Journal of Colloid and Interface Science 494 (2017) 8–14

Contents lists available at ScienceDirect

Journal of Colloid and Interface Science

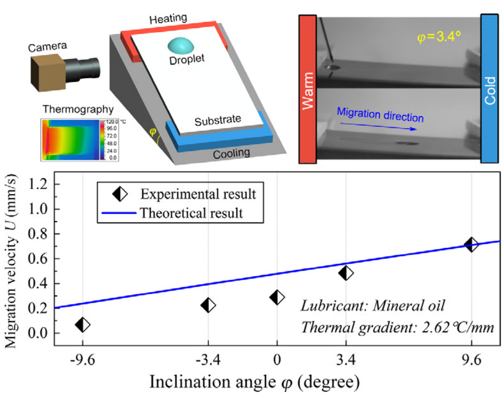
journal homepage: www.elsevier.com/locate/jcis

On the migration of a droplet on an incline

Qingwen Dai [a,c], M.M. Khonsari [b,*], Cong Shen [b], Wei Huang [a], Xiaolei Wang [a,c]

[a] College of Mechanical and Electrical Engineering, Nanjing University of Aeronautics & Astronautics, Nanjing 210016, China
[b] Department of Mechanical and Industrial Engineering, Louisiana State University, 3283 Patrick Taylor Hall, Baton Rouge, LA 70803, USA
[c] Jiangsu Key Laboratory of Precision and Micro-Manufacturing Technology, Nanjing 210016, China

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 2 December 2016
Revised 13 January 2017
Accepted 17 January 2017
Available online 18 January 2017

Keywords:
Thermocapillary migration
Surface tension
Inclination angle
Lubrication approximation

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-

* Corresponding author.
E-mail address: khonsari@me.lsu.edu (M.M. Khonsari).

http://dx.doi.org/10.1016/j.jcis.2017.01.055
0021-9797/

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

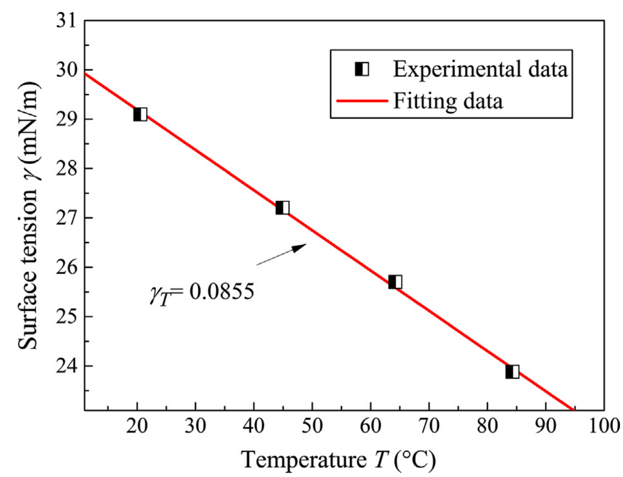


Fig. 1. Surface tension and temperature correlation of the mineral oil.

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