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Research paper

Acceleration or deceleration of self-motion by the Marangoni effect

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ABSTRACT

We investigated the water-depth dependence of the self-motion of a camphor disk and camphor boat. With increasing water depth, the speed of motion of the camphor disk increased, but that of the camphor boat decreased in an annular one-dimensional system. We discussed the difference in the water-depth dependence of the speed of the camphor objects in relation to Marangoni flow. We concluded that Marangoni flow, which became stronger with increasing the water depth, positively and negatively affected the speed of the disk and boat, respectively.

1. Introduction

Studies of a self-motion of an inanimate system is activated by surface sciences, e.g., the self-motion of oil droplets induced by difference in the surface tension or Marangoni flow [1–9], and self-motion of nanoparticles driven by chemical reactions on their surfaces [10–12]. These investigations not only increase understanding of the mechanism of biological locomotion but also aid the development of autonomous motors.

The motion of a camphor disk or camphor boat on water has been investigated as an example of a simple self-propelled system, in which the driving force is considered to be differences in the surface tension [13]. In the camphor system, differences in surface tension are generated by the heterogeneous distribution of camphor molecules spreading out from the camphor grain to the water surface [13–19]. The spreading of camphor molecules is not a normal diffusion process but an advection–diffusion process, which has been referred to be 'development' in the past [20]. A camphor boat, which is a plastic film with a camphor grain at its edge, moves toward the area of higher surface tension, i.e., the direction opposite to the side with exposed camphor [20,21]. In contrast, the direction of the motion of a camphor disk is determined by fluctuations depending on its initial floating state [13,14].

Systems in which motion changes depending on the shape of the camphor grain [17] or boat [22], size and shape of the chamber [23], or coupling with chemical reactions [13] have been reported. Concerning the mechanism of motion, the dependence of motion on the water depth has not been thoroughly investigated because the surface tension, which is considered to be the origin of the driving force, should be independent of the water depth. However, there have been several reports on the motion of camphor particles being dependent on the water depth in the chamber [23–25], and these reports discuss the mechanism of motion in relation to Marangoni flow [26–33]. Marangoni flow is generated at an immiscible interface with a surface tension gradient [34–37]. The magnitude of Marangoni flow increases with increasing water depth [37]. Therefore, Marangoni flow may play an important role in determining the speed of the camphor particles.

In this study, we investigated the self-motion of a camphor disk and boat while varying the water depth. The dependence of speed of the camphor disk on water depth is different from that for a camphor boat in an annular one-dimensional chamber. In order to explain this different effect of water depth, we propose that Marangoni flow plays an important role in the motion of both the camphor disk and boat.

2. Experiments

Camphor was purchased from Wako Chemicals (Kyoto, Japan). Water was distilled and then purified using a Millipore Milli-Q filtering system (pH = 6.3, resistance > 20 MΩ). We prepared the camphor disk and boat, as shown schematically in Fig. 1a. Two camphor disks with different sizes (diameters: 10 mm and 3 mm, thickness: 1 mm in both disks, masses: 70 mg and 5 mg) were prepared by compression with a hydraulic pump (20 MPa) for

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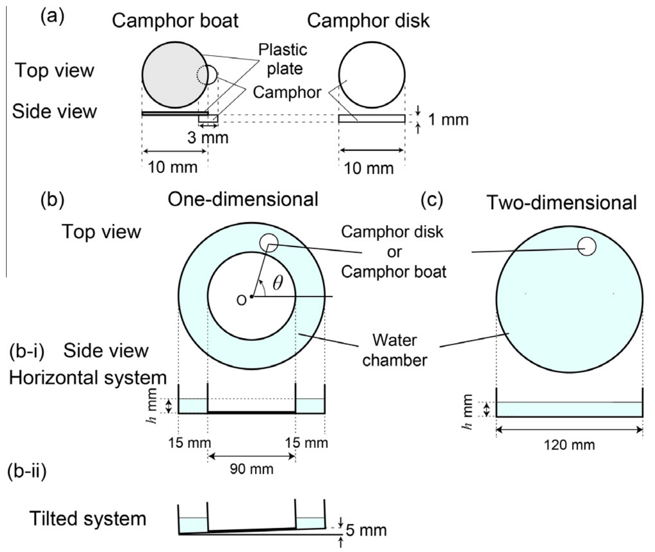

Fig. 1. Schematic illustration of the (a) camphor boat and camphor disk, (b) annular one-dimensional system on a (i) horizontal system and (ii) tilted system, and (c) two-dimensional system, where h and O denote the water depth and the center of the system, respectively. The position of the camphor in the one-dimensional system is represented by the angle θ.

the larger disk and manually for the smaller disk. To shape the disk, a pellet die set for Fourier transform infrared spectrometry was used. The larger camphor disk was used as a camphor disk without further fabrication. The smaller camphor disk was attached to one edge of a polyethylene terephthalate plastic disk (thickness: 0.1 mm, diameter: 10 mm) using adhesive, and this was used as the camphor boat. For the aqueous phase, water was poured into an annular glass chamber (inner diameter: 90 mm, width: 15 mm, water depth (h): 4.2–33.6 mm) for use as a one-dimensional system (Fig. 1b) and a glass Petri dish (diameter: 120 mm, water depth: 5–20 mm) as a two-dimensional system (Fig. 1c).

The horizontal system was tilted using a silicone sheet as a spacer (height: 5 mm) to vary the water depth within a single water chamber. The position of the camphor disk or boat is described as the radial angle (θ) in the annular chamber, as shown in Fig. 1b.

The motion of both the camphor disk and boat was monitored using a digital video camera (DCR-HC48, SONY, Tokyo, Japan; minimum time-resolution 1/30 s) in an air-conditioned room at

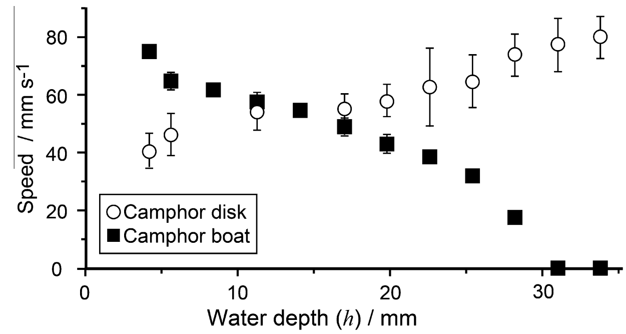

Fig. 3. Average speeds of the camphor disk (open circles) and camphor boat (filled squares) for 2 min in relation to the water depth (h) in the one-dimensional horizontal system. Error bars indicate a standard deviation calculated from data of at least four examinations.

298 ± 2 K and then, analyzed using an image-processing system (ImageJ, National Institutes of Health, Gaithersburg, USA). At least four examinations with observation times of more than 2 min were performed for each condition.

To visualize Marangoni flow around the camphor disk and boat in the aqueous phase, visualization particles composed of styrene–divinylbenzene (DIAION, HP20S, Mitsubishi Chemical Co., Tokyo, Japan; particle size: 100–200 μm, particle density: 1.01 g mL^{-1}) were dispersed into the aqueous phase. The density of the aqueous phase was adjusted by the addition of urea. A homogeneous dispersion of the visualization particles for evaluating the surface and convective flows was obtained at a 17 w/w% urea aqueous solution (density: 1.1 g mL^{-1}). This solution was poured into a plastic container (length: 300 mm, width: 15 mm, water depth (h): 5 or 20 mm) and the glass Petri dish. To monitor the convective flow, the camphor boat or disk was fixed on the water surface with a platinum wire (diameter: 0.5 mm, length: 10 mm), and motion of the visualization particles around the camphor boat or disk was monitored with the digital video camera (SONY DCR-VX700, maximum frame rate: 30 fps). As for the camphor disk system, the platinum wire was physically inserted into the center of the camphor disk. As for the camphor boat system, the platinum wire was adhered to the center of the plastic disk. To reduce the effect of curvature of the chamber on optical access, we used a rectangular chamber for the observation of the convective flow.

The surface tension of the water phase was measured using a Surface-Interface Tension Meter (CBVP-A3, Kyowa Interface Science Co. Ltd., Saitama, Japan).

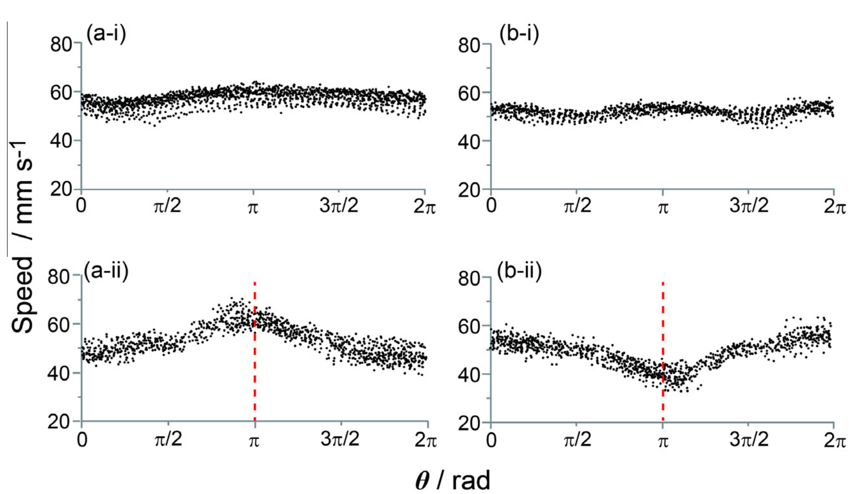

Fig. 2. Relationship between the position (θ) and speed of the (a) camphor disk and (b) camphor boat in the (i) horizontal (h = 20 mm) and (ii) tilted systems. The broken lines mark the position of the greatest water depth ($\theta = \pi$ rad). The direction of motion was anticlockwise, i.e., the positive direction of θ.