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# Manipulating thermocapillary migration via superoleophobic surfaces with wedge shaped superoleophilic grooves



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# G R A P H I C A L A B S T R A C T



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# ABSTRACT

*Hypothesis:* Thermocapillary migration is a phenomenon that liquid droplets can move from warm to cold regions on a nonuniformly heated surface. We expect to construct functional surfaces to manipulate the migration of liquid lubricants on rubbing surfaces.

*Experiments:* Superoleophobic surfaces with wedge shaped superoleophilic grooves of varying geometrical parameters are fabricated, and migration experiments of typical liquid lubricants are performed on the designed surfaces.

*Findings:* Manipulation capacity of the designed surfaces on the migration of liquid lubricants is confirmed, and the mechanism is revealed. An effective method using superoleophobic surfaces with wedge shaped superoleophilic grooves to reconcentrate the migrated lubricants is highlighted. Moreover, a general design philosophy for patterns of wedge shaped groove is proposed.

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# 1. Introduction

Thermocapillary migration describes an intriguing phenomenon that liquid droplets can move from warm to cold regions on a nonuniformly heated surface in which the thermal unbalance induced surface tension gradient provides the driving force [1–4]. Attributing to its potential applications in the liquid self transportation, condensation heat transfer, miniature rolling bearings,

\* Corresponding author. E-mail address: daiqingwen@nuaa.edu.cn (Q. Dai). and micro fluidic devices, abundant researches have be devoted to control this interfacial thermal flow, and among which surface modification is a feasible and effective approach [5–8].

Chemically, depositing coatings of different wettability or wettability gradient [9–11] on solid surfaces can drive water droplets moving spontaneously. Physically, fabricating structures pattern with disparate topographies in terms of shape [12], dimension [13], area density [14], or arrangement mode [15–17] on surfaces can also accelerate or decelerate this motion. Nowadays, scholars are trying to combine the two methods together to achieve a reinforced effect. Sommers et al. [18] fabricated a hydrophilic aluminum surface containing a hydrophobic copper background for propelling water droplets. Yasuda et al. [19] designed a hydrophilic film with wedge shaped patterns on a hydrophobic substrate, which can transport water droplets rapidly. Cheng et al. [20] achieved a wedge shaped superhydrophilic surface on a superhydrophobic layer, on which water droplets can move easily.

These findings have revealed that constructing geometry or wettability differences on a solid surface can achieve a controllable movement of water droplets on it. However, it is noticed that most of the reported investigations are focused on manipulating the water droplets. Since the surface tension of water is much higher than other types of liquids such as mineral, synthetic, or ester oils, which can totally wet these surfaces, thus ordinary wettability differences perform practically no function for liquids with low surface tensions.

Given the fact that thermocapillary migration of liquid lubricants on rubbing surfaces can result in a starved or dry lubrication condition, is it possible to construct a surface to manipulate the migration of liquid lubricants? If it works, will the constructed surfaces be able to reconcentrate the migrated lubricants back to the designated regions when the thermal gradient fades, what is the function mechanism? To date, little researches on these aspects exist. Implementing these functions is of special importance for scientific research and has a great application prospect in modern machinery.

Hence, superoleophobic surfaces with wedge shaped superoleophilic grooves are fabricated on pure aluminum surfaces, and the manipulation capacity on typical liquid lubricants is investigated. The effects of vertex angle and depth of wedge shaped grooves are discussed. Using superoleophobic surfaces with wedge shaped superoleophilic grooves to reconcentrate the migrated lubricants is highlighted and the pattern configuration of wedged grooves is confirmed.

# 2. Materials and methods

# 2.1. Materials

Solids. In this study, all substrates are made of high purity aluminum (99%) with dimensions of 70 mm  $\times$  28 mm  $\times$  2 mm, and the untreated surfaces are initial oleophilic. The testing surfaces were firstly polished with sandpapers (mesh number of 1600) to remove the residual oxidation layer; then via electrochemical anode dissolving processing in an aqueous solution of NaCl (0.4 mol/L) with a current density of 0.7 A/cm<sup>2</sup> for 7 min, irregular micro rough structures were generated on these surfaces; further, substrates were dipped into boiling water for 25 min to form irregular nano structures on these micro rough structures; finally, by immersing the substrates into an aqueous solution of pentadecafluorooctanoic acid (PFOA, CF<sub>3</sub>(CF<sub>2</sub>)<sub>6</sub>COOH, 0.02 mol/L, purchased from Aladdin, China) for chemical modification, superoleophobic surfaces were produced. Superoleophilic wedge shaped grooves were directly fabricated on the superoleophobic surfaces with laser treated method (LP020, NIALT, China), of which the output power and processing velocity of laser is 5 W and 500 mm/s, respectively. By setting different processing times of 1, 4, and 8, wedge shaped superoleophilic grooves with different depths were fabricated.

The detailed technological process is shown in Fig. S1 (in Supplementary material), and geometric parameters of the prepared surfaces are listed in Table 1. Fig. 1 confirms the morphology and component of a micro/nano structured surfaces, on which the apparent contact angles of paraffin oil are 140° and nearly 0° respectively. The micro/nano structures are irregularly distributed on the surface, and the average surface roughness of superoleophobic and superoleophilic regions is approximately 4.8 um and 1.7 um, respectively (Fig. S1). Although surface roughness would affect the migration performance [21], this influence is not evaluated in the present work since all specimens are fabricated via a same technological process.

**Liquids**. To test the manipulation capacity of the prepared surfaces, four typical liquid lubricants of paraffin oil, synthetic polyalphaolefin (PAO4), silicone oil, and diester (purity > 95%, Sinopec Yangzi Petrochemical Company, China), as received, are employed and their properties are shown in Table 2. Paraffin oil is a typical mineral base lubricants derived from crude oil, while PAO4 is a typical synthetic base oil and has an excellent lubricating property under extreme temperature condition. Silicone oil and diester are widely used due to their excellent anti foam and oxidation properties, respectively.

To confirm the superoleophobic properties, apparent contact angles of these lubricants on the prepared surfaces were measured via a sessile drop method (SL200KS, Solon, China). Dosage of the droplets was 6  $\mu$ L and images were taken within several seconds after the equilibrium state reached, besides, surface tensions of these liquid were also measured via the Wilhelmy plate method (A101Plus, Solon, China), all the measured results are shown in Fig. 2. Since the values for apparent contact angle on the designed oleophobic surfaces are about 140° or higher (closely to the superoleophobic state), while on the oleophilic ones are about 5° or smaller (superoleophilic state), these surfaces are described as superoleophobic and superoleophilic in this study.

#### 2.2. Methods

The schematic diagram of migration apparatus is illustrated in Fig. S2 (in Supplementary material). In brief, the available migration length is 50 mm, via setting the temperature of the heating and cooling elements to 110 and 0 °C simultaneously, a thermal gradient of 2.2 °C/mm could be generated along the length direction of specimens. An automatic moving platform is adopted to detach the substrate from the heating and cooling components to remove the applied thermal gradient. Before migration tests, the specimens are ultrasonically cleaned by ethyl alcohol and rinsed by deionized water. As the set thermal gradient formed, lubricant droplets with a certain volume of 6  $\mu$ L are initially placed at the vertex of the wedged groove, as shown in Fig. S2. A digital camera is employed to monitor the whole migration. Regarding the advancing edge of the migrated liquid as reference, the migration distance and velocity can be calculated.

Moreover, three non-dimensional parameters of the Bond (*Bo*,  $\frac{\rho g R_0^2}{\gamma}$ ), Reynold ( $Re \frac{\rho U R_0}{\mu}$ ), and capillary (*Ca*,  $\frac{\mu U}{\gamma}$ ) numbers are employed to describe the experimental situation, where  $R_0$  is the planar radius of the droplet [22]. The corresponding initial values of these non-dimensional parameters are calculated and shown in Table 2.

#### Table 1

Geometric parameters	of the prepared	surfaces in	this study.

Туре	Depth, µm	Vertex angle ( $\psi$ ), ° Initial width, $\mu$ m Wedge		Wedged groove length, mm
Single	5	4, 6, 8, 10	500	50
	25			
	50			
Pattern	5	10	300	15 (each)



Fig. 1. SEM images and EDS of the fabricated (a) superoleophobic and (b) superoleophilic structures; (c) a superoleophobic surface with a wedge shaped superoleophilic groove of a vertex angle of 4°.

#### Table 2

Properties of the tested lubricants and their initial values of the inherent parameters, Bo, Re, and Ca.

Lubricant	Molecular formula	Density, g/cm <sup>3</sup>	Dynamic viscosity, mPa·s (at 40 °C)	Во	Re	Са
Paraffin oil	$n C_n H_{2n+2}$ (n = 16–20)	0.82	4.6	18.16	30.8	0.0035
PAO4	$C_{10}H_{21}(C_{10}H_{20})_{n}H$	0.85	16.6	17.05	6.60	0.0085
Diester	$C_{26}H_{50}O_4$	0.914	21.2	18.97	5.86	0.0119
Silicone oil	(C <sub>2</sub> H <sub>6</sub> OSi)n	0.963	100	29.94	0.17	0.0109



Fig. 2. Surface tensions and apparent contact angles of the tested lubricants on the prepared surface.

# 3. Results

# 3.1. Basic manipulation capacity

Fig. 3 shows the basic migration performance of liquid lubricants on surfaces with different structures subjected to a thermal gradient of 2.2 °C/mm. As shown in Fig. 3a, a paraffin oil droplet can migrate rapidly on a superoleophobic surface with a superoleophilic wedged groove (vertex angle of  $6^\circ$ , depth of  $25 \,\mu$ m) towards the divergent direction (from vertex to bottom edge of a wedged groove), and the migration distance is approximately 40 mm within 15 s. While the migration distances on a superoleophilic surface with the same wedged groove and a superoleophilic surface without wedged groove are nearly the same (approximately 24 mm). Besides, oil droplet can hardly migrate on a superoleophobic surface. It is believed that a superoleophobic surface with a superoleophilic wedged groove can accelerate the migration effectively, and this manipulation capacity is further confirmed by different lubricants of PAO4, paraffin oil, diester, and silicone oil, as shown in Fig. 3b. Compared to our previously published results, this manipulation capacity is robust, of which the increment in migration distance is approximately two to three times higher than surfaces just featured with parallel [23] or radial [24] microgrooves pattern without coatings.

Note that the migration distances of PAO4, paraffin oil and diester are in the same order of magnitude, approximately 40 mm, while the distance of silicone oil is 16 mm. It is because the thermal gradient induced interfacial force constitutes the dominating driving force for the migration, which is balanced by the viscous resistance force generated within the liquid. Ideally, the migration velocity can be described as [25]:  $V \approx (h/\mu)d\gamma/dL$ , where *h* and  $\mu$  is the height and viscosity of the droplet,  $d\gamma$  is the surface tension change along the drop length *dL*. As shown in Fig. 2, the surface tension of silicone oil is approximately 20 mN/m while the others are approximately 30 mN/m, it means that the driving force for silicone oil is smallest. Besides, the viscosity of silicone oil is much



Fig. 3. Basic migration performance of (a) paraffin oils on four different surfaces, and (b) four different lubricants on a superoleophobic surface with a superoleophilic wedged groove.

higher than these of the others, which could generate a larger viscous resistance force. These are the main reasons for the lowest migration velocity of silicone oil. Besides, the small contact angle and surface tension of silicone oil make it more easily to wet a solid, which contributes to the migration to a certain degree.

Overall, the differences in the migration distance mainly origins from the property of liquids. Since the manipulation capacities of the designed surfaces on PAO4, paraffin oil and diester are nearly the same, paraffin oil is employed in the following sections.

# 3.2. Effects of vertex angle and groove depth on the manipulation capacity

Fig. 4a exhibits the migration phenomena of paraffin oil droplets on wedge shaped surfaces with varying vertex angles of 4, 6, 8, and  $10^{\circ}$  and a fixed depth of 5 um under a thermal gradient of 2.2 °C/mm. Attribute to the superoleophobic coating around each wedged groove, all droplets are confined to the groove. Migration distance on surface with a vertex angle of 4° is highest. As the quantitative results shown in Fig. 4b, initially, the migration distance increases rapidly and the velocity is fast, the increment of migration distance and decrement of migration velocity becomes smooth as time elapsed. After 15 s, the surface with a vertex angle of 4° yields a longest migration distance of 45.1 mm. The migration distances on these surfaces are, in descending order of 4°, 6°, 8°, 10°. However, at the very beginning 2 s (shadow region), the surface with a vertex angle of 10° yields a fastest migration velocity, and the initial migration velocity on these surfaces are in acceding order of 4°, 6°, 8°, 10° on the contrary.

Fig. 4c presents the effect of wedged groove depth on the manipulation capacity. Experiments are performed on surfaces with wedge shaped grooves with varying depths of 5, 25 and



Fig. 4. (a) Dynamic migration process of paraffin droplets on wedge shaped surfaces with varying vertex angles of 4, 6, 8, and 10°. (b) Detailed migration distance and velocity versus elapsed time. (c) Effect of the wedged groove depth on the manipulation capacity.

50  $\mu$ m, and vertex angles of 4, 6, 8, and 10°. For the sake of comparison, the average migration velocity within 15 s is calculated. It is noticed that for each depth, the general trend of the average velocity on surfaces with different vertex angles are consistent, that is, in descending order of 4°, 6°, 8°, 10°. While for a specific vertex angle, the average velocities on surfaces with different depths of 5, 25, and 50  $\mu$ m are nearly the same.

# 3.3. Reconcentration capacity

The above results indicate that designed surfaces could enhance the migration in the divergent direction, so what will happen if the divergent direction is right opposite to the direction of thermal gradient? Can this structure reconcentrate the migrated droplet back? Keeping this in mind, migration tests are performed in both divergent and convergent direction.

As shown in Fig. 5, on the surface with a vertex angle of  $10^{\circ}$  and a depth of 5 µm, the droplet migrates much faster in the divergent direction than in the convergent direction (Stage I). As time elapsed, most lubricant migrates to the cold side and the thermal gradient maintains this status for quite a long time (Stage II). When removing the applied thermal gradient, the paraffin oil droplet almost remains where it located (square region) on the surface with a divergent wedged groove, just with a slight diffusion. However, it is interesting to see that on the surface with a convergent wedged groove, the paraffin oil flows from the cold to warm regions rapidly. It means that in lubrication system encountered with thermal gradients, one can reconcentrate the migrated liquid lubricants back to the designed regions by taking advantage of this special capacity for a stability and durability lubrication conditions.

## 3.4. Pattern configuration of wedged grooves

Fig. 6a shows the manipulation capacity of three typical pattern configurations of wedge shaped grooves, the vertex angle is  $10^{\circ}$  and groove depth is 5 µm, the detailed migration process can be seen in the Video S1 (in Supplementary material). Compared to a single wedge shaped groove (blue line), the surface with a pattern of wedge shaped grooves with sharp corners unexpectedly yields a slower migration velocity (black line). While chamfering these corners can result in a significantly enhanced migration distance, which is nearly twice than that of the single one.



Fig. 5. Reconcentration capacity of superoleophobic surfaces with superoleophilic wedged grooves when the thermal gradient fades.

Previously, Comanns et al. [26] found that this asymmetric pattern could enable directional liquid transport and extend the transport distance. To confirm the differences between pattern configurations, the microscopic migration processes on patterned surfaces with smooth and sharp corners are recorded and shown in Fig. 6b and c (VHX500, Keyence, Japan). Initially, oil droplets can freely spread within the wedged grooves on these surfaces (Fig. 6b1, 2 and c1, 2). Situations become complex when the droplets encountered with the connection regions. For the surface with sharp corners (Fig. 6b3, 4), the migration is obstructed by the featured edges significantly, and the obstruction effect continues gathering the liquid at the corners, slowing down the migration velocity. Moreover, the gathered liquid can deform the advancing contact line, forming a curved triple phase interface, this curved interface can also generate a Laplace pressure there, acting as a resistance for migration. These effects together weaken the manipulation capacity. While for the surface with smooth corners (Fig. 6c3, c4), smooth corners do not have the ability to gather the liquid there. Although the advancing contact line is deformed to a certain degree, this deformation is not as significant as that of the sharp ones to generate a robust obstruction effect. Moreover, grooves with chamfered edges have an overall smaller width than the single channel, this would also contribute to a faster migration velocity. The results reveal that when designing the patterns of wedge shaped grooves, special attentions should be paid to the regions between the connected grooves.

# 4. Discussion

# 4.1. Superoleophilic and superoleophobic property

For a droplet resting on an ideal smooth surface, Young equation presents the relation between the equilibrium contact angle ( $\theta_E$ ) of the droplet makes with the solid surface and the surface tensions of solid/gas ( $\gamma_{SG}$ ), solid/liquid ( $\gamma_{SL}$ ), and liquid/gas ( $\gamma$ ) [27,28]:

$$\cos\theta_E = \frac{\gamma_{SG} - \gamma_{SL}}{\gamma} \tag{1}$$

When the surfaces are rough, the apparent contact angle of drops on rough surfaces can be evaluated by the famous Wenzel and Cassie–Baxter formulas [29,30]. If the liquid fills up all the topological variations of the rough surface (Wenzel state), the apparent contact angle ( $\theta_r^W$ ) can be expressed as [31–33]:

$$\cos\theta_r^W = r\cos\theta_E \tag{2}$$

where *r* is the ratio of the real to the projected area covered by the liquid.

If the droplet settles on the peaks of the protrusions or bumps, this is referred to as a composite contact with the rough substrate (Cassie–Baxter state), the apparent contact angle  $(\theta_r^{C})$  can be expressed as [34–36]:

$$\cos\theta_r^{\ C} = \phi_s - 1 + \phi_s \frac{\gamma_{SC} - \gamma_{SL}}{\gamma}$$
(3)

where  $\phi_S$  is the area fraction of the solid/liquid contact.

With the above Wenzel and Cassie–Baxter formulas, the superoleophilic and superoleophobic property is understandable. Since the initial aluminum surface is oleophilic, roughening the surface can significantly increase the ratio of the real to the projected area covered by the liquid (r). Based on Eq. (2), the apparent contact angle ( $\theta_r^W$ ) would decrease accordingly. Therefore, roughening the oleophilic aluminum surfaces via laser can achieve a superoleophilic property. According to Eq. (3), a smaller  $\gamma_{SG}$  can yield a larger apparent contact angle. Modifying a rough surface with a quite low energy material of PFOA can transform to the oleophobic



Fig. 6. (a) Pattern configuration of the wedge shaped superoleophilic grooves on superoleophobic surfaces; optical microscope migration process of paraffin oil droplets on surfaces with patterns of wedge shaped grooves with (b) sharp and (c) smooth corners.

stage. The reported works by Song et al. [37,38] have revealed that when the irregular micro/nano rough structures are coated with PFOA, Cassie–Baxter state holds, it means that the liquid can remain on top of the asperities and trap air in the interstices, generating a superoleophobic property.

Generally, the migration is caused by the surface tension gradient. On a superoleophilic surface, since the adhesion work between aluminum surface and oil molecules is much higher than the cohesive work of lubricant molecules, when the surface tension of liquid changes due to a thermal gradient, the interaction between liquid and solid can yield a migration. However, when the surface is coated with a low surface energy material of PFOA, the adhesion work becomes much lower than the cohesive work. Consequently, the liquid droplet remains stationary on superoleophobic surfaces.

# 4.2. Manipulation mechanism

In this study, the geometric dimension of droplets grows far beyond its capillary length ( $L_c = \sqrt{\gamma/\rho g} \approx 1.6$  mm) as the migration progresses, and the liquid lubricants are always confined to the wedged groove due to the robust interface between the super-oleophilic and superoleophobic regions. The capillary force due to wedged groove can be ignored here, and increasing the depth of wedged groove has little effect on the manipulation capacity. Nevertheless, when the droplet volume increases to a certain extent, it would affect the manipulation capacity.

To explain the manipulation mechanism, a theoretical sketch of a migrated droplet on superoleophobic surface with a wedge shaped superoleophilic groove ( $\alpha$  is the vertex angle) is shown in Fig. 7. The droplet is assumed to be a sector with a radius of *R* (*L* = 2*R*) and a corresponding central angle of  $\delta$  ( $\delta$  = 2 $\alpha$ ). Since the surface tension of liquid ( $\gamma$ ) decreases with increasing temperature, this variation can be described as:

$$\gamma_x = \gamma_0 + C_T \gamma_T x \tag{4}$$

where  $\gamma_0$  denotes the surface tension at a reference temperature, and  $\gamma_x$  denotes the surface tension at the position *x*,  $\gamma_T$  denotes the surface tension coefficient,  $C_T$  denotes the constant thermal gradient.

Due to the basic superoleophilic property in the wedge shaped groove (apparent contact angle  $<5^{\circ}$ ), the liquid droplet can be



**Fig. 7.** Migrated droplet on a superoleophobic surface with a wedge shaped superoleophilic groove: (a) side view and (b) plan view, (c) Theoretical external force acting on the droplets on surfaces with different vertex angles.

regarded as a thin film and curved at edges, the lubrication approximation theory holds. Following the theoretical derivations proposed by Brochard [39], Subramanian et al. [40] and Dai et al. [41,42], this thermal gradient induced driving force ( $F_{thermal}$ ) acting on the droplet per unit area can be expressed as:

$$F_{Thermal} = \frac{2}{R} \int_{0}^{\delta/2} \gamma_{x} \cos\theta_{oleophylic} \cos\delta d\delta$$
  
$$= \frac{2}{R} (\gamma_{0} + C_{T} \gamma_{T} L) \sin\alpha \cos\theta_{oleophylic}$$
(5)

Referring to the migration phenomenon shown in Fig. 4a, the lubricants always remain in the superoleophilic groove by superoleophobic surface, as the side view shown in Fig. 7b, this wettability gradient can yield a structure force ( $F_{Wedge}$ ) on the droplet, affecting the migration. Although the pinning effect of groove could also leads to the enhancement of spreading along the groove [43,44], this effect is not taken into consideration due to a single groove here. Assuming that the apparent contact angle changes abruptly from superoleophobic region to the superoleophilic region, and integrating the surface tension force acting along the three phase contact line, the wedge shaped groove induced structure force ( $F_{Wedge}$ ) acting on the droplet per unit area can be expressed as [18,45]:

$$F_{Wedge} = \frac{2}{L} (\gamma_0 + C_T \gamma_T L) \sin \frac{\alpha}{2} (\cos \theta_{oleophylic} - \cos \theta_{oleophobic})$$
(6)

For a migration occurs in the divergent direction of the wedged groove, both the thermal driving force ( $F_{Thermal}$ ) and the structure force ( $F_{Wedge}$ ) would contribute to the migration; while in the convergent direction, the structure force ( $F_{Wedge}$ ) would weaken the movement. Since the capillary force acts on both sides of the droplet and this force is far smaller than the thermal driving force ( $F_{Thermal}$ ) and the structure force ( $F_{Wedge}$ ), it is ignored here. Then, the total external forces acting on the droplets can be written as:

$$\begin{cases} \Phi^{+} = F_{Thermal} + F_{Wedge}, \text{ divergent dirction} \\ \Phi^{-} = F_{Thermal} - F_{Wedge}, \text{ convergent dirction} \end{cases}$$
(7)

By substituting the surface tension ( $\gamma = 28.7 \text{ mN/m}$  at 20 °C), surface tension coefficient ( $\gamma_T = 0.08 \text{ mN/m}^\circ\text{C}$ ), apparent contact angles of  $\theta_{oleophilic} = 2^\circ$  and  $\theta_{oleophobic} = 140^\circ$  and other values into Eq. (7), the theoretical external forces ( $\Phi^+$  and  $\Phi^-$ ) are calculated and plotted versus the position of the droplet's front edge, as shown in Fig. 7c.

It can be seen that a larger vertex angle can yield a higher external force  $(\Phi^+)$  in the divergent direction. Therefore, at the very beginning, the migration velocity on the surface with a vertex angle of 10° is highest, this is consistent with the experiment results shown in Fig. 4b (shadow region). The theoretical external force  $(\Phi^+)$  is in a significant level initially and decreases linearly with the position of the droplet's front edge. As a droplet migrates forward, the front edge needs to wet much more superoleophilic area in the groove but limited by the finite volume, it means that the external force  $(\Phi^+)$  needs to drive much more lubricant to wet the surface with a larger vertex angle. That is the reason why the final migration distance on the surface with a vertex angle of 10° is shortest (Fig. 4b). Note that when a migration occurs in the convergent direction, the external force  $(\Phi^{-})$  acting on the droplet is nearly zero on each surface, it indicates that the structure force  $(F_{Wedge})$  is of the same order of magnitude as the thermal driving force ( $F_{Thermal}$ ). The motion of liquid droplets in the convergent direction of the wedged groove is a normal wetting phe-Therefore, designing nomenon. this wedge shaped superoleophilic and superoleophobic surfaces in the opposite direction to the thermal gradient can reconcentrate the migrated droplet back effectively.

## 5. Conclusions

Previous researches have proven that constructing wettability gradient [9,10] disparate topographies in terms of shape [12], dimension [13], area density [14], or arrangement mode [15–17], and wedge shaped patterns [18–20] on solid surfaces can control the movement of water droplets effectively. In this work, we further put forward the manipulation strategy of functional surfaces on the migration of liquid lubricants with low surface tensions.

Superoleophobic surfaces with wedge shaped superoleophilic grooves of varying geometrical parameters are fabricated, and the manipulation capacity are verified, which could be enhanced with a smaller vertex angle of wedge shaped groove. This manipulation capacity is robust, of which the increment in migration distance is approximately two to three times higher than surfaces featured with parallel [23] or radial [24] microgrooves pattern without coatings.

The existing theoretical models on smooth surfaces or surfaces with patterned structures assumed the migration as a steady state process [24,46]. Since prepared surfaces are heterogeneous and with irregular micro/nano structures of peaks and pits, these structures can strongly keep the liquid lubricants at the superoleophylic regions, results in a time depended film thickness, thus the migration is indeed an unsteady state flow. The presented theoretical derivation clearly reveals the manipulation mechanism, and provides a preliminary information on the manipulation capacity of the wedge shaped superoleophylic and superoleophobic surfaces.

An effective method using superoleophobic surfaces with wedge shaped superoleophilic grooves to reconcentrate the migrated lubricants is proposed, and a general design philosophy for patterns of wedge shaped groove is proposed. This study advances the manipulation strategies for the thermal flow and has great application prospect in modern machinery encountered with the migration.

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## **Appendix A. Supplementary material**

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jcis.2019.09.094.

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