h = 0$ °C) is of quite low temperature and high viscosity, and the film substrate becomes much thick. The heat transfer was thus weakened, resulting in larger ΔT_f than that of the film at $T_0 = 60$ °C and $T_h = 30$ °C. Ma^* also varies with the Reynolds number. For the cooled

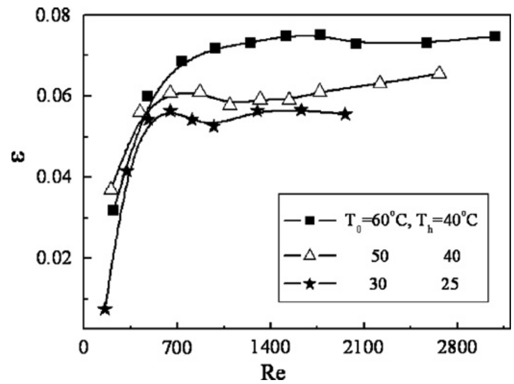


Fig. 13. Variations of ε versus *Re* for cooled liquid films.

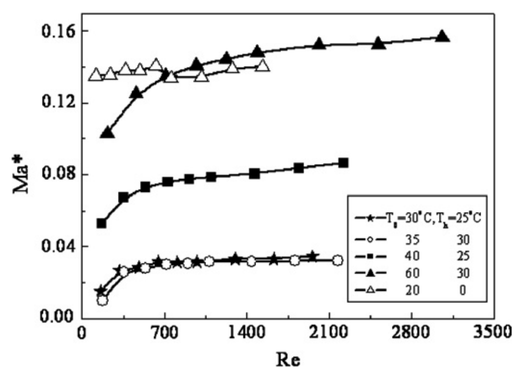


Fig. 14. Variations of Ma* with *Re* for the cooled film under different heating conditions.

films, as given in Fig. 14, Ma* increases slightly with a rise in *Re* due to the increasing $|\Delta T_f|$ and the decreasing $\alpha\mu$.

The extension of the cooled films has scarcely been experimentally studied. Our work demonstrates that the liquid distribution is determined by the heating temperature difference. Moreover, for the cooled film, large Marangoni effect could retard the heat transfer, but improve the wettability of the cool liquid.

3.2. Influence of Marangoni effect on the flow of heated/cooled films

It is quite necessary to discuss the effect of the physical properties such as surface tension, the liquid viscosity and the surface energy of the plate on the distribution of the heated/cooled films. After that, the influence of Marangoni effect on the non-isothermal films could be evaluated.

3.2.1. The effect of the physical properties of the liquid and the plate

The physical properties such as surface tension, viscosity of the liquid and surface energy of the plate, usually determine the liquid distribution on a solid surface. In general, the lower surface tension makes the liquid spread better on a solid surface. Since liquid surface tension decreases with the temperature increasing, the heated films should be distributed more widely than the cooled films according to the wetting ability analysis. In the same way, the large solid surface energy means small contact angle and is also favorable to the distribution of the film. However, in our experimental observations, then heated films were contracted and the cooled films were extended, which was right contrary to the above analysis. Therefore, the surface tension and the solid surface energy cannot be the reason of the contraction or extension of the non-isothermal film.

Like the surface tension, the liquid viscosity also deceases with the increasing temperature. This probably means that the variations of the viscosity with the temperature would strongly affect the non-isothermal films flow (Wilson and Duffy, 2003; Kabova and Kuznetsov, 2002; Kabova, 2003; Goussis and Kelly, 1987; Wilson and Duffy, 2002; Goussis and Kelly, 1985). However, according to our experiments, as shown in Fig. 15, the film of pure water was remarkably contracted. It was greatly enlarged, when about 50 ppm *n*-octanol was added as the surfactant. The surfactant of such low concentration can hardly change the film's viscosity, but it either strongly disturbs the surface tension gradient, or reinforces the wetting ability of the liquid through the surface tension reduction. Therefore, the variations of the viscosity with temperature are not the main reason for the contraction or the extension of the non-isothermal films. It has been reported that the variations of viscosity determined the most important characteristics of the liquid film: the smallest thickness of the film and the degree of heating of its free surface (Kabova and Kuznetsov, 2002). That is, the variations of the liquid viscosity effectively influence the surface temperature distribution and the surface tension gradient. Therefore, the so-called thermoviscosity effects probably influences the non-isothermal film flow by changing the temperature field of the film. In this way, it can be concluded that the film contraction or

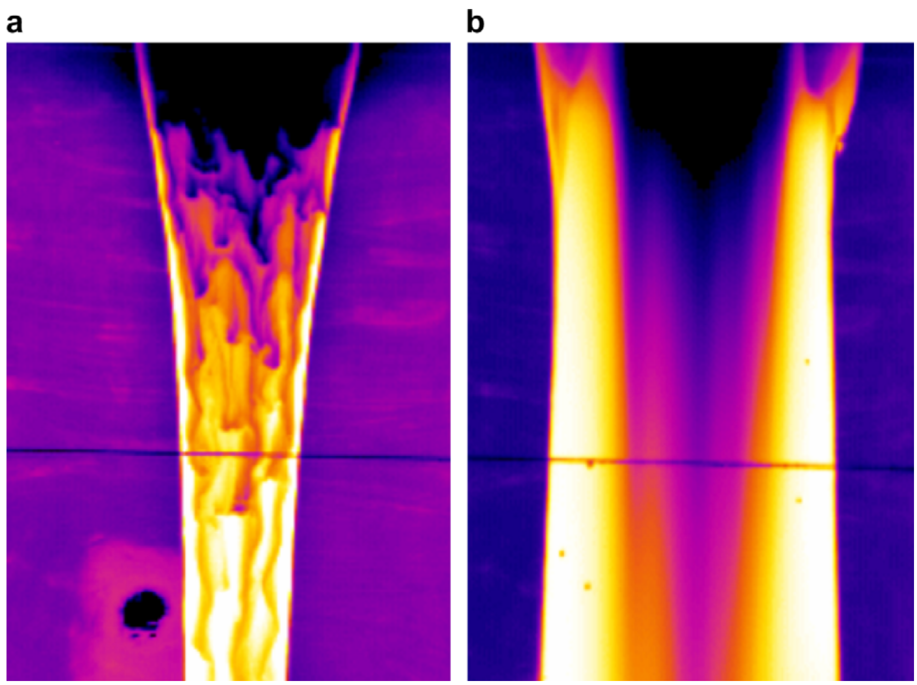


Fig. 15. Thermal images of the film ($\Gamma = 0.06$ kg m^{-1} s^{-1}, $T_0 = 25$ °C and $T_h = 60$ °C). (a) pure water and (b) *n*-octanol aqueous solution at 50 ppm.

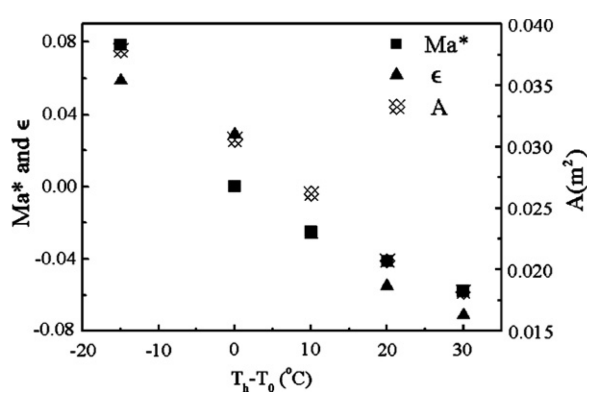


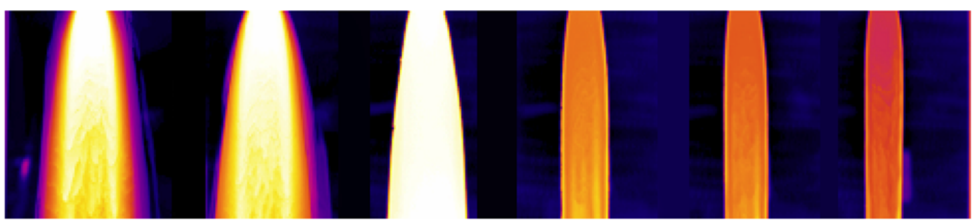
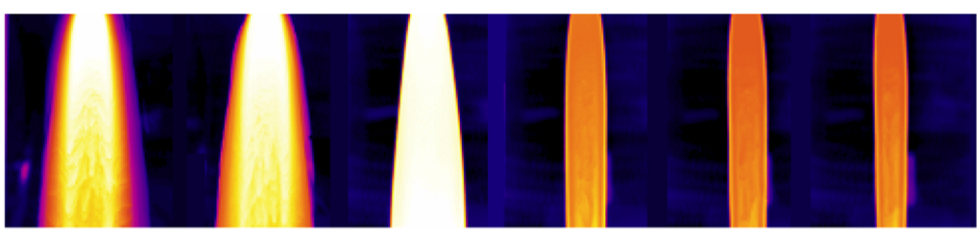
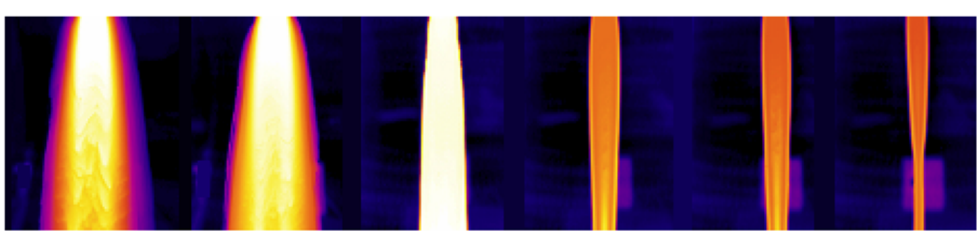
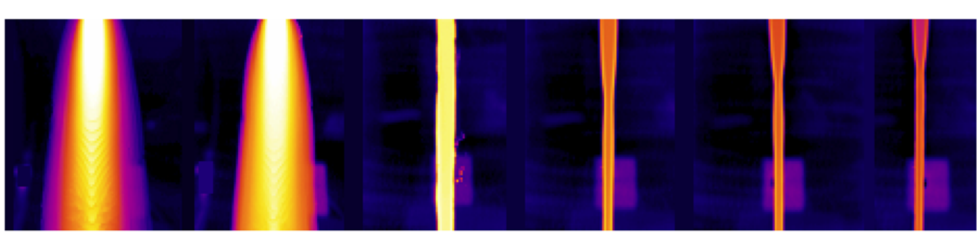
Fig. 16. Variations of Ma*, ε and A with the heating temperature differences ($T_0 = 40$ °C, $\Gamma = 0.18$ kg m^{-1} s^{-1}).

extension is intrinsically caused by the lateral surface tension gradient which is influenced by the variations of the viscosity.

3.2.2. The influence of the Marangoni effect

As can be seen in Figs. 6 and 11, the lateral temperature variations in the cooled/heated films are more predominant than that in the streamwise direction. As investigated by other researchers (Joo et al., 1996; Kabov et al., 2002; Ponter and Davis, 1968; Sultanovic et al., 1997), the streamwise Marangoni effect could affect the surface waves due to the non-uniformity of the temperature in the waves. In general, for a cooled film, owing

Table 2
Thermal images of water films down from a tube-like exit ($T_0 = 50$ °C)

Flow rate (m^3/s) 10^5	T_h(°C) 0.83	1.1	1.4	1.7	1.9	2.2
30						
26						
18						
10						

to the higher temperature at the peak, the local Marangoni flow may retard the surface waves and reduce their amplitudes. On the contrary, for a heated film, the Marangoni effect could reinforce the surface waves due to the higher surface tension at the peak. This probably induces rivulet formations in the transverse direction and sometimes cause breakdown of a film that is intensively heated. Since the surface wave consequentially reinforces the heat transfer of the film by decreasing the thickness of the film substrate that controls the transfer processes (Hetsroni et al., 1996; Chu and Dukler, 1974), the Marangoni effect therefore enhances the heat transfer of a heated film, but reduces the heat transfer of a cooled one.

In this work, special attentions are paid to the lateral Marangoni effect that caused peculiar liquid distribution of the non-isothermal films. The contraction/extension of the heated/cooled films is very similar to the non-isothermal spreading of liquid drops on horizontal plate. Heating (cooling) retarded (augmented) the spreading process of the non-isothermal liquid drops by creating Marangoni flows (Ehrhard and Davis, 1991). It is therefore quite reasonable that the contraction/extension is caused by the lateral Marangoni effect in a non-isothermal film. For a cooled film, the surface tension gradient exists from the rim to the center, inducing the Marangoni flow to eliminate this gradient, so as to cause the film extension. When a film is heated, the surface tension gradient induces the Marangoni flow in the opposite direction of the surface tension gradient, resulting in the contraction.

Based on the variations of the surface tension and the sign of the modified Marangoni number, the systems for the non-isothermal liquid films can be classified in three categories (Zuiderweg and Harmens, 1958), namely, positive systems in which the film surface tension increases, negative systems in which the surface tension decreases and neutral systems in which there is no appreciable surface tension difference. Accordingly, a heated film is a negative system with $\mathrm{Ma}^* < 0$, $A < A_0$, $\varepsilon < 0$; a cooled film is a positive system with $\mathrm{Ma}^* > 0$, $A > A_0$, $\varepsilon > 0$; while an isothermal film can be regarded as neutral(wherein A_0 is denoted as the interfacial area of an isothermal film).

The Marangoni effect in the non-isothermal liquid films is decided by the heating temperature difference $(T_\mathrm{h} - T_0)$. It is shown in Fig. 16, that Ma^*, ε and A all decrease linearly with a rise of $(T_\mathrm{h} - T_0)$. This indicates that the distribution of the liquid film is determined by the heating conditions, i.e., by the Marangoni effect due to the variations of surface temperature.

3.3. Experiments on the liquid films formed through a tube-like exit

The liquid films formed through a tube-like distributor, were also investigated to examine the influence of the film initial condition on the flow. The similar results were obtained as that of the film formed through a long narrow gap. As shown in Table 2, the cooled film is extended distinctly, while the heated film is contracted though there is a slight extension in the initial flow. The isothermal films are extended with their width located between those of the heated and cooled films. Similarly, the interface area decreases with the decreasing heating temperature difference, indicating notable influence of the Marangoni effect on the film's distribution.

4. Conclusions

In this work, the Marangoni effect on the liquid distribution of heated/cooled film flowing over a vertical solid plate was experimentally investigated by using the infrared imaging technology. It is found that the distributions of the non-isothermal films are sensitive to the heating conditions. The heated/cooled film is contracted/extended evidently by the lateral Marangoni effect that is prominent in the transverse direction. There are $\mathrm{Ma}^* < 0$, $A < A_0$ and $\varepsilon < 0$ for a heated film, while $\mathrm{Ma}^* > 0$, $A > A_0$ and $\varepsilon > 0$ for a cooled film.

The contraction or extension of the non-isothermal film is determined by the heating temperature difference $(T_\mathrm{h} - T_0)$ and flow rate. Larger heating temperature difference corresponds to the less flow area. For the cooled film, the Marangoni number rises with the increasing Reynolds number. For the heated films, the Marangoni effect is dominant at low flow rate, but becomes limited when the Reynolds number is large enough. The experimental results for the heated films are quite consistent with Joo's conclusion (Joo et al., 1996). It was also shown that the flow of the heated film was greatly changed when trace level surfactant was added to the liquid film. This indicates that the viscosity variations in the non-isothermal flow probably influence the non-isothermal film flow by changing the temperature field of the film. Therefore, the contraction or extension of the films is mainly caused by the lateral surface tension gradient, which may be determined by the variations of the viscosity.

Acknowledgements

The authors are grateful to the financial support from the National Natural Science Foundation of China (No. 20576050).

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