SELF-PROPULSION OF LIQUID DROPS BETWEEN NON-PARALLEL STRUCTURES AT LEIDENFROST STATE

by

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Abstract

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In this work, we explored self-propulsion of a liquid drop between non-parallel structures at a temperature above its Leidenfrost point**.** A theoretical model was first developed to determine conditions for a drop to move away from the corner of two non-parallel plates. Subsequently, these results were validated by experiments. Finally, in Leidenfrost states, both lyophilic and lyophobic drops were shown to have the same dimensional movements away from the corner of two non-parallel plates.

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Chapter 1

INTRODUCTION

A liquid drop may show a different behavior in its Leidenfrost state, i.e., when its temperature is above its Leidenfrost point. At such a temperature, a vapor film is formed between the drop and its substrate.[1] This film reduces the rate that the heat is transferred from the substrate. Consequently, the liquid drop may have a longer life time. For example, a water drop may vanish within 10 s when the substrate temperature is around the boiling point, while the drop may exist over 1 min in its Leidenfrost state.[2]

In recent tests, when Isopropyl alcohol (IPA) drops were put between two non-parallel Al plates at three different temperatures, we have also observed some interesting phenomena. The boiling and Leidenfrost temperatures of IPA were measured on an Al plate to be 85 ^{o}C and 115 ^{o}C, respectively. At room temperature (around 25 ^{o}C), which was below its boiling point, a drop transported towards the corner of two non-parallel Al plates (Fig. 1-1a). However, it moved away from this corner at 125 ^{o}C, which was above its Leidenfrost point (Fig. 1-1b). Even if it lost contact with the top plate, it still kept moving till it ran out of our 80-mm-long bottom plate. At 100 ^{o}C, which was between its boiling and Leidenfrost points (Fig. 1-1c), an IPA drop did not move between two plates. Instead, as expected, it vanished within several seconds due to evaporation.

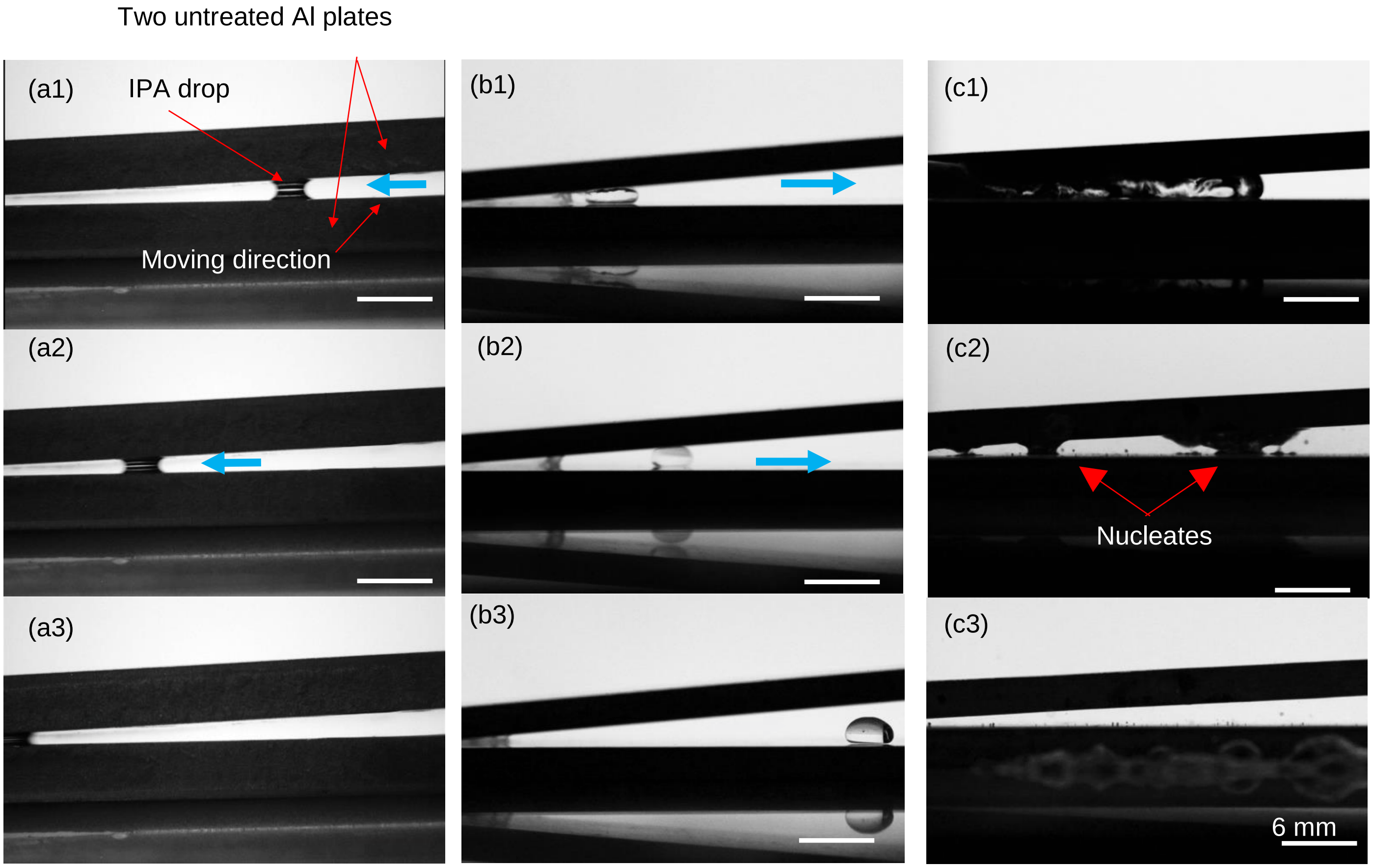

Figure 1-1: At 25 ^{o}C, after an IPA drop had been placed between two Al plates, (a1, a2) it moved towards the corner formed by the two plates, and (a3) finally filled this corner. At 215 ^{o}C, after an IPA drop had been placed between two Al plates, (b1, b2) it moved away from the corner formed by the two plates, and (b3) finally left the plates. At 100 ^{o}C, after an IPA drop had been placed between two Al plates, (c1, c2) it initiated nucleate boiling, and (c3) finally evaporated.

In the previous works, we explored the behavior of a liquid drop between two non-parallel plates.[3] We derived a criterion to judge drop movement. That is, when the difference between advancing and receding contact angles was less than the apex angle of the two plates, a liquid drop with an apparent contact angle less than 90° should move towards the corner of these two plates. This criterion applied to our room-temperature case. In this case, the apex angle was 5°, while receding and advancing contact angles were 13° and 18°, respectively. Accordingly, the IPA drop should move towards the corner of the two plates at this temperature. Meanwhile, in a previous work,[3] we have also shown that, when a liquid drop with an apparent contact angle larger than 90° was first squeezed and then relaxed by decreasing and increasing the apex angle of the two plates, respectively, it should move away from the corner. On the other hand, we have not derived conditions for a drop to have this dimensional movement when the two plates have to remain stationary. To address the behavior of the IPA drop at 115 °C, such conditions are derived in this work.

It has been reported that a liquid drop is also capable of having dimensional movement on ratchets at a temperature above its Leidenfrost point.[4,5] This movement is induced by a viscous vapor flow that emerges between the drop and ratchets.[4] However, the corresponding driving mechanism may not be applicable here, since the Al plates in our tests have flat surfaces. Asymmetric wettability of surface structures may direct drop movement as well,[6,7] whose driving principles are also different from ours.

Chapter 2

THEORITICAL MODEL

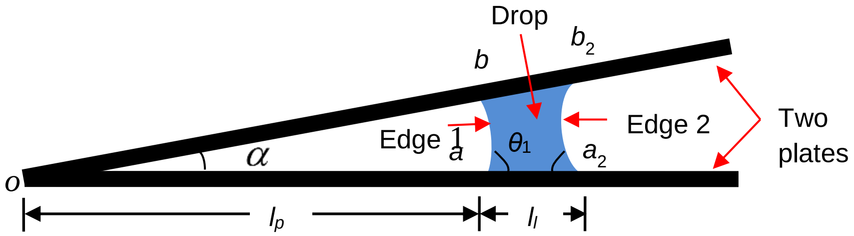

Figure 2-1: Cross-sectional schematic of a liquid drop placed between two non-parallel plates.

For simplicity, the left and right edges of the liquid drop are called “Edge 1” and “Edge 2”, respectively. Use o and α , respectively, to denote apex edge and angle of the two plates. Let a_1 and b_1 denote the two points that Edge 1 intersects with the bottom and top plates, separately, and set a_2 and b_2 to be the two intersecting points that Edge 2 forms with the bottom and top plates, respectively. Use l_p to denote the distance between o and a_1, and let l_l be the length of a_1a_2. Let θ_1 represent equilibrium contact angle[10] at a_1 and b_1, and use θ_2 to stand for the one at a_2 and b_2. Set θ_{adv} and θ_{rec} to be, respectively, advancing and receding contact angles. Then, both θ_1 and θ_2 vary between θ_{adv} and θ_{rec}. Let p_{w1} and p_{w2} denote the liquid pressures at Edges 1 and 2, respectively.

According to our previous work,[3] these pressures can be expressed as:

$$p_{w1} = \frac{-\gamma\cos(\theta_1 - \frac{\alpha}{2})}{l_p \sin\frac{\alpha}{2}} + p_a, \tag{1}$$

$$p_{w2} = \frac{-\gamma\cos(\theta_2 + \frac{\alpha}{2})}{(l_p + l_l)\sin\frac{\alpha}{2}} + p_a, \tag{2}$$

where p_a denotes atmospheric pressure.

It follows from Eqs. (1) and (2) that the pressure difference, $(p_{w1} - p_{w2})$, is

$$p_{w1} - p_{w2} = \frac{-\gamma\cos(\theta_1 - \frac{\alpha}{2})}{l_p \sin\frac{\alpha}{2}} + \frac{\gamma\cos(\theta_2 + \frac{\alpha}{2})}{(l_p + l_l)\sin\frac{\alpha}{2}}. \tag{3}$$

To make the drop move away from the plate corner, we should have

$$(p_{w1} - p_{w2}) > 0. \tag{4}$$

With the aid of Eq. (3), consideration of Ineq. (4) results in the following claim:

if and only if

$$\theta_{rec} > (\frac{\pi}{2} + \frac{\alpha}{2}), \tag{5}$$

$$(1 + \frac{l_l}{l_p}) > \frac{\cos(\theta_{adv} + \frac{\alpha}{2})}{\cos(\theta_{rec} - \frac{\alpha}{2})}, \tag{6}$$

then a liquid drop that is put between two non-parallel plates moves away from the corner of the two plates.

This claim is proved below. Let $(p_{w1}-p_{w2})_{\min}$ represent the minimum value of the pressure difference for fixed l_l, l_p and α. According to monotonically decreasing property of cosine functions, it follows from Eq. (3) that

$$(p_{w1}-p_{w2})_{\min}=\frac{-\gamma\cos(\theta_{rec}-\frac{\alpha}{2})}{l_p\sin\frac{\alpha}{2}}+\frac{\gamma\cos(\theta_{adv}+\frac{\alpha}{2})}{(l_p+l_l)\sin\frac{\alpha}{2}}, \tag{7}$$

which happens at the moment that the drop begins to move away from the corner. At this moment, θ_1 and θ_2 equal θ_{rec} and θ_{adv}, respectively. If Ineqs. (5) and (6) hold true, then, by Ineq. (7), it is readily shown that

$$(p_{w1}-p_{w2})_{\min}>0. \tag{8}$$

This inequality means that $p_{w1}>p_{w2}$ for any allowed θ_1 and θ_2. Consequently, due to the pressure difference, Edge 2 is pushed away from the corner. Thus, Ineqs. (5) and (6) form a sufficient condition for the liquid drop to transport away from the corner. Meanwhile, with the aid of Ineq. (7), it is also readily shown that, if Ineq. (8) holds true, then Ineqs. (5) and (6) should be satisfied. Accordingly, these two inequalities also from a necessary condition for the drop to move away from the corner.

Ineqs. (5) and (6) and Eq. (3) are three important relations that we have obtained. They also provide two design guidelines for ensuring a drop to transport away from the corner of two non-parallel plates. First, Ineq. (5) indicates that both θ_{rec} and θ_{adv} should be greater than $\frac{\pi}{2}$. Second, to make Ineq. (6) easier to satisfy, we should have small α, small contact angle hysteresis, and large drop size. Small values of α and angle hysteresis reduce the right-hand side of this inequality, while the large drop size increases l_l, thus increasing the left-hand side. Also, as observed from Eq. (3), the pressure difference, which provides a driving force, increases with both the decrease in α and increase in l_l. Accordingly, small α and large drop size also increase the driving force.

Chapter 3

EXPERIMENTAL DESIGN AND METHODS

In this work, we have done three types of experiments. IPA drops were tested in the first type, which was described on the first section, while water drops were examined in the second and third types of experiments. The three types were mainly used to explore the behaviors of liquid drops above their Leidenfrost states.

As in the first type of experiments, either of the second and third types of experiments included three tests, which were, respectively, performed at three different temperatures as well. The only difference between the second and third types of experiments is: the Al plates used in the third type of experiments are spray-coated with Glaco (Glaco Mirror Coat 'Zero', Soft 99 Co.), which is a super-hydrophobic coating at room temperature,[8,9] while the ones adopted in the second type are not coated with any additional material. The Al plates used in the second type of experiments are the same as the ones used in the first type. Thereafter, for simplicity, they are called "untreated plates," while the Al plates that are covered with Glaco are named "Glaco-covered plates." Since IPA etched Glaco coating, we did not test this liquid on Glaco-covered plates.

At room temperature, receding and advancing contact angles are measured by first putting a liquid drop on a plate and then slowly tilting the plate until the drop begins to move down. A different way is adopted to measure contact angles at a temperature above Leidenfrost point. In Leidenfrost state, a drop is easy to hover around. Hence, the drop is first pinned on a plate using a needle. Its receding and advancing contact angles are then determined by slightly lifting and pressing the drop, respectively, employing the needle. In this work, three measurements are taken for each contact angle with an error of 2^{o}. The mean values of the contact angles are given in Table 3-1 and 3-2.

Table 3-1

Type	Boiling temperature with an error of 5 °C	Leidenfrost temperature with an error of 5 °C	Receding contact angle with an error of 2° at room temperature	Advancing contact angle with an error of 2° at room temperature	Contact angle hysteresis at room temperature
IPA drop on an untreated Al plate	85 °C	115 °C	13 °	18 °	5 °
Water drops on untreated Al plates	100 °C	215 °C	35 °	66°	31 °
Water drops on Glaco-coated Al plates	100 °C	170 °C	135 °	139 °	4 °

Table 3-2

Type	**Receding contact angle with an error of 2° above Leidenfrost point**	**Advancing contact angle with an error of 2° above Leidenfrost point**	**Contact angle hysteresis at room temperature above Leidenfrost point**
IPA drop on an untreated Al plate	180°	180°	0°
Water drops on untreated Al plates	180°	180°	0°
Water drops on Glaco-coated Al plates	180°	180°	0°

Chapter 4

EXPERIMENTAL RESULTS AND DISCUSSIONS

4.1 CONTACT ANGLES AND LEIDENFROST POINTS

As observed from Table 3-1, in the corresponding Leidenfrost states, apparent contact angles of IPA and water drops were above 90° on untreated plates. Also, contact angle hysteresis was small. The same results apply to the case of water drops on the Glaco-coated plate.

Figs. 4-1(a)-4-1(c) give representative images of IPA and water drops on Al plates in their Leidenfrost states.

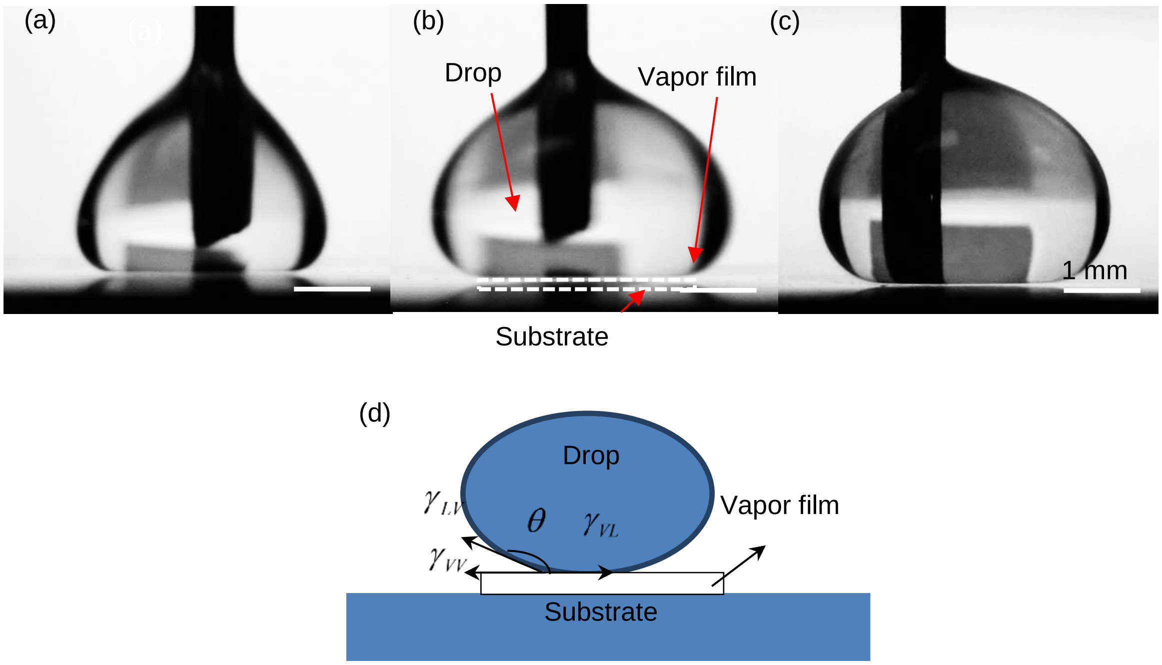

Fig. 4-1: In Leidenfrost states, (a) IPA drop on an untreated plate, (b) water drop on an untreated plate, and (c) water drop on a Glaco-covered plate. (d) Surface tensions at the edge of a drop in Leidenfrost state (schematic).

They were pinned on their substrates using a needle to obtain clear images. It can be seen that a vapor film with a thickness of 0.1 to 0.2 mm was formed between a liquid drop and the plate. Due to the existence of this vapor film, the drop did not have direct contact with the plate, and it sat on the film instead. Accordingly, as shown in Fig. 4-1(d), the surface tensions at the edge of a stationary drop were related by well-known Young-Dupré equation,[10] which was

$$\gamma_{VV} = \gamma_{VL} + \gamma_{LV} \cos\theta , \tag{9}$$

where γ_{VV} , γ_{VL} and γ_{LV} denoted surface tensions of vapor/vapor, vapor/liquid, and liquid/vapor interfaces, respectively. Since γ_{VV} may be neglected, by Eq. (9), $\cos\theta$ should be -1 to make this equation hold true. This result means that, even if apparent contact angle may be below 90° at room temperature, it should be 180° to make the drop stationary. Meanwhile, the contact angle hysteresis was mainly induced by surface defects. Since the drop sat on the vapor film, the original surface defects on the plate surface should have less effect on the drop. Accordingly, the contact angle hysteresis was small.

It is also noted that Leidenfrost point of a liquid is related to the substrate. For example, water has Leidenfrost temperatures of 215 °C and 170 °C, respectively, on untreated and Glaco-coated plates. This difference has been previously discussed in refs. 1 and 2. The microstructures on the Glaco coating enabled a drop to have less contact with the substrate, thus making it easier to form a vapor film underneath the drop at a relatively lower temperature. Accordingly, Leidenfrost point was lowered down.

4.2 VALIDATION OF THE THEORETICAL MODEL

The testing results of the second and third types of experiments were similar to their counterparts in the first type. The only exception is the first test of the third type. In this test, the result was similar to that of the third test in each type of experiment (Figs. 1-1c, 4-2a and 4-2b). In summary, there were five tests, in which liquid drops moved away from the plate corners: the third test of each type of experiments, and the first two tests of the third type.

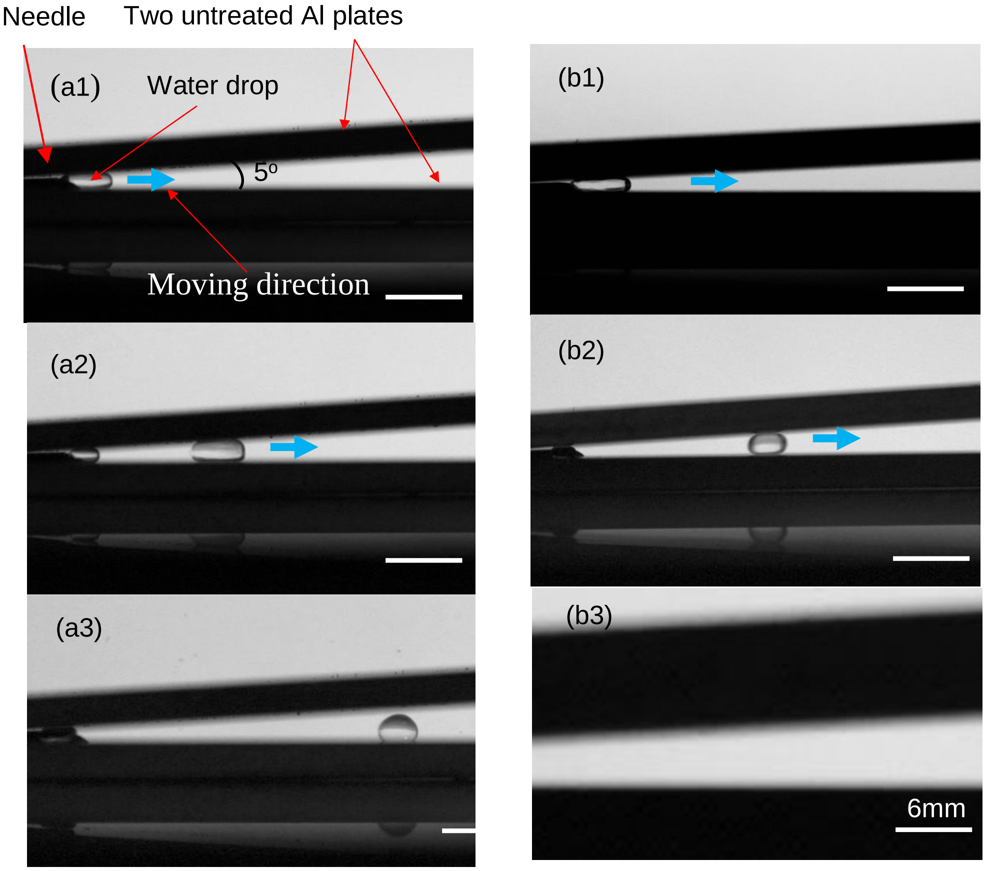

Figure 4-2: Water drops moved away from the corners of: (a1)-(a3) two untreated plates at 240^0 C, and (b1)-(b3) Glaco-coated plates at 190^0 C.

We examined whether Ineqs. (5) and (6) were met in these four tests. In the case of the third test of the first type of experiments (Fig. 1-1c), the receding and advancing contact angles of an IPA drop were 143° and 148°, respectively (Table 1). Also, the ratio of $\frac{l_l}{l_p}$ in our high-temperature test was estimated to be 4.78 (Fig. 1-1b). Accordingly, Ineqs. (5) and (6) were satisfied, which explains why the IPA drop moved away from the plate corner. Likewise, we found that these two inequalities were also met in the third test of either second or third type of experiments. Since no heating was involved in the first test of the third type, it provided us more flexibility to examine the two inequalities. According to the theoretical model, when Ineq. (5) is met, a drop may still remain stationary when Ineq. (6) is violated. Based on the second design guideline given in Sec. 2, there are two approaches to make this inequality satisfied. The first method is to increase the drop size, while the second one is to decrease α. Both approaches were validated in the first test of the third type of experiments. As seen from Fig. 4-3(a), a small water drop was difficult to detach from a needle, since the Glaco coating was less wetting than the needle.

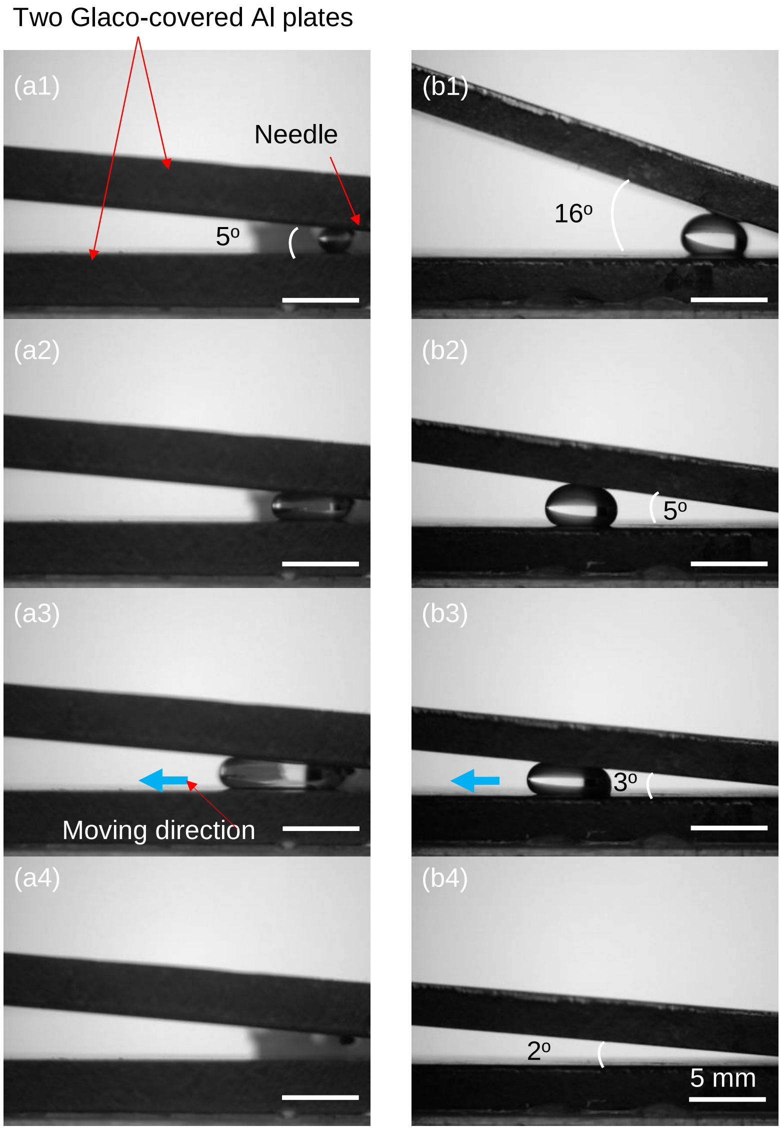

Figure 4-3: Two different approaches to drive a water drop away from the corner of two Glaco-covered plates: (a1) – (a4) increase the size of the drop at a fixed apex angle, and (b1) – (b4) fix the drop size while gradually reduce the apex angle.

However, when l_l was increased to 7.8 mm, the corresponding driving force was larger than pinning force of the needle, enabling the drop to move away from both the needle and plate corner. Meanwhile, as observed from Fig. 4-3(b), when the apex angle was decreased from 16^o to 5^o by slowly lowering down the top Glaco-coated plate using a micrometer, a water drop began to transport away from the plate corner. It stopped after travelling about 15 mm. When the top plate was further lowered down to 3^o, it started to move again.

In the second test of the third type, on a Glaco-coated plate, a water drop also moved away from the corner of the plates. Different from the second test of the first two types of experiments, a water drop did not vanish within 10 s. Instead, it could exist for at least 1 min before it completely evaporated. It was considered that initiation of nucleate boiling was suppressed at the Glaco surface.[8] Also, such a textured superhydrophobic surface eliminated the collapse of the vapor film, resulting in a stable vapor film at a temperature above the boiling point.[9] Accordingly, the water drop had a longer life time in the second test of the third type of experiments, and it should also have large contact angles and small contact angle hysteresis. In addition, we found that Ineqs. (5) and (6) were also satisfied in this test.

In addition, it is noticed that a liquid drop ran much farther and faster in its Leidenfrost state than at room temperature. For example, in Leidenfrost state, between two Glaco-coated plates, a water drop kept moving at least 80 mm till it moved out of the plate. The average speed was about 14 cm/s. On the other hand, at room temperature, a water drop had a travelling distance no more than 25 mm, and its average speed was around 5 cm/s. These differences indicate that non-parallel plates are more efficient to propel liquid drops in Leidenfrost state. Such differences are considered to be mainly induced by two factors. First, a drop moves on a solid surface at room temperature, while it runs on a vapor film at a high temperature. Accordingly, the drop suffers a much higher drag force at room temperature. Second, a drop is more energetic at a high temperature, and its collision with the two plates gives it a bouncing force which also drives the drop to move away from the plate corner.

Chapter 5

SUMMARY AND CONCLUSIONS

In this work, we explored the behaviors of liquid drops between non-parallel structures at a temperature above Leidenfrost point through theoretical and experimental investigations. According to the established theoretical model, a large liquid drop should be capable of transporting away from the corner of two non-parallel plates that have small apex angle, if the following two conditions are met: (i) apparent contact angles are larger than 90º, and (ii) contact angle hysteresis is small. At a temperature above Leidenfrost point, due to the existence of a vapor film between a drop and its substrate, both lyophobic and lyophilic drops satisfy these two conditions, and a liquid drop also move faster and farther than at room temperature.

Future Work

- A structure with channels can be designed and fabricated to direct both lyophilic and lyophobic drops to move along the same direction.
- Effect of super hydrophobic coating on thermal exchange between liquid drop and substrate opens possibilities for new applications.
- Efficient heat-exchangers can be designed with less aqueous drag.
- Advantage of propulsion of water drop at a moderate temperature can be used in cooling electronic packages.

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Biographical Information

Manjarik Mrinal received his B.E. degree from Acharya Institute of Technology in India in 2012. To pursue an advance degree in Mechanical Engineering, he got enrolled in Master in Mechanical Engineering in the University of Texas at Arlington. He joined the Micro/Nano Systems lab under Dr. Chen Luo and started working as a research assistant.

During his master's program he worked on theoretical and experimental validation of oil-water separation using hydrogel coated meshes. His current research focuses on driving mechanism of a liquid on ratchet and propulsion of liquid in non-parallel channels in Leidenfrost state. He is very curious to learn new theories and technologies. In future he would pursue his studies further and go for a Phd. Degree.