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On the migration of a droplet on an incline

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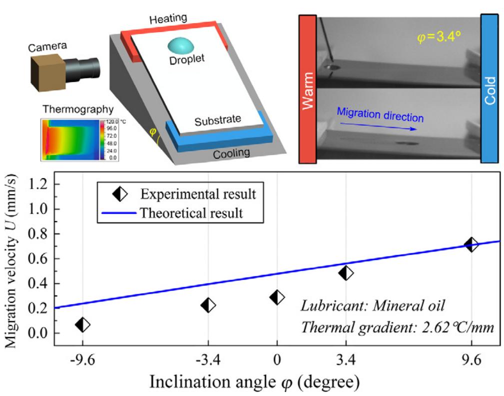
GRAPHICAL ABSTRACT



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ABSTRACT

A liquid droplet placed on a nonuniformly heated solid surface will migrate from a high temperature region to a low temperature region. The present study reports the results of an experimental investigation on the migration behavior of mineral oil droplets subjected to a thermal gradient on an inclined plane. A particular attention is paid to the relationship between the critical inclination angle and thermal gradients. It is shown that there exists a critical inclination angle at which the droplet migration is halted. This critical inclination angle can be readily predicted using analytical expressions derived in this paper. This study puts forward the understanding of the interface phenomenon of thermocapillary migration on an incline. The knowledge of the critical inclination is important in applications where the migration on an incline must be obstructed to retain adequate lubrication in the desired location.

1. Introduction

Surface tension driven migration is an intriguing phenomenon that substantially affects the variation in the interfacial tension of a liquid in a manner that will provide the driving force on the liquid to induce motion from the low tension to high tension regions [1–5]. The interfacial tension of a liquid droplet on a surface can be reduced substantially by increasing the surface temperature [6,7]. This implies that when placing a liquid droplet on an isothermal smooth surface, the thermal gradient can induce the droplet migration from the high temperature to low temperature regions.

This kind of migration is widely encountered in machinery from engines to compressors to mixers and in vital mechanical components such as piston rings and bearings [8]. In a mechanical sys-

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tem, thermal gradients are present either due to the proximity to a heat source or they are spontaneously generated by the friction between the lubricated surfaces in relative motion [9]. In some applications, one may desire to intentionally promote liquid migrate via the temperature difference [10]. In others, the application may require one to minimize the lubricant migration in order to ensure that adequate lubrication is present where it is needed [11]. Thus, research is needed to better understand the nature of liquid droplet migration and means to control it.

Clearly, a liquid droplet placed on a horizontal homogenous surface will remain stationary unless acted upon by an external force or a thermal gradient [12–15]. If a droplet is placed on a plane tilted at an angle, then the unbalanced forces between the down plane component of the droplet gravity, the viscous resistance force, and the capillary force can provide the necessary driving force to induce motion [16]. A previous research on liquid droplets on a stage titled solid surface demonstrated that contact line forces could be described in terms of contact angles and surface tension [17]. Later, a theoretical model was developed for predicting static droplet shapes and critical droplet motion on an inclined plane and provided a clear understanding of how a droplet can be retained on smooth hydrophobic surfaces [18]. Many insightful experimental and theoretical studies have subsequently been reported that explore the droplet motion on an inclined surface in the absence of thermal gradients [19–23].

When a surface subjected to a uniform thermal gradient is inclined, the thermal capillary migration behavior will become complicated. Not only does the thermal gradient (surface tension) but also the inclination (gravity) will affect the force balance in the vicinity of the three phase contact line of the droplet. The previous researches on the thermocapillary migration have neglected the role of gravity with published experimental work confined to the investigation of motion on a horizontal plane. Meanwhile, most studies on the droplet motion on an incline do not consider the effect of the thermal gradient. A review of the open literature also reveals that an analytical model for describing the combined effect of gravity and a thermal gradient is currently lacking and that a systematic research of the migration behavior is needed. Indeed, the investigation on this interface phenomenon is of significant importance in the understanding of wetting and spreading behavior of a liquid on a nonuniformly heated and inclined solid surface.

In another aspect, previous researches normally use the migration velocity to characterize the migration features [24,25]. The implementation of the initial migration procedure is somewhat fickle since the spreading is initially rapid and slows down gradually. Thus, it is difficult to measure the migration distance and calculate the velocity at the initial state [26]. Moreover, in applications where the migration rate is very slow, it can take more than 200 h to measure the migration distance [27]. Using the inclination angle to describe the migration capillary provides a novel viewpoint and meaningful insight into this interface phenomenon.

In this paper, we report the results of an experimental and theoretical study of the thermocapillary migration of a liquid droplet on an incline. We experimentally investigate the migration velocity on an isothermal solid surface inclined at an angle and theoretically provide a realistic model for the prediction of the migration velocity. Comparisons between experimental and theoretical results are presented, and a particular attention is paid to the relationship between the inclination angle and the thermal gradient.

2. Experimental section

2.1. Materials

The metal specimen is made of SUS 316 stainless steel with dimensions of 76 mm × 30 mm × 3 mm with an average surface roughness R_a = 0.02 μm. An industrial mineral oil (Mineral Oil, product number: NF-70, Colonial Chemical Solutions, Inc., Savannah, Georgia, USA), as received, is utilized in all experiments reported in this paper. See Table 1 for property values. The dosage is kept constant at 5 μL using a microliter syringe. The surface tension of mineral oil is measured via the Wilhelmy plate method. Fig. 1 shows the measured surface tensions at various temperatures. It can be seen that the surface tension decreases with increasing temperature. The mean surface tension coefficient is calculated and utilized in the theoretical analysis, and the main physical parameters of mineral oil are listed in Table 1.

Table 1
Physical parameters of mineral oil at 20 °C.

Parameter	Mineral oil
Kinematic viscosity, mm^2/s	33.06
Density, g/cm^3	0.853
Surface tension coefficient, mN/(m °C)	0.0855

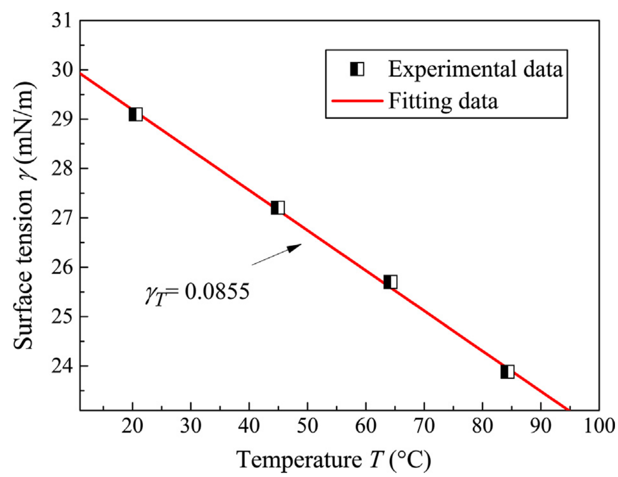

Fig. 1. Surface tension and temperature correlation of the mineral oil.

2.2. Method

The experimental apparatus designed for this study is shown in Fig. 2. The mental specimen is tightly attached to the heating and cooling elements to obtain a good thermal contact and the migration experiments are performed on it. The temperatures of the heating and cooling elements are controlled precisely to generate a unidirectional thermal gradient on the surface. The measured thermography demonstrates that the temperature decreases nearly linearly along the length of the specimen, and the average thermal gradient is used to analyze the results. The specific temperature values set in this study are shown in Table 2.

A digital video camera (SVSi, StreamView) is used to monitor the dynamic migration process. Via extracting the frames, the quantitative experimental data, including the droplet height h and migration distance (scales at the front edge of the droplet) are obtained. In all the experiments, the mineral oil is dropped at the same starting position. The droplet is permitted to migrate for 30 s to the cold side and the mean migration velocity is calculated.

3. Results and discussion

3.1. Migration properties

Fig. 3a shows the results of a series of oil migration experiments obtained with 5 μL mineral oil droplets subjected to a thermal

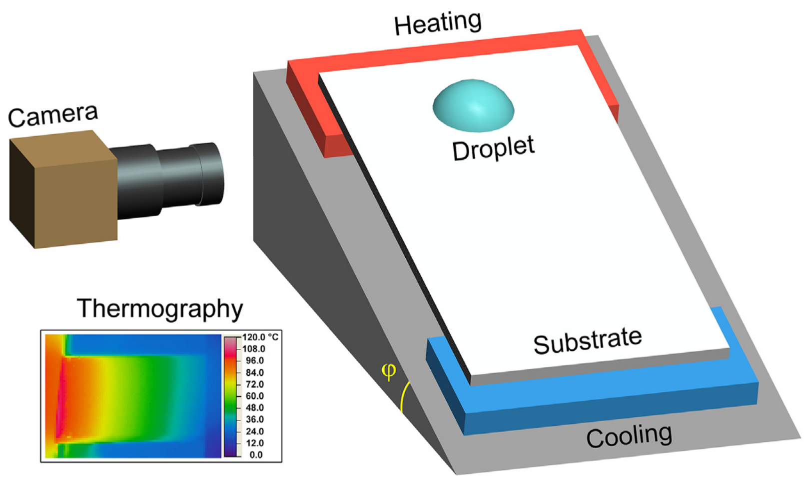

Fig. 2. Schematic diagram of the experimental apparatus.

Table 2
The specified temperatures of warm and cold sides in the study.

Temperature (°C)		Thermal gradient (°C/mm)
Cold side, T_C	Warm side, T_W	
0	100	2.38
0	110	2.62
15	125	2.62
0	120	2.86
0	132	3.14
15	147	3.14

The effective length of the testing surface is about 42 mm.

gradient of 3.14 °C/mm on a surface at different inclination angles. As shown in this figure, when the surface inclination angle is positive, the migration distance is increased, and that increasing the inclination angle will contribute to the migration distance. When the surface inclination angle is negative, the migration distance is smaller, and that the larger the inclination angle, the greater is the obstruction to the droplet's migration.

Fig. 3b shows the effects of inclination angle on the migration velocity under different thermal gradients. Experiments are performed on a surface with inclination angles of −9.6, −3.4, 0, 3.4 and 9.6 degrees subjected to the thermal gradients of 2.62 and 3.14 °C/mm. Note that increasing the inclination angle (from −9.6 degrees to 9.6 degrees) will accelerate the migration velocity gradually. Referring to Table 2, we set the temperature of the warm side 125 °C/110 °C and cold side 15 °C/0 °C to achieve a thermal gradient of 2.62 °C/mm. Under this thermal gradient, it is interesting to find that the migration velocity of T_W = 125 °C is faster than that of T_W = 110 °C, and a similar trend is observed when the thermal gradient increases to 3.14 °C/mm. The experimental results indicate that both the thermal gradient and the temperature of the warm and cold sides affect the migration velocity.

Given that the migration velocity decreases with decreasing inclination angle, we now proceed to determine the critical inclination angle at which the droplet migration is halted and it remains stationary. This is of particular interest in applications where one desires to ensure that adequate lubrication is present in a particular region of a component. Migration experiments are conducted under different thermal gradients to investigate the effect of inclination angle, and the cold side is maintained at T_C = 0 °C. At a thermal gradient of 2.38 °C/mm, the migration velocity is relatively low and the inclination angle is about −17.1 degree. When the thermal gradient increases to 3.14 °C/mm, the migration velocity is increased correspondingly and the inclination angle is approximately −28.3 degree. The results shown in Fig. 4 demonstrate that critical inclination angles exist for all the tested different thermal gradients.

3.2. Theoretical hypothesis

The experimental results exhibit that different migration velocities are obtained under different conditions, and there exists a critical inclination angle for a specified thermal gradient. To gain insight, we now proceed to perform an analytical derivation to analyze this motion. Referring to Fig. 5, consider a two dimensional model of a droplet on a plane with an inclination angle φ and exposed to a constant thermal gradient. The footprint of the droplet is specified at the positions of points A and B in the side view. The thermal gradient is considered to be constant, $\frac{\partial T}{\partial x} = const = C_T$. The inclination angle φ is positive when the heated part of the plane is located at a higher elevation than the cooler section.

The geometric features of the droplet have a significant influence on the theoretical model. Our experimental observation (Fig. 3a) reveals that the droplet shape tends to flatten to a thin pancake shaped configuration as the migration progresses. The droplet, therefore, behaves as thin film curved only at the rim. We ignore the variation of the contact angle induced by the thermal gradient, regarding it as a small constant value.

A previous study on the thermocapillary motion of a liquid drop on a horizontal solid surface has proven that the motion can be regarded as a quasi-steady process [28]. In this study, we adopt this assumption and utilize the thin-film lubrication theory to predict the migration velocity of the droplet. There exist three forces on a droplet migrating on an incline: the viscous resistance force, the gravity force, and the unbalanced Young force. These forces are described in the following section.

3.2.1. Viscous resistance force

Referring to Fig. 5, consider a droplet of height h and the width is L. The velocity in the droplet is governed by the Navier-Stokes and the continuity equations:

$$\frac{D\mathbf{V}}{Dt} = \mathbf{F} - \frac{1}{\rho}\nabla\mathbf{P} + \frac{\mu}{\rho}\nabla^2\mathbf{V} \quad (1)$$

$$\nabla\mathbf{V} = 0 \quad (2)$$

where **V** is the flow velocity, **F** is the inertial force, **P** is the pressure field, ρ is the density of the liquid, and μ is the dynamic viscosity.

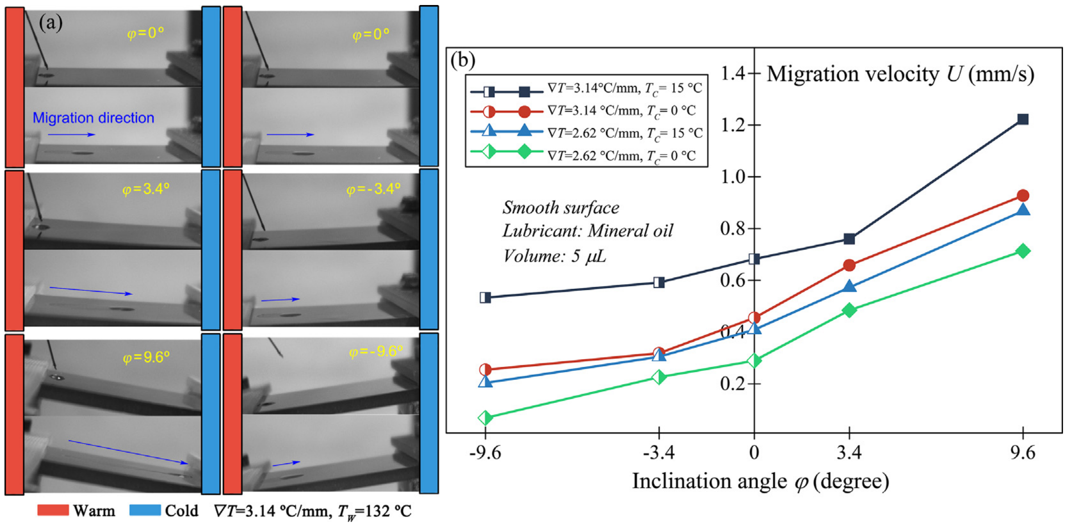

Fig. 3. (a) Thermocapillary migration of mineral oil droplet with volume of 5 μL on the smooth surface inclines in different angles, induced by a unidirectional thermal gradient of ∇T = 3.14 °C/mm and T_W = 132 °C. (b) Detailed results of migration velocities U under different experimental conditions.

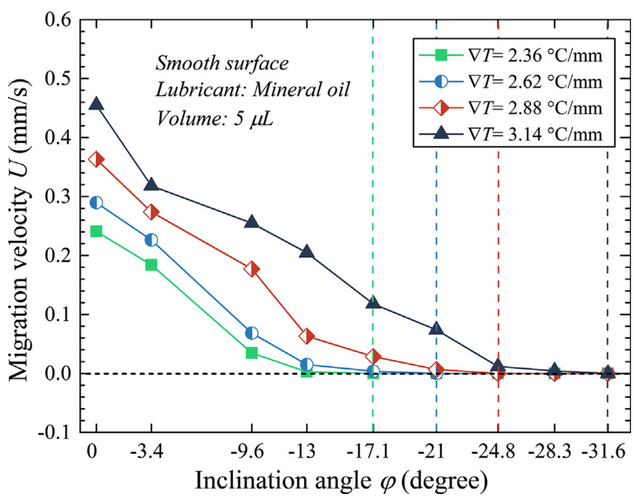

Fig. 4. The critical inclination angle φ of different thermal gradients under which the droplet migration is halted.

In processes involving thermocapillary migration, the velocity is very slow (creeping motion), the viscous force dominates the inertial forces, and the thin film lubrication approximation applies. Thus, Eq. (1) reduces to:

$$\frac{\partial P}{\partial x} = \mu \frac{\partial^2 V_x}{\partial z^2} \tag{3}$$

Assuming a reference frame traveling with the droplet, the droplet can be regarded as stationary and the substrate moves in the negative x direction with a constant speed U. The boundary conditions at $z = h(x)$ and $z = 0$ are:

$$\begin{cases} \frac{\partial V_x}{\partial z} = \frac{1}{\mu}\frac{\partial \gamma}{\partial x}, & z = h(x) \\ V_x = -U, & z = 0 \end{cases} \tag{4}$$

where γ is the surface tension of the liquid.

Integrating Eq. (4), applying the boundary conditions, and solving for the velocity field, we have:

$$V_x(z) = \frac{1}{\mu}\left[C_T \gamma_T z + \frac{1}{2} \cdot \frac{\partial P}{\partial x}(z^2 - 2zh)\right] - U \tag{5}$$

where γ_T represents the surface tension coefficient, $\gamma_T = \frac{\partial \gamma}{\partial T}$.

There is no volumetric flux passing through the vertical cross section of the droplet in the frame of moving reference. Therefore,

$$\int_0^h V_x(x, y, z)dz = 0 \tag{6}$$

Combining Eqs. (5) and (6), the viscous stress σ_{xz} at the solid–liquid interface satisfying this constraint is given:

$$\sigma_{xz(z=0)} = \mu\left(\frac{\partial V_x}{\partial z}|_{z=0}\right) = \frac{3\mu}{h}U - \frac{1}{2}C_T\gamma_T \tag{7}$$

Ignoring the change in the thickness at the rim of the thin film, i.e., h is constant between positions A and B (see Fig. 5), one arrives at the following equation for the viscous resistance force F_v:

$$F_v = \int_{x_A}^{x_B} \sigma_{xz(z=0)}dx = \frac{3\mu}{h}UL - \frac{1}{2}\gamma_T C_T L \tag{8}$$

3.2.2. Gravity force

The gravity force acting on the droplet per unit length can be described by the following relationship:

$$F_g = \frac{Mg \sin \varphi}{L} \tag{9}$$

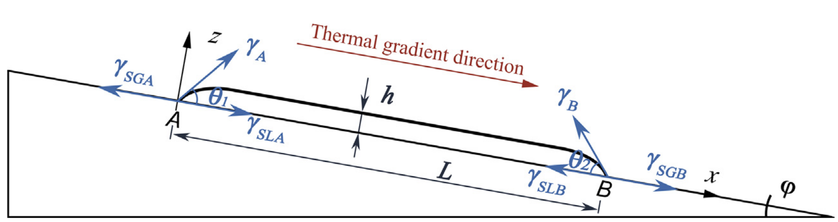

Fig. 5. Side view of a droplet film on an incline.

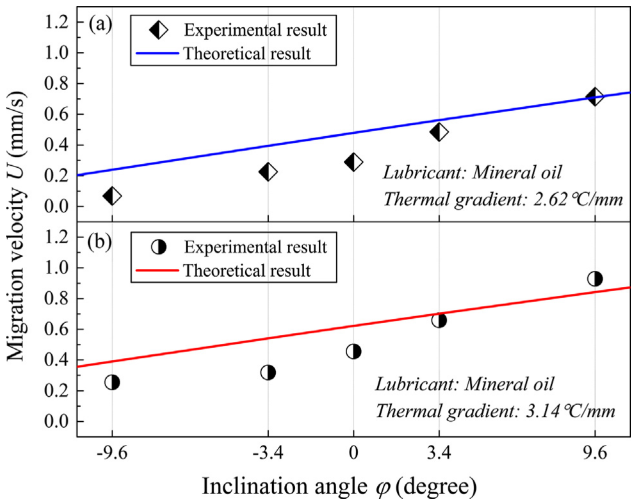

Fig. 6. Comparison between the experimental and theoretical results of migration velocity U plotted as a function of inclination angle φ, under a thermal gradient of (a) 2.62 and (b) 3.14 °C/mm.

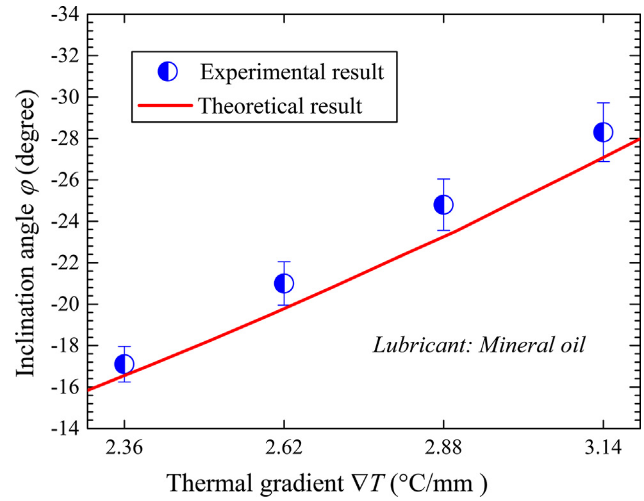

Fig. 7. Comparison between the experimental and theoretical results of critical inclination angle under different thermal gradients.

where M is the mass of the droplet, and g is the acceleration of gravity. When the inclination angle φ is positive, F_g acts as the driving force; If φ *is* negative, F_g represents a resistance force.

3.2.3. Young force

The Young's equation defines the interfacial tension force balance and contact angle in the vicinity of three phase contact line [29]:

$$\gamma_{SG} = \gamma_{SL} + \gamma \cos\theta \tag{10}$$

where γ_{SG} and γ_{SL} are the solid–gas and solid–liquid interfacial tension forces, respectively, θ is the equilibrium contact angle. The unbalanced Young force, i.e. the driving force (F_d) acting on the droplet, is;

$$F_d = (\gamma_{SG} - \gamma_{SL})_B - (\gamma_{SG} - \gamma_{SL})_A \tag{11}$$

The interfacial tension relationship between positions A and B (see Fig. 5) along the footprint of the droplet can be described as:

$$\gamma = \gamma_0 + \frac{\partial \gamma}{\partial x} x = \gamma_0 + C_T \gamma_T x \tag{12}$$

where γ_0 is the reference surface tension of the liquid.

Combining Eqs. (10)–(12), we arrive at the following equation for the driving force F_d:

$$F_d = \gamma_T C_T L \cos\theta \tag{13}$$

The force acting on the droplet under the unidirectional thermal gradient can be deduced from a balance between the driving and resistance forces, that is:

$$F_v = F_d + F_g \tag{14}$$

Substituting Eqs. (8), (9) and (13) into Eq. (14), the migration velocity can be described by the following relationship:

$$U = \frac{(2\cos\theta + 1)\gamma_T C_T L^2 + 2Mg \sin\varphi}{6\mu L^2} h \tag{15}$$

The expression for the droplet velocity in Eq. (15) can also be applied to an incline. Moreover, in the cases when the inclination angle is negative, under a specific thermal gradient C_T, there exists a critical inclination angle φ at which the liquid droplet remains stationary, i.e. $U = 0$. The critical angle can be predicted by letting $U = 0$ in Eq. (15):

$$C_T(2\cos\varphi + 1)\gamma_T L^2 + 2Mg \sin\varphi = 0 \tag{16}$$

Solving for the critical inclination angle φ, we arrive at the following relationship:

$$\varphi = -\arccos\left(\frac{-2\Psi^2 + \sqrt{3\Psi^2 + 1}}{4\Psi^2 + 1}\right) \tag{17}$$

where $\Psi = \frac{C_T \gamma_T L^2}{2Mg}$.

3.3. Theoretical validation

The comparison between the experimental and theoretical results of migration velocity under the thermal gradients of 2.62 and 3.14 °C/mm are shown in Fig. 6, and the cold side is maintained at $T_C = 0$ °C. Referring to Fig. 6a, as the scatter diagram exhibits, when the inclination angle is −9.6 degree, the migration velocity is about 0.1 mm/s, and it increases rapidly as the inclination angle increases. The line graph shows the theoretical result of the migration velocity. It can be observed that the predicted velocity results are in agreement with the experimental data both in trend and in magnitude. Fig. 6b presents the comparison between the experimental and theoretical results under a thermal gradient of 3.14 °C/mm. Note that the theoretical data agree quite well with the experimental result, and at the inclination angle of −9.6 degree, the migration velocity is about 0.25 mm/s. As expected, increasing thermal gradient clearly increases the migration velocity.

Fig. 7 presents the comparison between the experimental and theoretical results of the critical inclination angle under different thermal gradients. When the thermal gradient is 2.36 °C/mm, the theoretical value is a slightly lower than the experimental result. The critical inclination angle increases with increasing the thermal gradients. As the thermal gradient increases to 3.14 °C/mm, the theoretical value is lower than the experimental result, and the difference between experimental and theoretical results is a little bit larger than that at the thermal gradient of 2.36 °C/mm.

3.4. Further discussion

In the analytical model, we considered the cross section of the droplet to have a pancake shaped configuration. A variety of models are available for describing the motion of droplets on a solid surface driven by the thermal gradients, and when the droplets spread in the form of a thin film, the assumption of a thin pancake shaped configuration is indeed reasonable [30]. Accordingly, the deformation of the droplet shape during the migration is negligible and the quasisteady equilibrium can be assumed. The theoretical derivations in this study satisfy this constraint.

In general, a droplet resting on a solid surface has a spectrum of contact angles ranging from advancing contact angle, θ_A, to the receding contact angle, θ_R. This so-called contact angle hysteresis is induced by the resistance at the solid–liquid interface [31]. According to Tadmor's approach [14,32,33], this resistance will bring in a lateral retention force, $f_{||}$, acting on the droplet sliding along the surface:

$$f_{\parallel} = \frac{4\gamma^2 \sin\theta}{G}(\cos\theta_R - \cos\theta_A) \quad (18)$$

where G is the shear modulus associated with the solid surface.

The lateral retention force, $f_{||}$, will affect the force balance at the leading and trailing edges of the droplet, particularly in situations where a significant difference exists between θ_A and θ_R. In our theoretical model, the droplet is assumed to have a thin pancake-shaped configuration, and the equilibrium contact angle is regarded as a small constant value. Our experimental observations (Fig. 3a) also validates that the contact angle is negligibly small. Therefore, the lateral retention force is ignored in the theoretical derivation.

Three lateral forces act on the droplet: viscous resistance force, gravity force, and unbalanced Young force. In this study, we established an appropriate force balance at the leading and trailing edges of the liquid droplet by developing a 2D model, which makes the prediction of migration velocity relatively easy to realize. Nevertheless, the normal forces acting on the droplet influence the lateral forces [6], and this effect should be taken into consideration in the future studies. Moreover, a 3D model will be necessary to obtain more accurate predictions, at the expense of additional complications in the derivations and treatment.

The initial temperature of a droplet plays an important role in the acceleration phase at the beginning of migration, and can potentially affect the migration velocity [34]. Research also shows that the migration velocity due to thermal gradient is inversely proportional to the dynamic viscosity [35]. In the current model, as a relationship in Eq. (15) indicates, the migration velocity of a droplet is inversely proportional to the dynamic viscosity. Because for a liquid lubricant, the viscosity drops exponentially with increasing temperature [36]. Therefore, under the same thermal gradient, the liquid viscosity at $T_W = 125$ °C is lower than that at $T_W = 110$ °C. This is the reason that a higher initial temperature induces a faster migration velocity. Therefore, the migration velocity of $T_W = 132$ °C is faster than that of $T_W = 110$ °C, as revealed by the experimental results shown in Fig. 4b. Moreover, referring to Eq. (15), the migration velocity is proportional to the thermal gradient. The results shown in Figs. 3b and 4 verify the fact that migration velocity will increase with the increasing thermal gradient.

The theoretical results shown in Fig. 6 agree well with the experimental data both in trend and in magnitude; however, slight differences exist due to the factors described next. First, in the analytical model, the surface is assumed to be completely smooth. Our previous research [37] revealed that the migration velocity decreases with decreasing surface roughness under certain conditions. Therefore, the surface roughness influences the results of the migration velocity. Second, the current model ignores the rim of the droplet film and does not take the contact angle into consideration in the calculation. Moreover, as the migration progresses, there is a little residual oil leaving along its trajectory. Consequently, the volume of the droplet decreases a little and the migration velocity is affected.

The theoretical results shown in Fig. 7 reveal that the critical inclination angle increases with increasing the thermal gradients. However, slight differences exist between the theoretical calculation and experimental results. When the migration is halted, the viscous resistance force is nil. Therefore, the inclination angle becomes independent of the viscosity and the main difference comes from the thermal gradient C_T and the droplet width L. As indicated by the Eqs. (16), (17) and the theoretical results shown in Fig. 7, the inclination angle is proportional to C_T and L. In the current calculations, we use the observed value of L at the moment when the droplet was placed on the surface. Nevertheless, a droplet is more prone to spreading to the surrounding under higher temperature [38]. In other words, the higher the thermal gradient C_T, the larger the droplet width L becomes. This means that at a higher thermal gradient C_T, a larger value of L should be employed in the theoretical calculations. Accordingly, at a high thermal gradient the difference between the theoretical predictions and experimental measurements is larger. The results shown in Fig. 7 exhibit this trend. Thus, despite the simplicity of the model, the analysis provides useful insight into the phenomenon of thermocapillary migration on an inclined plane, which should be of interest in many engineering applications. While we have concentrated on the lubrication condition where a droplet motion is forced to stay stationary, in a particular application, one may wish to have the droplet move faster, and wet the surface quicker. Creating a thermal gradient on a surface or inkling the surface would promote the liquid wetting on the desired areas.

4. Conclusions

On the basis of the previously reported researches, the migration of a droplet is mainly performed on a horizontal plane. In the experimental aspect, researches are focused on the approaches to induce or impede the migration [6,8,12,24,34]. In the theoretical aspect, works are concentrated on the understanding of the mechanism [3,25,28,30,32]. Meanwhile, most studies on the droplet motion on an incline do not consider the effect of a thermal gradient [18–23,26]. Hence, the present work reports a systematic study on the thermocapillary migration of droplets on an incline. We hypothesize that surface forces and thermally driven forces can be balanced by adjusting the angle of an incline to control the motion of the droplet. Alternatively, if the angle is fixed, the thermal gradient (via adjusting the heat source or sink) to maintain the position of the droplet stationary. We show the validity of this hypothesis via experiments and an analytical derivation. This study puts forward the understanding of the interface phenomenon of thermocapillary migration on an incline. The knowledge of the critical inclination is important in applications where the migration on an incline must be obstructed to retain adequate lubrication in the desired location. Presently, our experimental results and analytical derivations deal with smooth surfaces. In the future, the role of surface finish, coating or surface texture can be introduced into the theoretical derivation and experiments and the interface interaction between the surface structure and liquid droplet can be investigated.

Acknowledgments

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.jcis.2017.01.055.

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