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Surface roughness and orientation effects on the thermo-capillary migration of a droplet of paraffin oil

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ABSTRACT

The Marangoni effect is an important phenomenon in which a surface tension gradient drives liquid flow to regions of high surface tension to form thin liquid films. Temperature gradient, evaporation, disparity of viscosity and surface roughness are all significant factors that can affect the oil migration behaviour. The purpose of this study was to determine the influence of surface roughness and surface topography orientation on migration behaviour under various temperature gradients. Specimens with different surface roughness were fabricated, and the migration behaviour of paraffin oil on each specimen was investigated using home-built testing equipment. The results show that the roughest surface with the grinding scars parallel to the temperature gradient exhibited the fastest migration velocity. Increasing the viscosity of paraffin oil decreased the influence of roughness on migration behaviour. Our results also indicate that the orientation of grinding scars determines the behaviour of temperature-driven migration, which guides the moving direction of drops and may act as a barrier impeding drop movement along the temperature gradient. When the temperature gradient was increased to a certain value, the barrier was broken through and the temperature gradient became the dominant factor affecting oil migration direction.

1. Introduction

The Marangoni effect, named after Italian physicist Carlo Giuseppe Matteo Marangoni, was first identified in the "tears of wine" phenomenon in a wine glass. Because water has a higher surface tension and lower volatility than alcohol, the evaporation of alcohol in a wine glass will result in an inhomogeneous alcohol concentration, thereby generating a surface tension gradient on the surface pulling the liquid wine up the side of the glass and spreading it into a thin film. The film eventually converges to a droplet and falls back into the wine like tears [1]. This phenomenon is also called thermo-capillary convection (or migration or creep), in which the existence of a surface tension gradient drives liquid flow to regions of high surface tension. Marangoni performed a detailed investigation of surface-tension-driven movement on a fluid interface, which was generated by substantial variations in composition or temperature [2]. In the early 20th century, Bénard experimentally studied hexagonal convection in thin liquid films, providing a further explanation of the Marangoni effect with respect to film formation and instabilities [3].

In addition to the aforementioned evaporation-induced surface tension of liquids, there are other mechanisms that drive the surface-tension-driven migration of liquids, which results in the liquids spreading slowly on metal surfaces without any external force. Temperature gradients on a surface and differences in liquid viscosity can significantly change the surface tension of liquids; on a micro-rough surface, the radius of curvature varies with depth and can cause a variation in the surface tension, which drives a liquid to spread across the surface, similar to capillary action [4].

Experimental and theoretical research on surface-tension-driven migration (i.e., the Marangoni effect) has been carried out for centuries [5–7]. It was been ascertained that the Marangoni effect plays an important role in the fundamental physics of interfacial flows [8,9]. Moreover, this phenomenon should be carefully considered in industrial applications, such as the flip-chip and hard disk industries, in which the migration of lubricant films has strong effects on device performance [10]. For example, the frictional heat generated by asperities on the bearings of tribological surfaces can create a temperature gradient between the contact area and surroundings, which changes the surface tension of the liquid lubricants on the surface and ultimately results in lubricant migration from the contact area to a relatively lower-temperature area

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[11]. In a microgravity environment, i.e., an environment featuring an extremely low vacuum pressure, a large temperature range (−60 °C to 200 °C), and intense radiation [12], liquid lubrication is still required for low-torque applications [13]. Under these conditions, surface-tension-driven forces constitute one of the most significant factors affecting lubricant flow behaviour and lubrication failure. Therefore, it is necessary to control migration to guarantee the lubricant lifetime of moving mechanisms in space [14].

The surface tension and viscosity of liquids, the thickness of liquid films, temperature gradients, and surface topography influence the migration behaviour of liquids. Previous studies have investigated available anti-creep applications such as chemical coatings and surface structure designs. For instance, painting low-surface-energy compounds around a lubrication region can form effective creep barriers [4]. Fote et al. investigated the migration of hydrocarbon thin films under temperature gradients and different surface finishes. The results showed that for thin liquid films in vacuum, a temperature gradient could drive the migration from a warm to cold area at nearly the same migration rate as in air; additionally, the results showed that rough surfaces exhibited lower migration rates than smoother surfaces [15]. Hu and Larson performed a thorough theoretical study on the effects of Marangoni stresses on flow in an evaporating droplet; his results revealed that the latent energy of evaporation broke the boundary of the free surface and produced thermal gradients that generated Marangoni stresses and, subsequently, internal flow [1]. Klien et al. carried out experiments on oil drops on grounded and grinded surfaces, with scratches angled against the temperature gradient, and demonstrated that surface topography has a strong influence on the migration of oil [16].

It has been previously demonstrated that the migration velocity of a liquid decreases with increasing viscosity under a certain temperature gradient. However, it is clear that further studies are needed to quantify the effects of the above-mentioned factors. Therefore, we aimed to study the relationship between migration velocity, viscosity, and temperature gradient. On the other hand, the influence of surface topography cannot be ignored when considering the Marangoni effect, and large numbers of products have emerged where the surface has been structured, textured or engineered to provide a particular function [17–20]. In this study, special attention was given to the influence of surface roughness and topography orientation on migration behaviour under various temperature gradients.

2. Experimental

2.1. Apparatus

Fig. 1 shows a schematic diagram of the apparatus used in this experiment. Aluminium was chosen as the block material due to its excellent heat conductivity. Two temperature-controlled aluminium blocks were fixed on a horizontal platform. One block could be heated by an embedded ceramic plate heater to the desired temperature. The other block was immersed in ice water to maintain at a constant temperature of 0 °C.

A metal substrate, i.e., the specimen, was placed between the cooling and heating blocks. The two ends of the metal substrate were tightly attached to the blocks to achieve good thermal conductivity. By cooling and heating the blocks, a temperature gradient could be generated along the length of the metal substrate.

To obtain the real-time temperature gradient of the sample surface, a thermal imaging acquisition device (Fluke, USA) and thermocouples were used to obtain the distribution of temperature on the sample surface.

A digital video camera was used in this experiment to monitor the entire process of liquid migration. Key frames of the video were then extracted to calculate the velocity of migration using image and video manipulation software.

2.2. Specimen preparation

Paraffin oil migration experiments were performed on metal substrates with dimensions of 100 mm × 30 mm × 2.32 mm. All substrates were made of 45# carbon steel. The upper surface was ground. By changing the grinding direction, the specimens could be machined to specific surface roughnesses with different orientations. The surface roughness in this article was measured on area of 1 mm × 1 mm by surface mapping microscope (Rtec instruments, USA). Fig. 2 shows a typical surface topography obtained using an optical microscope and a 3D profiler. The surface roughness was dependent on whether coarse grinding or fine grinding was used.

2.3. Test procedure

To rule out the effects of additives on oil migration, paraffin oils with different viscosities were chosen for all experiments because they were obtained from crude oil fractionation. A microlitre syr-

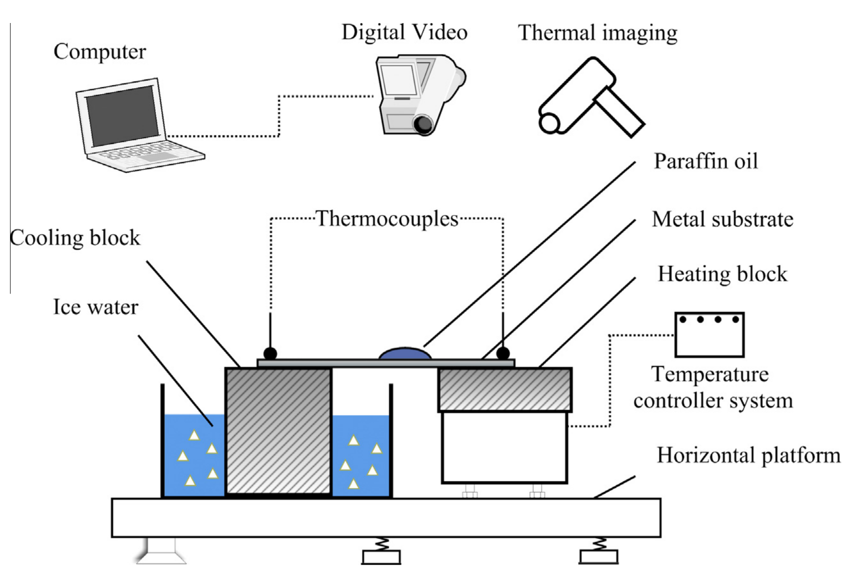

Fig. 1. Schematic diagram of experimental apparatus.