Supporting Information (SI)

Height-dependent oscillatory motion of a plastic cup with a camphor disk floated on water

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1. Movies of self-propelled object on water in Figs. 2 and 4.

Movie S1: Movie of self-propelled object at h = 0 mm of oscillatory motion in Fig.2a (100× speed)

Movie S2: Movie of self-propelled object at h = 1.0 mm of oscillatory motion in Fig.2b (100× speed)

Movie S3: Movie of self-propelled object at h = 1.8 mm of oscillatory motion in Fig.2c (100× speed)

Movie S4: Movie of self-propelled objects from top view under the UV light irradiation for h = 0 in Fig.4a (30× speed)

Movie S5: Movie of self-propelled objects from top view under the UV light irradiation for h = 0.5 mm in Fig.4b (30× speed)

2. Comparison of the amount of camphor molecules that accumulate inside the cup.

The green color intensities were analyzed at points P_{in} and P_{first} near the inner walls of the plastic cup and around the camphor disk in the diffusion region (Fig. S1a). The green intensities at P_{in} are denoted I_{in}, those at P_{first} before acceleration are denoted I_{first}, and their relative intensities I_{in}/I_{first} were also calculated (Fig S1b). The average values of I_{in}/I_{first} before acceleration were 0.92 ± 0.01 and 1.00 ± 0.03 at h = 0 and 0.5 mm, respectively.

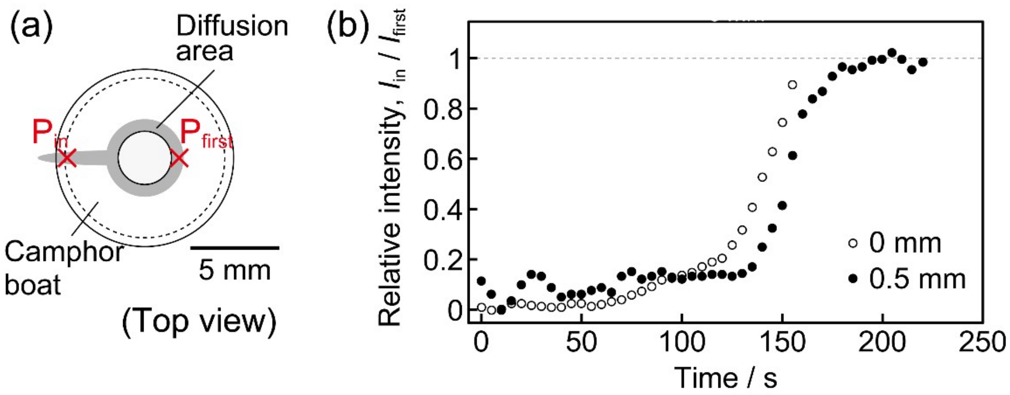

Fig. S1 The location of P_{in} and $P_{first,}$ near the inner wall of the cup and around the camphor disk, respectively. (b) Time-course of the relative intensity, I_{in}/I_{first}, for h = 0 (white circles) and 0.5 mm (black circles). $t = 0$ when the object was initially floated on water.

3. Camphor concentration remained under the cup after 5 s of acceleration

Figs. S2a and S2b show the snapshots of the self-propelled object from top view at h = (a) 0 and (b) 0.5 mm, respectively. At h = 0 and h = 0.5 mm, the times after 1/3 seconds from moved. We estimated the camphor concentration under the cup by relative intensity I/I_{first} (Fig. S2c).

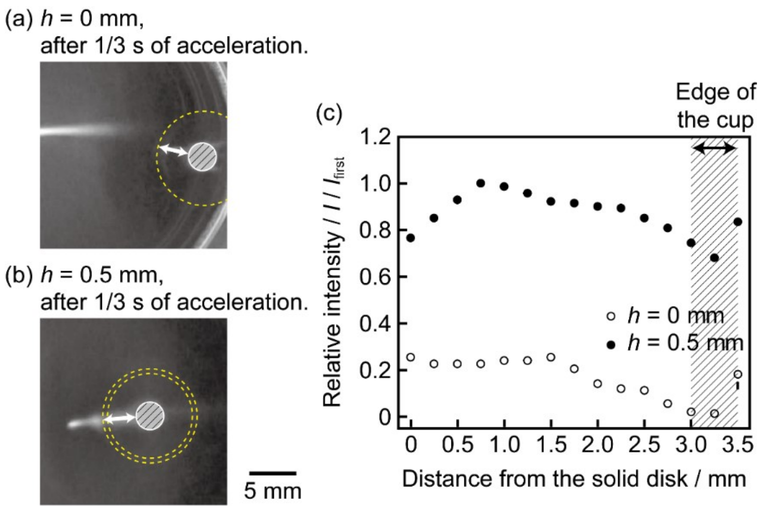

Fig. S2. Snapshots of the self-propelled objects (top view) for h = (a) 0 (upper) and (b) 0.5 mm (lower) 1/3 s after the acceleration. (c) Relative intensity, $I_{\mathrm{in}}/I_{\mathrm{first}}$, of camphor under the cup as a function of the distance from the edge of the camphor disk to the edge of the plastic cup at $h = 0$ (white circle) and 0.5 mm (black circle). The green intensities on the white arrow lines marked in (a) and (b) were analyzed individually.

4. Determination of the diffusion coefficients of camphor molecules, $\bar{D}_1$ and $\bar{D}_2$

The diffusion length (L) of camphor molecules under the plastic cup was analyzed to evaluate two types of the diffusion coefficients of camphor molecules under the plastic cup, $\bar{D}_1$ and $\bar{D}_2$. In the 1st diffusion, isotropic and gradual diffusion ($L < 1$ mm) and rapid and anisotropic diffusion ($L \geq 1$ mm) were observed. Figure S3 shows that time variation of the L^2 value, and this transition is not linear. Although the actual diffusion process is much complicated due to the cup shape and motion of the boat, we modeled the diffusion process by a one dimensional diffusion with position-dependent diffusion coefficient for simplicity. In this model, we estimated diffusion coefficient, as the time-averaged diffusion coefficient.

Actually, the time-averaged value of the diffusion coefficient for the 1st diffusion, $\bar{D}_1$, was expressed by eq. (S1).

$$\bar{D}_1 = \frac{1}{t_1 - t_0}\int_{t_0}^{t_1} D_1 dt = \frac{1}{t_1 - t_0}\frac{1}{2}\left[L^2\right]_{t_0}^{t_1} \#(S1)$$

where t_0 is the start time of 1st diffusion, t_1 is the time when the 1st diffusion is finished, and L is the diffusion length. The values of $\bar{D}_1$ was estimated as 4.14×10^{-8} m^2 s^{-1}.

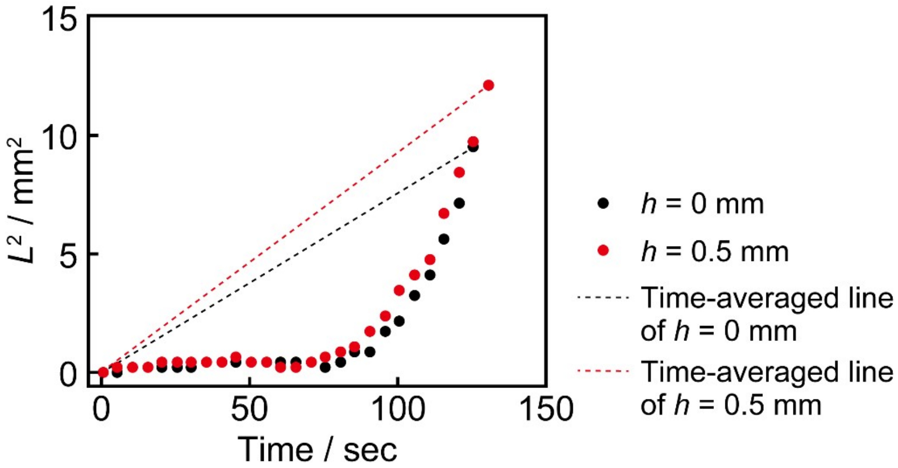

Fig. S3. Time variation of the L^2 of the diffusion region for camphor molecules under the plastic cup at h = 0 (black), and 0.5 (red) at first diffusion ($L \leq 3.5$ mm, $L^2 \leq 12.25$ mm^2). Black and red dotted line were time-averaged line of the L^2 from t_0 (= 0 s) to t_1 (= 125 s) of h = 0 and 0.5 mm, respectively. $\bar{D}_1$ was obtained based on time-averaged line of the L^2 from t_0 to t_1.

The time-averaged value of the diffusion coefficient for the 2nd diffusion, $\bar{D}_2$, was expressed by eq. (S2).

$$\bar{D}_2 = \frac{1}{t_2 - t_1}\int_{t_1}^{t_2} D_2 dt = \frac{1}{t_2 - t_1}\frac{1}{2}\left[L^2\right]_{t_1}^{t_2} = \frac{1}{2}\frac{1}{t_2 - t_1}\left(l_d + l_h\right)^2 \#(S2)$$

where t_1 is the start time of 2st diffusion, t_2 is the time when the 2nd diffusion is finished, L is the diffusion length, l_h is the height of the plastic cup (= 0 and 0.5 × 10^{-3} m), l_d is the thickness of the plastic plate (= 0.2 × 10^{-3} m). The diffusion coefficient $\bar{D}_2$ was estimated as 3.38 × 10^{-9} m^2 s^{-1}.

Table S1. The diffusion coefficient, $\bar{D}_2$, calculated from the time taken for the camphor to diffuse along the z-axis for $l_h = 0$ and 0.5×10^{-3} m.

l_h (m)	t_2 (s)	$\bar{D}_2$ ($m^2\ s^{-1}$)
0	27	2.27×10^{-9}
0.5×10^{-3}	107	5.24×10^{-9}
	Average value of $\bar{D}_2$	3.38×10^{-9}

5. Calibration curve on green intensity *versus* concentration of 7-hydroxycoumarin

Fig. S4 shows the green intensity of the water phase depending on the concentration of 7-hydroxycoumarin (7-HC) under the UV light irradiation. From the calibration curve ($R^2 = 0.9986$) in Fig. S4, the relationship between the concentration of 7-HC (C_{hc}, mol L^{-1}) and the green intensity (I) is described in eq. (S3).

$$I = 5527.7\ C_{hc} + 64.1 \tag{S3}$$

As 1 w/w% 7-HC is mixed with camphor, the concentration of camphor (C_{cam}, mol L^{-1}) is expressed as eq. (S4).

$$C_{cam} = \frac{162.14 \times 99}{152.23} C_{hc}, \tag{S4}$$

where the molecular weights of camphor and 7-HC are 152.23 and 162.14 g mol^{-1}, respectively. Based on eqs. (S3) and (S4), the relationship between I and C_{cam} is given as eq. (S5).

$$I = 52.423\ C_{cam} + 64.082 \tag{S5}$$

At h=0, the green intensity (I) outside the cup just before acceleration was 222. Therefore, the threshold camphor concentration just before the acceleration, C_0, was estimated to be 3 mmol L^{-1} based on eq. (S5).

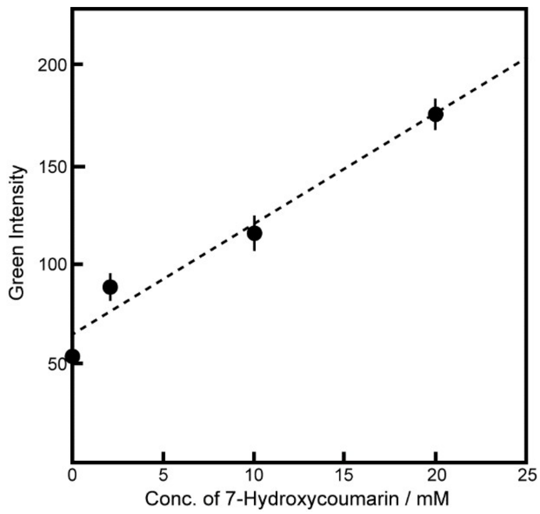

Fig. S4. The calibration curve on the green intensity *versus* the concentration of 7-HC.

6. Evaluation of the friction coefficient, μ, as a function of h

The friction coefficient, μ, on the motion for the five different objects was evaluated based on the previous paper.[17] μ was almost independent of h under the present conditions, as shown in Fig. S5.

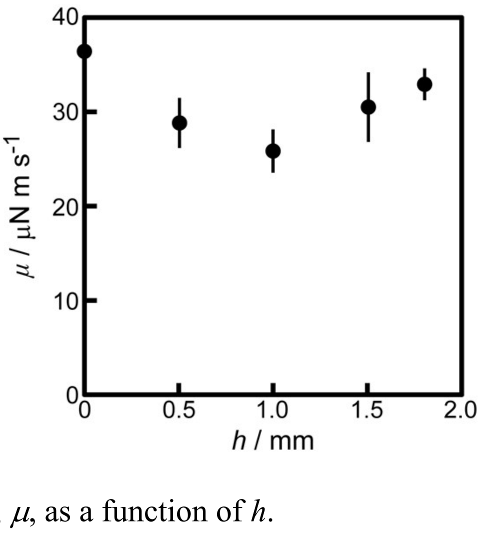

Fig. S5. The friction coefficient, μ, as a function of h.