Colloids and Surfaces A: Physicochem. Eng. Aspects 497 (2016) 167–170

Contents lists available at ScienceDirect

Colloids and Surfaces A: Physicochemical and Engineering Aspects

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

No migration of ionic liquid under temperature gradient

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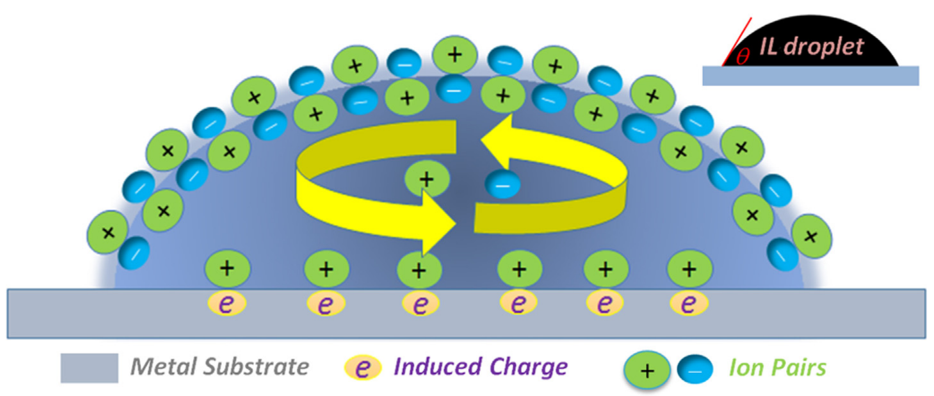
HIGHLIGHTS

- No migration of ionic liquid was observed under temperature gradient.
- The strong Coulombic force increases bonding strength at liquid/solid interface.
- Surface tension of ionic liquid is promoted by ions alternation.
- The Coulombic interactions in interior part increase the droplet's cohesive work.
- The no migration property reinforces the possibility of ionic liquid as lubricant.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 23 December 2015
Received in revised form 29 February 2016
Accepted 1 March 2016
Available online 4 March 2016

Keywords:
Migration
Ionic liquid
Temperature gradient
Surface tension
Lubrication

ABSTRACT

Droplet migration under temperature gradient is ubiquitous throughout science and engineering. For the molecular type lubricants, the migration performance can be well described by a dynamic model based on Marangoni effects. However, no migration of ionic liquid droplet was observed under temperature gradient. The abnormal behavior may originate from a combination of ordering structure of ions in the interfaces as well as the Coulombic interactions in interior part. The finding reinforces the possibility of ionic liquid as lubricant.

1. Introduction

Thermo-capillary migration is an important phenomenon that surface thermal gradients will drive liquid to flow from warm to cold regions. The physical explanation of the movement is that the thermal gradient produces a gradient of interfacial tension along the droplet surface, which propels the droplet toward regions where its interfacial tension would be reduced [1]. This thermally induced migration plays a key role in the fluidic controls and mechanical lubrication aboard spacecraft due to the changeable temperatures (−60 to −200 °C) and microgravity [2]. Oil migration not only reduces the amount of fluid available for lubrication, it also increases the exposed surface area of the fluid [3]. As a direct result, the lifetime of spacecraft is reduced.

Usually, an anti-migration coating [4] or mechanism geometry [5] is proposed to obstruct liquid migration. Besides, seeking novel lubricants with low migration tendency is also an effective way

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http://dx.doi.org/10.1016/j.colsurfa.2016.03.002
0927-7757/

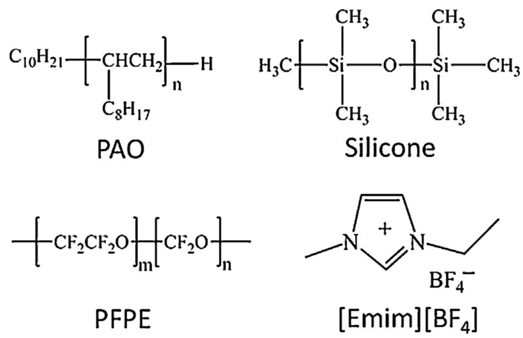

Fig. 1. Chemical structures of the traditional lubricants and IL.

for the spacecraft moving assemblies to sustain acceptable performance throughout the operational lifetime [6].

Ionic liquids (ILs) are organic salts with melting points below 100 °C and its potential as lubricant was recognized for the first time in 2001 [7]. After that, lots of group carried out research works in this area [8–11]. Thanks to their properties of thermal stability, non-volatile and reasonable viscosity-temperature behavior, ILs appear to be suitable candidates as new aerospace lubricants [12–14]. In this paper, distinct migrating manner of ILs was observed and the authors believe that this phenomenon, up to now unexplored, is of particular interest in the field of space lubrication.

2. Experimental details

Here we will focus on the thermally driven of droplet on horizontal surface. The apparatus used in this study includes two temperature-controlled aluminium blocks placed on a horizontal platform. A metal (304 stainless steel) substrate with surface roughness *Ra* in the range of 10–20 nm was attached between the cooling and heating blocks, so that a temperature gradient could be generated along the surface. Each time, the lubricant was dripped at the same location of the warm side and the motion of the droplet was monitored with a camera. Detailed description of the instrument and test process can be found in relevant literatures [15,16].

In this study, 1-ethyl-3-methylimidazolium tetrafluoroborate (99.9% purity) IL ([Emim][BF_4]) was chosen for its potential application prospects. The [Emim]$^+$ cations form a pillar with the β-carbon of the ethyl group sticking out of the imidazolium-ring plane [17]. For comparison, several popular molecular type lubricants used in space were also tested, including, polyalphaolefin (PAO), silicone and perfluoropolyether (PFPE). Their chemical structures are shown in Fig. 1. Before the migration test, a rotation viscometer was used to analyze the viscosity of the liquids. The contact angle was measured by a contact angle goniometer using an optical subsystem to capture the profile of a pure liquid on a solid substrate. Surface tension of the lubricants was measured by the Wilhelmy plate method. By measuring the surface tensions at a variation temperature of the lubricants, the thermal coefficient of surface tension can be obtained. A summary of the main properties are listed in Table 1.

Table 1
Physical properties (20 °C) of the liquids.

Properties	PAO	Silicone	PFPE	IL
η	45	100	883	45
θ	7 ± 1°	/	/	57 ± 1°
γ	29.02	20.53	18.74	45.56
$d\gamma/dT$	−0.0814	−0.0456	−0.0337	−0.0795

η is the viscosity (mPa•s), θ is the contact angle (°) and '/' means the value of contact angle is too small to measure, γ is the surface tension (mN/m), $d\gamma/dT$ is the thermal coefficient of surface tension (mN/mK).

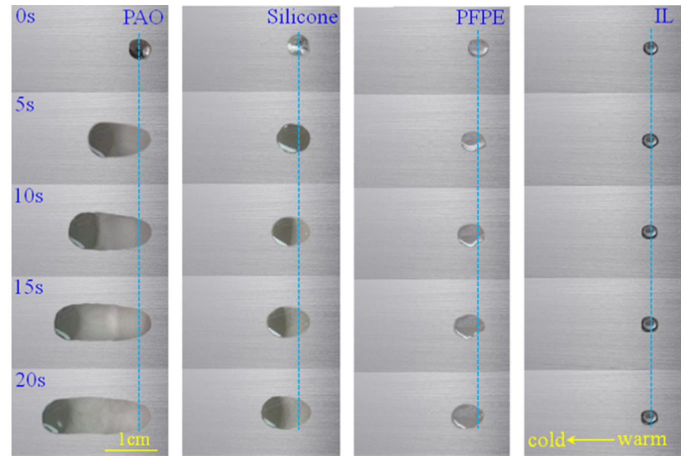

Fig. 2. Images of lubricant migration traces at different moment on substrates (temperature gradient: 2.33 °C/mm, lubricant mass: 4 μL).

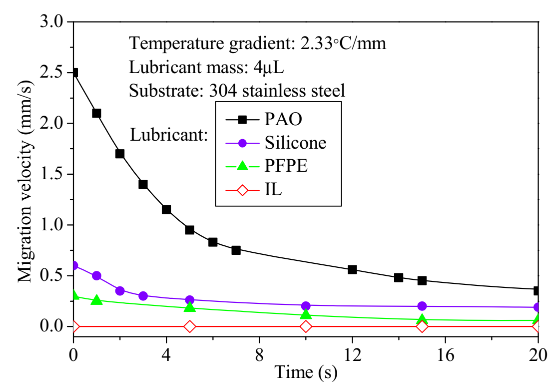

Fig. 3. Migration velocities as a function of the test time.

3. Results and discussion

Fig. 2 shows a bird's eye view of liquid migration process at the different time under temperature gradient of 2.33 °C/mm. The droplets of the molecular type lubricants, as expected, migrate at different levels along the temperature gradient. However, the IL remains stationary during the test time. Fig. 3 presents the velocity of induced migration as a function of the time. It shows that the highest initial velocity of the molecular type liquid reaches 2.5 mm/s and it decreases gradually and flattens later. For IL, the visible rate is zero. During the experimental process, the no migration behavior was also found when using several kinds of other ILs even under a higher temperature gradient of 5.0 °C/mm and a droplet volume of 10 μL.

For the molecular type lubricants, they appear a similar migration performance. The migration results can be well described by a dynamic model based on Marangoni effects [18]. Considering a droplet moving on a solid surface in response to a positive thermo capillary stress $\tau(x)$ are as follow [19]:

$$\tau(x) = \frac{d\gamma}{dT} \times \frac{dT}{dx} \tag{1}$$

where γ is the liquid-vapor surface tension, T is the liquid surface temperature. The stress produces a velocity gradient in the liquid could be written as[20]:

$$\frac{dV(x,z)}{dz} = \frac{\tau(x)}{(T)} \tag{2}$$

where z is in the direction perpendicular to the solid surface, $V(x, z)$ is the liquid velocity in the x direction, and $\eta(T)$ is the temperature