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Electric Current Generation by Camphor Boats*

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The spontaneous generation of an electric current was examined by means of a camphor boat. The camphor boat attached a small magnet was spontaneously circled around a coil in a petri dish, resulting in the generation of an induced electric current. Moving modes of the camphor boat were determined by the shape of the petri dish and the camphor boat. The angular velocity of the camphor boat was about π/sec. The influences of the distance from the coil to the magnet and of the angular velocity on the generated electricity were also examined.

Keywords: chemo-mechanical; nonequilibrium; nonlinear

INTRODUCTION

The research of molecular layers has been widespread in science, engineer, pharmacy, and medical fields. The flexibility of the molecular layers was applied to various devices such as drug delivery systems [1], sensors [2], hydrophobic films [3], the histidine tagging (His-tag) technique [4], and so on. Among these researches, the authors have especially focused on the dynamic applications of the molecular layers. Recently, the authors had succeeded to obtain an induced current using the spontaneous motion of the molecular layer at nitrobenzene/water interface [5]. However, the value of the induced current was too small (~0.3 μA). The improvement of the induced current generated

*An induced electric current generation was established by a camphor boat.

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system was needed. In the former system, a nitrobenzene droplet spontaneously carried a small magnet around a coil in water because of the spontaneous interface tension change which was caused by the adsorption and desorption of the surfactant layers at nitrobenzene/water, resulting in the induced current. Thus, the value of the induced current depends on the amplitude of the interface tension change. As a corollary of this consideration, the interface tension change at air/water is more suitable for our induced-current-generated system, compared with the change at nitrobenzene/water interface. We focused on the spontaneous interface tension change by camphor layers at air/water interface.

The spontaneous motion of camphor disks was firstly reported by Rayleigh in 1890 [6]. When a camphor grain attached to a film and put on the water surface, various spontaneous motions are observed [7]. This film is called a "camphor boat." Following his report, the spontaneous motion was studied by many scientists for understanding nonequilibrium systems and building a new chemo-mechanical transducer under isothermal conditions [8–11]. The camphor movements on the water surface were theoretically determined by Kitahata *et al*. [12]. Nakata *et al.* had reported that the selection of the spontaneous-movement modes was depended on the conditions of the camphor flakes attached to the boat and the shape of container [7]. However, this spontaneous motion has not been applied for engineering systems. In this paper, as the first report of the engineering application of the camphor boats, a spontaneous electric-current generated system using the camphor boats is examined.

MATERIALS AND EXPERIMENTS

Preparation of the Camphor Boats

The front of a polyethylene terephthalate (PET) film was cut as a streamline shape (1.7 mm long and 0.8 mm width) (Fig. 1). Two holes (1 mm dia.) were prepared at the back of the film for putting camphor grains. A magnet (Neodymium, 2 mm dia., 2 mm thickness; 0.05 g, 3100 G, N-005, Niroku Seisakusho, Co. Ltd., Japan.) was attached to the PET boat by an adhesive. Neodymium is a light magnet (7.3 g/cm^3 density); thus, it could be supported on the thin PET boat. The total weight of the boat and the magnet was 0.0624 g. A magnet's direction was fixed vertically to avoid the influence from terrestrial magnetism: The N polar was foreside. Camphor grains ((+)-Camphor, Wako, 0.005 g each) were put on the each hole of the boat.

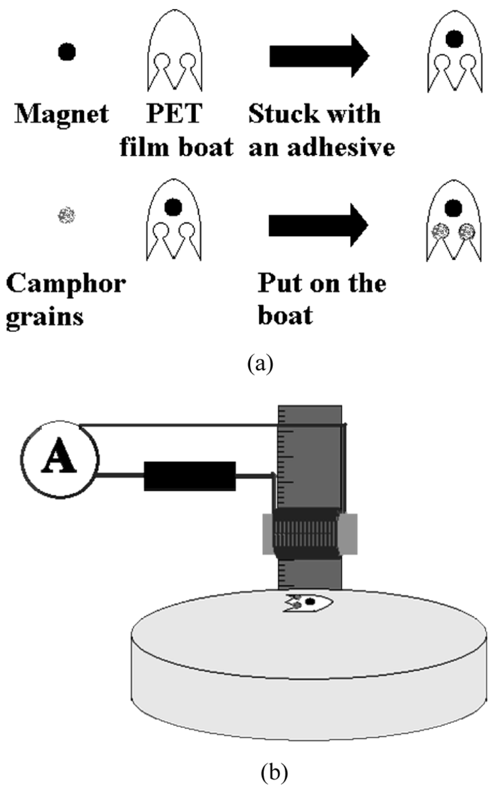

FIGURE 1 Preparation procedure of our camphor boat (a) and the measurement system of the induced electric current (b).

Measurement of the Induced Currents

Thirty-milliliter pure water was poured in a 9 cm Petri dish. A coil (4 mH, 8 mm dia., 3 cm long) was set near the water surface. The boat with the camphor grains was gently put on the water surface. The distance from the coil (4 mH, 8 mm dia., 3 cm length) to the magnet on the boat was changed from 3 to 22 mm. A 4.7 Ω resistor was connected in series with the coil. The total circuit resistance was 140 Ω (and that of the picoammeter used was 80 Ω). The induced electric current were measured by a picoammeter (Model 6487, KEITHLEY).

Measurement of the Surface Pressure

The experimental set-up is almost same as the measurement of the electric current measurement: except the dipping of the Wilhelmy plate. The time-dependent surface pressure was measured by a L.B. FILM PRESSURE METER (FACE). Simultaneously, the movement of the boat was monitored with a digital video camera (OLYMPUS, μ790SW).

RESULTS AND DISCUSSIONS

Electric Current Generation

The camphor boat was continuously rotated along the inside wall of the petri dish (Fig. 2). The angular velocity was about 180°/sec. Electric current was generated whenever the magnet was passed through the bottom of the coil (Fig. 3a). The electric current was observed as a plus shape. In the pulse, the current value was changed from plus to minus. This is because, when a magnet was came close to the bottom of the coil, a magnetic flux density was increased, resulting in the plus current; and when a magnet passed through the bottom of a coil, the magnetic flux density was decreased, resulting in the minus current.

The average value of the distance-dependent current is shown in Figure 3b. Obviously, electric current is depended on the distance from the coil to the magnet. In the case of a cylindrical magnet, the

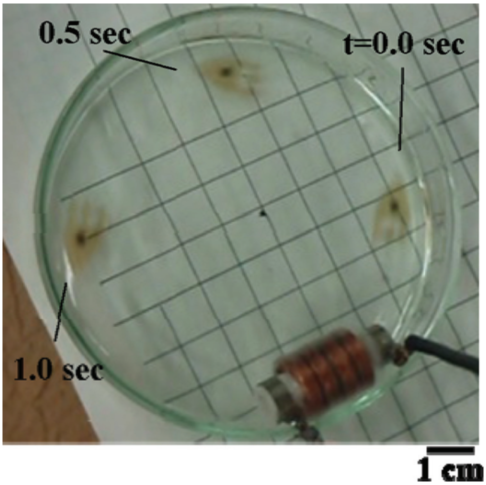

FIGURE 2 A time trace of the self-motion of a camphor boat with a time interval of 0.5 s. This photo indicated that the camphor boat was continuously rotated along the inside wall of the petri dish.

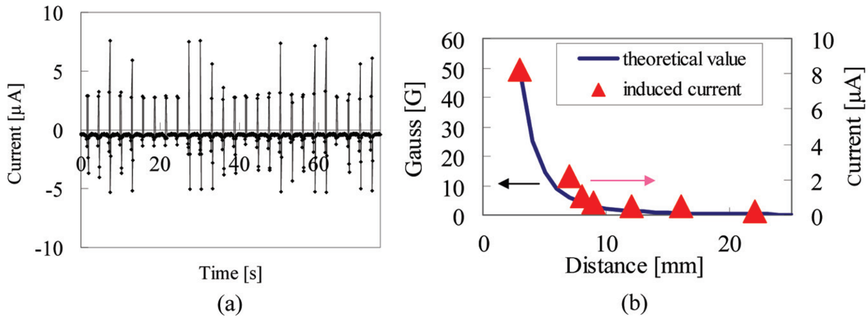

FIGURE 3 The experimental induced current at the 3 mm distance (a) and the experimental induced current and the theoretical density of the magnetic flux depending on the distance from the coil to the magnet (b).

magnetic field is described as [13],

$$B = \frac{Br}{2}\left[\frac{(\ell + L_m)}{\sqrt{(\ell + L_m)^2 + D^2/4}} - \frac{\ell}{\sqrt{\ell^2 + D^2/4}}\right]$$

where B_r is the remanent flux density, l is the distance from the magnet, L_m is the thickness of the magnet, and D is the diameter of the magnet. The theoretical values were also plotted in Figure 3b. As shown in Figure 3b, the experimental results were well fitted on the theoretical values.

An induced current is extremely related with a magnetic field. As the magnetic fields increased, the induced currents was proportionally increased. Thus, we could obtain the theoretical induced current maximum from the magnetic field maximum: The theoretical maximum of the induced current should be derived when the distance from the coil to the magnet is 0. The approximate expression of the experimental induced current is:

$$y = 11335x^2 - 533543x + 7 \times 10^6$$
$$R^2 = 0.8463$$

R^2 becomes slightly low. This might be because the setting of the distance from the coil to the magnet was in manual procedure, and the external magnetic field was not shielded. Based on this expression, we can get the theoretical maximum induced current value as ~200 μA.

Surface Pressure

The driving force of the spontaneous motion of the camphor boats is surface tension. The time-dependent surface pressure was shown in Figure 4. The surface pressure were measured every 10 seconds and the angular velocity were measured every 10 laps. The surface pressure and the angular velocity were changed nonlinear.

Kitahara *et al.* has been succeed to describe the spontaneous movement of the camphor grains as [12],

$$r(c) = \frac{\gamma_0}{c + \tilde{c}},$$

$$\frac{\partial c}{\partial t} = -kc + D\nabla^2 c + G(r, \theta),$$

$$G(r,\theta) = \begin{cases} \alpha(c_0 - c) & \text{if the point is inside the grain,} \\ 0 & \text{otherwise.} \end{cases}$$

Here, c represents the density of the camphor layer. The terms, $-kc$ and $D\nabla^2 c$, correspond to the sublimation and diffusion of the camphor layer, respectively. $G(\mathbf{r}, \theta)$ is the term of development of the camphor layer from the grain.

The movement of the camphor boat might be similar with the camphor grains. Thus, as described in the above equation, the movements of the camphor boats also depends on the velocity of the sublimation and the diffusion of the camphor layer. A camphor is less soluble in water (solubility = 0.12 g/100 mL). Therefore, camphor molecules were diffused on water surface and these moleculese are stratified. The camphor layers made the weak surface activity, and caused

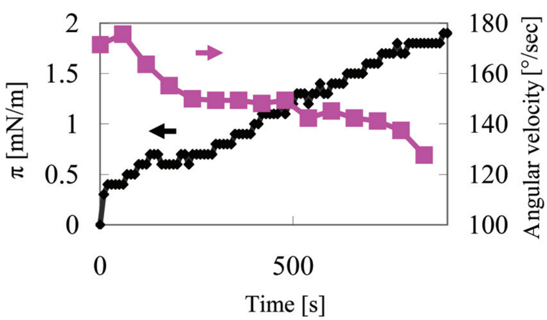

FIGURE 4 Time traces of the angular velocity and the surface pressure. The angular velocity was measured every 10 laps. The surface pressure was measured every 10 s.

Marangoni-flow. The sublimation and the diffusion are depended on the number of camphor layers. This dependence may be the reason of the nonlinear change of the time-dependent surface tension change. As the camphor layers were spread on the water surface, the surface tension became decreased, resulting in the decrease of the angular velocity.

Based on these phenomenon, we minutely describe for Figure 4. At the first step, when the camphor boat was continuously rotated along the inside wall of the petri dish, the convection flow was generated for a few minutes, resulting in the rapid diffusion of the camphor. These are why the angular velocity was rapidly increasing and rapidly decreasing in Figure 4. These results suggested that we should consider about the sublimation of the camphor grains and the effect of the camphor layer flow, at least when we used a camphor boat, not a simple camphor grain. As time progresses, induced current will decrease because angular velocity is progressively diminish.

CONCLUSIONS

The authors have developed induced current generated systems using the dynamics of the molecular layers. In this paper, the spontaneous interface tension change by the camphor layer at air/water interface was applied on the current generated system, resulting in the maximum 27 times the induced current of the previous systems. This result is a part of the new electric current generated system using molecular layers, and shows the further possibilities of the chemomechanical transduction in the dynamic molecular layers.

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