Mini-Generator of Electrical Power Exploiting the Marangoni Flow
Inspired Self-Propulsion

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ABSTRACT: The mini-generator of electrical energy exploiting Marangoni soluto-capillary flows is reported. The interfacial flows are created by molecules of camphor emitted by the "camphor engines" placed on floating polymer rotors bearing permanent magnets. Camphor molecules adsorbed by the water/vapor interface decrease its surface tension and create the stresses resulting in the rotation of the system. The alternative magnetic flux in turn creates the current in the stationary coil. The long-lasting nature of rotation (approximately 10−20 h) should be emphasized. The brake-specific fuel consumption of the reported generator is better than that reported for the best reported electrical generators. Various engineering implementations of the mini-generator are reported.

1. INTRODUCTION

Micro- and mini-generators of electrical energy are receiving a considerable amount of interest from both theoretical1 and application points of view.2−6 Electromagnetic2−5 and electrostatic6 microgenerators should be distinguished. A diversity of power sources was involved for micropower generation including exploitation of external vibrations,2 microscale combustion of hydrocarbon fuels,3 chemical energy,7 and in particular the conversion of liquid-phase hydrogen to usable hydrogen gas (H2).8 We report the centimeter-scaled electromagnetic mini-generator converting the energy of soluto-capillary flows into electromagnetic energy. More accurately speaking, we suggest the mini-generator based on the self-propelled rotor based on the Marangoni flows.9−15 Self-propulsion, driven by Marangoni flows, is a result of unbalanced surface tension forces.9−15 The Marangoni flow is created as a result of gradients in chemical concentration or temperature at the liquid/vapor interface.13−15 The profoundly developed theory of the effect has been addressed recently in ref 15. Thermo- and soluto-capillary Marangoni flows were successfully used for a number of technological applications such as microfluidic devices,16 inkjet printing,17 miniature rolling bearings,18 spreading of emulsions,19,20 and micro-robotics.21,22 The possibility of manufacturing electrical energy with self-propelled droplets has been demonstrated recently in ref 23. We demonstrate the possibility of manufacture of the electrical energy with the self-propelled rotator driven with Marangoni solute-capillary flows.9−15

2. RESULTS AND DISCUSSION

The experimental system is shown in Figure 1. Deionized water, used as supporting liquid, was purified by a synergy UV water purification system from Millipore SAS (France), and its specific resistivity was $\hat{\rho} = 18.2 \text{ M}\Omega \cdot \text{cm}$ at 25 °C. The plastic dish (ø 420 mm) was filled with deionized water, and the height of the supporting liquid $h_i$ was $10 \pm 0.5 \text{ mm}$. Camphor, C$_{10}$H$_{16}$O (96%), was supplied by Sigma-Aldrich. The experiments were recorded with a Logitech C310 camera. Movies were processed using the VirtualDub-1.10.4 software and specially developed software. All of the experiments were performed at ambient conditions (SATP). Two-, four-, and six-pole polymer (PP (polypropylene)) rotors were used for the generation of ac, as depicted in Figure 2a−c. The PP film thickness was 0.08 mm.

Neodymium magnets ($m = 1 \text{ g}$; diameter 6 mm) were located on the rotor, as depicted in Figure 2a−c ($B \cong 0.5 \text{ T}$ as measured at the surface of the magnet and $B \cong 0.4 \text{ T}$ as established in the vicinity of the coil). Magnetic fields were

Received: July 21, 2019
Accepted: August 19, 2019
Published: September 5, 2019

DOI: 10.1021/acsomega.9b02257
ACS Omega 2019, 4, 15265−15268

Figure 1. Scheme of the microelectric power generator is depicted. i is the alternative current.
measured by the 1-Axis dc/ac Model GM2 gaussmeter manufactured by AlphaLab, Inc. (USA). The lab-made coil was used in the scheme. The coil contained 800 loops of copper wire with a diameter of 0.1 mm. The coil’s outer diameter was 15.3 mm, and the internal diameter was 6.5 mm. The coil’s resistance was $R = 35 \Omega$, and the coil’s mass was $m \approx 2$ g. The resistance $R = 35 \Omega$ was connected to the coil. The maximal voltage on the resistance was $U = 1.6$ mV. The voltage loss was measured with a SOUNTRON MS8213 multimeter.

The evaporation of camphor was studied as follows: the mass loss was controlled for engines with diameters of 6.5 and 4 mm and with areas of camphor evaporation $S = (3.3 \pm 0.1) \times 10^{-5}$ m$^2$ and $S = (1.3 \pm 0.1) \times 10^{-5}$ m$^2$, respectively. Camphor was evaporated under a temperature $T$ of 25 °C and humidity $RH$ of 0.45 for 5 h. The average specific rate of the evaporation of camphor for both engines was established as $\dot{m} = (0.86 \pm 0.1) \times 10^{-2}$ and $(1.4 \pm 0.1) \times 10^{-2} \frac{g}{m^2 s}$, respectively (as related to the unit surface of evaporation), as illustrated in Figure 3 ($\dot{m} = \frac{m}{t}$). Camphor mass loss was measured with a four-decimal place analytical balance ASB-220-C2.

Two kinds of “camphor engines” with nozzle diameters of 4 and 6.5 mm were used in the research. The camphor engines with a nozzle diameter of 4 mm were used for the two-pole rotor (see Figure 2a); the camphor engines with a nozzle diameter of 6.5 mm were used for the four- and six-pole rotors (see Figure 2b,c). The parameters of the camphor engines are summarized in Table 1.

### Table 1. Output Parameters of the Camphor Engines

| diameter of the camphor engine $D$ (mm) | average rate of camphor evaporation $\dot{m}$ (g/s) |
|----------------------------------------|---------------------------------|
| 4                                      | $1.8 \pm 0.5 \times 10^{-7}$    |
| 6.5                                    | $2.8 \pm 0.6 \times 10^{-7}$    |

Rotors were driven by the Marangoni interfacial soluto-capillary flows, depicted schematically in Figure 4. Molecules of camphor evaporated from engines were adsorbed partially by the water/vapor interface, as shown in Figure 4. The adsorbed molecules of camphor decreased the surface tension of water, thus giving rise to the misbalance of surface stresses, resulting in Marangoni flows, driving the rotors, as shown in Figure 4.
depicted in Figure 4 and illustrated in Movies S1 and S2. The rotating magnets attached to rotors produced alternating magnetic flux, resulting in AC produced in the coil. The quantitative output parameters of generators exploiting the reported rotors are summarized in Table 2.

| rotor       | maximal power $P_{\text{max}}$ (W) | specific power, related to the unit mass of the generator $fl$ (W/kg) | brake-specific fuel consumption (BSFC) $\hat{f}$ (g/kW h) |
|-------------|-------------------------------------|---------------------------------------------------------------------|--------------------------------------------------------|
| two-pole    | $\sim 5 \times 10^{-3}$            | $\sim 10^{-2}$                                                     | 5 $\pm$ 10                                            |
| four-pole   | $\sim 5 \times 10^{-3}$            | $\sim 6.25 \times 10^{-1}$                                        | 20 $\div$ 25                                          |
| six-pole    | $\sim 10^{-7}$                     | $\sim 5 \times 10^{-3}$                                           | 15 $\pm$ 20                                            |

The power-to-weight ratio $\hat{f}$ of the reported generators is worse than the corresponding parameters reported for hydroelectric turbines, thermoelectric generators, electrochemical (galvanic), and electrostatic cell systems and fuel cells. Contrastingly, the brake-specific fuel consumption (abbreviated BSFC and denoted as $\frac{P}{m}$) is better than that reported for the best reported electrical generators; compared with the data supplied in Table 2, BSFC $= 135.5$ g/kW h is reported for the General Electric 9HA combined cycle engine.26

It is noteworthy that the effect of the self-propulsion of the so-called camphor boat is a well-known phenomenon.27,28,30 It should be emphasized that, in our device, there is no direct contact between camphor and water. The Marangoni flows are due to the evaporation of camphor, followed by its adsorption by the water/vapor interface, and not due to the dissolution of camphor.27,28,30 The evaporation of camphor is a relatively slow process. This leads to the low expenditure of camphor and consequently to the aforementioned high values of BSFC supplied in Table 2. The long-lasting nature of rotation lasting approximately a dozen of hours should be emphasized. The rotor removes the molecules of camphor adsorbed by the water/vapor interface, providing each time the “fresh” water surface ready for adsorption of the next portion of camphor molecules. This fact explains reasonably the unusually long-lasting nature of the rotation, making it especially suitable for the small-scale generation of electric power. The suggested system supplies the continuous rotation of the rotor for 10–20 h, which is much better than that reported recently in ref 30, where the supramolecular host–guest chemistry strategy enabling prolongation of the lifetime of Marangoni flows was suggested. The decay of the frequency of rotation of the rotors of different lengths with time is shown in Figure 5.

In our previous publication,24 we suggested the following scaling law for the quasi-stationary frequency of rotation of the rotator

$$f \approx \frac{3 \Delta \gamma}{2 \eta L} \quad (1)$$

where $\Delta \gamma$ is the jump in the surface tension of water due to absorption of camphor and $\eta$ is the water viscosity. It is seen from Figure 5 that the scaling dependence $f \sim \frac{1}{L}$ qualitatively holds for the two-pole rotors; namely, the quasi-stationary frequency of rotation decreases with the length of the rotor.

The temporal decrease of the frequency of rotation may be fitted with eq 2

$$f = f_0 \exp\left(-\frac{t}{\tau}\right) \quad (2)$$

where $\tau$ is the characteristic timescale of the rotation decay established as $\tau \approx 10$ h.

3. CONCLUSIONS

In conclusion, we report the mini-electrical generator transforming the energy of interfacial Marangoni flows into electrical energy. Interfacial flows are created by camphor molecules given off by the camphor engines placed on the floating polymer rafts bearing permanent neodymium magnets creating magnetic fields of $B \cong 0.4 \sim 0.5$ T. The absorption of camphor molecules by the water surface gives rise to the local decrease in the surface tension, thus giving rise to the rotation of rafts. Stationary coils immersed in the alternative magnetic flux produce alternative electrical current. The rather surprising long-lasting rotation of rafts is noteworthy.31–33 Rafts rotate continuously without recharging of the engines with camphor approximately 10–20 h. The proposed mini-generator enables diversification of fuel sources, introducing the plant-based camphor into the list of organic fuels. The generator will work in the absence of light when solar energy is unavailable.

ASSOCIATED CONTENT

Supporting Information
The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acsomega.9b02257.
Movie depicting the rotation of the rotor (L = 180 mm) (AVI)

Movie depicting the long-lasting rotation of the rotor (18 h of rotation) (AVI)

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Notes

The authors declare no competing financial interest.

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