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Intermittent motion of a camphor float depending on the nature of the float surface on water

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ABSTRACT

The periodic motion of a camphor float on water was investigated as a simple example of an autonomous motor. When a camphor disk that was connected to the center of a larger plastic disk was floated on water, intermittent motion (alternating between rest and rapid motion) was observed. The period of intermittent motion decreased with an increase in the hydrophobicity of the plastic film, which depended on the density of carbon powder that had been adhered to the plastic film with a laser printer. When a square plastic film with half-hydrophobic and half-hydrophilic surfaces was used as the camphor float, the direction of intermittent motion was mostly toward the hydrophilic side. These phenomena are discussed in relation to the diffusion of camphor molecules at the film/water interface and the surface tension around the film as the driving force.

1. Introduction

The development of artificial motors that mimic biological motors is important not only to increase our understanding of energy transduction and chemotaxis in biological systems but also for creating novel artificial motors that are sensitive and adapt to the environment [1]. All motor organs or organelles in living organisms work under almost isothermal and nonequilibrium conditions, e.g., a flagellar motor is driven by the membrane potential of potassium ion and the pH gradient. Several artificial systems that exhibit self-motion under conditions of chemical nonequilibrium have been studied experimentally [2–16] and theoretically [17–19] under almost isothermal conditions. More than a century ago, the self-motion of small camphor scrapings floating on water was reported by Tomlinson [20]. Rayleigh also studied the retarding effect of contaminating oily substances on the self-motion of a camphor scraping [21].

We have investigated the characteristic features of the self-motion of a camphor system depending on the internal conditions (e.g., scraping morphology and chemical structure of the camphor derivative) [22,23], external conditions (e.g., temperature, surface tension, chemical stimuli, and the shape of the cell) [24–28], and chemical reactions as an autonomous motor [29,30]. In addition, the essential features of self-motion could be qualitatively reproduced by numerical calculations [22,24–26,28]. In one of these studies, we reported the intermittent motion, i.e., cycling between motion and rest, of a camphor disk connected to the center of a plastic disk [26]. The duration of the resting state could be controlled by changing the diameter of the plastic disk. The mechanism of intermittent motion can be discussed in relation to the slow accumulation and rapid development of a layer of camphor molecules under the plastic disk.

In this study, we investigated the effect of the plastic film in contact with water on intermittent motion. The period of intermittent motion decreased with an increase in the hydrophobicity of the plastic film, which was changed by adding toner from a laser printer. When a square film, half of which was printed with toner, was used as the camphor float, uni-directional intermittent motion was observed with a high probability. These phenomena are discussed in relation to the diffusion of the camphor molecules at the solid film/water interface during the resting state and the development of a camphor layer from the film during the acceleration of motion.

2. Experimental

Camphor was obtained from Wako Chemicals (Kyoto, Japan). Water was first distilled and then purified with a Millipore Milli-Q filtering system (pH of the obtained water: 6.3, resistance: >20 MΩ). A camphor disk (diameter: 3 mm; thickness: 1 mm; mass: 5 mg) was prepared using a pellet die set for FTIR. A camphor float was

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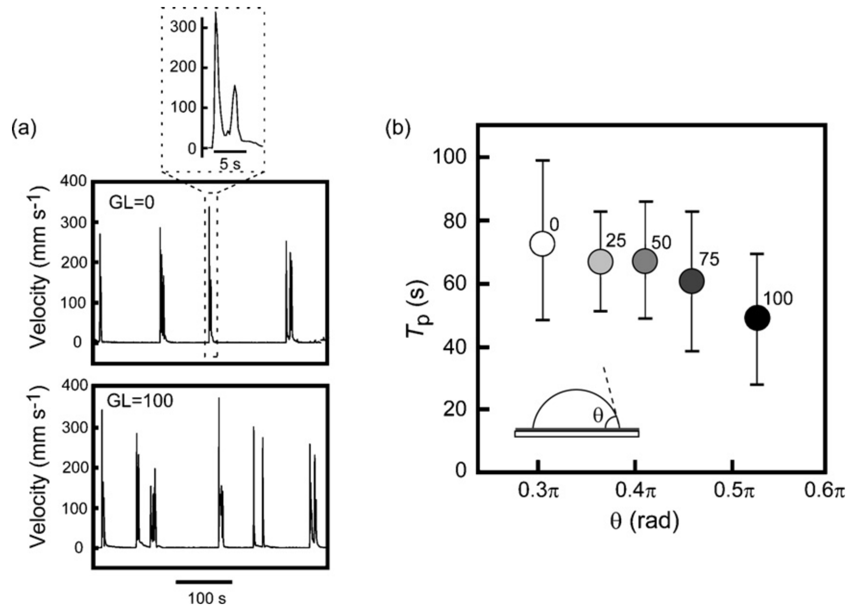

Fig. 1. (a) Time variation of the velocity of a camphor plastic float (diameter of the disk: 10 mm) for GL = 0 (top) and GL = 100 (bottom). The inset shows the detail profile at rapid motion with the expansion of the time axis. The second peak in the inset was caused by collision with the wall of the chamber. (b) Relationship between θ and the period of intermittent motion (T_p). Numbers and shaded circles in (b) are the GL value and the actual GL. θ is the contact angle of a water droplet on a polyester film with different densities of toner.

prepared by connecting the camphor disk to the center of either a polyester film (thickness: 0.1 mm) to create a camphor plastic float or a glass disk (diameter: 12 mm; thickness: 0.15 mm) to create a camphor glass float, and the camphor disk was placed in contact with the water surface. To change the hydrophobicity of the plastic surface, toner particles were adhered to one side of the plastic disk (diameter: 10 mm) with a laser printer, and the density of toner was changed by adjusting the gray level (GL) with computer software. To change the hydrophobicity of the glass surface, fluorocarbon resin (90% 1,1,1,2,3,4,4,5,5,5-decafluoropentane, 10% perfluorocarbon) was sprayed (FC-115, Fine Chemical Japan Co., Ltd., Japan) on one side of the glass disk, and the density of the fluorocarbon resin was changed by altering the distance between the spray and the disk. For the water phase, 250 ml of water was poured into a square plastic dish (0.0256 m^2, water level: 10 mm).

The movement of the camphor float was monitored with a digital video camera (SONY DCR-VX700, minimum time-resolution: 1/30 s) in an air-conditioned room at 298 ± 2 K, and then analyzed by an image-processing system (ImageJ, National Institutes of Health, USA). About 10 cycles of intermittent motion were recorded for each examination, and at least five examinations were performed for each set of experimental conditions, and thus 50–70 data were used to analyze the features of motion for each set of conditions. The concentration of camphor dissolved in water was measured with an absorptiometer (Shimazu Co., UV-1600PC, Kyoto, Japan).

3. Results

The effect of the surface of the plastic film was investigated by changing the hydrophobicity of the surface with a laser printer. Fig. 1 shows (a) the time variation of the velocity of the camphor plastic float for GL = 0 and 100, and (b) the relationship between the contact angle θ and the period of intermittent motion (T_p) for the camphor plastic float. Here, θ is the contact angle of a water droplet (30 μl) on a polyester film with different densities of toner. Intermittent motion, i.e., repetition of rapid acceleration → slow deceleration → rest, was observed. θ proportionally increased with GL between GL = 0 and 100. The ratio between the resting time (T_r) and T_p for one cycle of intermittent motion, T_r/T_p, was 0.8–0.9. Although the periodicity of intermittent motion was not very high, the average value of T_p decreased with an increase in θ.

Adsorbance at 285 nm, which was the maximum absorbance of camphor in water, was measured to evaluate the adsorption of camphor molecules to carbon particles. The absorbance of 6 mM camphor aqueous solution and that of the solution (5 ml) after the filtering with an excess amount of carbon particles (5 g) were 0.283 and 0.035, respectively.

To investigate the effect of the hydrophobicity of the surface of the camphor float with another float material and another adhesive substance, the surface of the glass disk was sprayed with a fluorocarbon resin. Fig. 2 shows T_p for the camphor glass float depending on θ. T_p for the camphor plastic float (GL = 0) is also shown for comparison with the features of intermittent motion of a glass float with the same circular shape and size (diameter: 12 mm). T_p decreased with an increase in θ, and the relationship between θ and T_p for the camphor glass float was similar to that for the camphor plastic float.

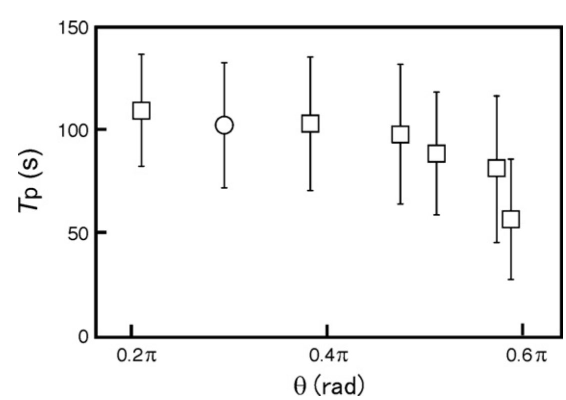

Fig. 2. Relationship between θ and the period of intermittent motion (T_p) of a camphor glass float coated with fluorocarbon resin (empty square). θ is the contact angle of a water droplet on a glass plate with different densities of fluorocarbon resin. An empty circle denotes the data for a camphor plastic float (diameter of the plastic disk: 12 mm) without toner.