Microscale engine swimming underwater powered by Marangoni convection

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Abstract
This study proposes a prototype of a microscale engine swimming underwater powered by Marangoni convection. The engine is a layered disk with a hole and holds a bubble ring in a gap between the layers. When the liquid-gas interface at the hole edge has the surface tension gradient, the engine gains the thrust force as the reaction of Marangoni convection. In a temperature Marangoni convection experiment, one side of the engine was heated by a laser, to make temperature gradient on the liquid-gas interface. It was confirmed that Marangoni convection was generated while the expanding bubble plugged the hole, to prevent the flow penetrating through the hole. In a concentration Marangoni convection experiment, pure water and acetic acid were injected toward the hole at each side, to make concentration gradient. The engine successfully generated jet-like flow through the hole to drive itself by 1.2 mm. PIV analysis visualized the flow field around the engine and the velocity profile of the jet. The jet direction was not stable because of the non-uniformity of the concentration on the gas-liquid interface and the magnitude of the jet velocity gradually diminished with the diffusion of acetic acid. The thrust force of the engine was estimated as 270 nN by calculating the momentum conservation equation of the flow around the engine.

Key words: Marangoni convection, Thermocapillary, Concentration, Micro-robot, PIV analysis, Surface tension

1. Introduction

Microscale robots swimming in liquid and moving toward their targets have been envisaged for medical and biological applications, such as a drug delivery robot(Iacovacci et al., 2015), a self-propelled capsule endoscope(Gao et al., 2010), and mobile micro-scissors(Tange et al., 2013). Masoud et al. (2012) proposed a computational model of a maneuverable micro-swimmer with propulsive flaps actuated by the swelling and deswelling of responsive gel. However, such actuators using flapping fins or propellers utilize the inertial motion of the liquid to move; these are not the most suitable forms of microscale robots since inertial force becomes weaker than viscous force and surface tension in microscale. On the other hand, Marangoni convection, flow induced by the surface tension gradient on a gas-liquid interface, has attracted attention as a microscale fluid handling technique used for a droplet motion controller(Chaudhury and Whitesides, 1992) and a microscale mixer(Yamada and Ono, 2015). Besides, Marangoni convection has been utilized to drive rigid objects floating on the liquid surface, including micromirrors on a droplet(Dhull et al., 2011), micro motors on a water surface(Maggi et al., 2015), floating mini-robots(Visvanathan et al., 2009), and laser-driven small objects on a water surface(Okawa et al., 2009). Since these devices need a gas-liquid interface to drive them, there has been no report on surface tension-driven devices moving underwater.
This paper proposes a prototype of the microscale engine swimming underwater powered by Marangoni convection. The engine consists of layered thin disks with circular holes, and it has a narrow gap between the outer disks to hold a bubble ring and realize a gas-liquid interface in the hole. Driving tests of the engine were conducted to confirm the movement of the engine due to the temperature or concentration gradient in the hole. The Marangoni flow around the engine in the temperature gradient experiment on the hole was confirmed, but a thermally expanded bubble plugged up the hole to prevent the flow penetrating through the hole. On the other hand, the engine in concentration gradient successfully produced the jet flow through the hole and drove itself due to the reaction force of the flow. The flow field calculated from PIV showed that the jet was not unidirectional, and it became weaker as the concentration differences were diminished. The force was calculated as 270 nN by using the momentum equation. This paper aims to propose a novel driving principle for the underwater robots and confirm the principle experimentally with some prototypes. The optimizations of design parameters of the device and the quantitative evaluation of these parameters will remain as future works.

2. Microscale engine swimming underwater

![Structure of a microscale swimming engine.](image1)

![Photo of the engine holding a bubble ring.](image2)

The structure of the microscale swimming engine developed in this study is schematically shown in Fig. 1. The engine consists of three thin layered disks with a circular hole. Each disk was made of SU-8 3050, using the photolithography technique. The disk diameter was 3 mm and the hole diameters of the outer disks, \( d \), are 1 mm. The hole of the middle disk is larger than those of the outer disks, and is composed of a thin gap between the outer disks. Hydrophobic paint, CYTOP, was painted on the inner wall of the outer disks, to repel water. The gap can hold a ring-shaped air bubble underwater, to cover the hole’s edge with a gas-liquid interface. Figure 2 illustrates the engine successfully holding air bubbles within the gap underwater and the gas-liquid interface around the hole edge. The total thickness of the engine was about 600–626 µm. The dimensions and shape of the engine were heuristically determined to keep the air bubble within the gap.

![Schematics of driving principles of the microscale swimming engine.](image3)

Figure 3 shows how the Marangoni convection drives the microscale swimming engine underwater. To utilize temperature gradients in water, one side (the front side) of the engine was painted in black, with nongloss aqueous spray, to increase heat absorption rate, and it was heated by a blue laser, as shown in Fig. 3(a). The interface of the heated side was warmer than that of the opposite side. As the surface tension of water became smaller with temperature increase, the Marangoni convection flows from the hot side (the front side) to the cold side (the rear side). Similarly, the concentration gradient at the interface also induces the Marangoni flow. The concentration difference between the front side and the rear side was realized with injections of...
acetic acid solution to the front side and pure water to the rear side as shown in Fig. 3(b). In both cases, the Marangoni convection in the hole sucked the front side fluid into the hole and ejected it from the rear side. The reaction force of the ejecting fluid moved the engine from the rear side to the front side. The horizontal (along the central axis of the hole) thrust force, $F_x$, can be estimated as the imbalance of the surface tension applied on the hole edges of both sides such as

$$F_x = F_{\text{rear}} - F_{\text{front}} = (\pi d \sigma_{\text{rear}} \cos \theta_{\text{rear}}) - (\pi d \sigma_{\text{front}} \cos \theta_{\text{front}}),$$

where $\sigma_{\text{front}}$ and $\sigma_{\text{rear}}$ are the surface energy at the edges of the front and the rear sides of the engine, respectively. Also, $\theta_{\text{front}}$ and $\theta_{\text{rear}}$ are the angles of the interface against the horizontal direction at each side. This equation indicates the engine moves forward when the surface tension at the rear side is stronger than that on the front side.

3. Experimental system and method

Figure 4 is the whole experimental systems used in the temperature gradient experiment (a) and the concentration gradient experiment (b). Both systems consist of an acrylic vessel, a green laser (wavelength of 532 nm) for PIV, an optical system, and a CMOS camera. The acrylic vessel (10 mm × 10 mm × 70 mm) was filled with pure water and tracer particles (of 20 µm in diameter) dyed with Rhodamine B (fluorescence wavelength of 580 nm). The swimming engine was hung with a thin copper wire (of 0.10 mm in diameter) and immersed in the vessel. The hanging wire is loosely hooked to confirm the movement of the engine; it was fixed tightly for PIV measurement. A cylindrical lens converted a green laser beam to a laser sheet and a mirror beneath the vessel introduced the laser sheet into a vertical plane along the central axis of the engine hole. PIV particles in the plane were excited by the green laser to emit the fluorescence. The CMOS camera with a long pass filter (transmission limit wavelength of 560 ± 5 nm) recorded the motion of the engine and the PIV particles.

During the temperature gradient experiment, a 2 W blue laser (wavelength of 532 nm) heated the front side of the engine to generate the temperature difference between the sides of the engine as shown in Fig. 4(a). The laser output was controlled with a PWM control device. During the concentration gradient experiment, on the other hand, acetic acid solution and pure water were injected toward the front and rear sides of the engine, respectively, by syringe pumps through the PEEK tubes (of 0.2 mm in inner diameter), as depicted in Fig. 4(b).

4. Results and discussion

4.1. Temperature gradient experiment

Figure 5 shows a typical flow field around the engine during the temperature gradient experiment. The red horizontal and vertical dashes in Fig. 5 indicate the central axis of the engine hole and the bisector of the engine. A yellow dashed square depicts the outline of the engine. Arrow size and color illustrate the magnitude of the velocity calculated by PIV analysis. A stable convection was not observed when the laser output was less than...
30% of the full output. When the output of the heating blue laser was 30% and more of the full output, upward flow due to natural convection was observed along the engine surface of both sides of the engine. Horizontal flow through the hole was not confirmed, while downward flow and circulation on the front side (the right side) were observed. It was indicated that a thermally expanded air bubble in the engine gap plugged up the hole, and the non-uniformity of temperature on the bubble surface at the front side induced the Marangoni convection in front of the hole, not inside the hole. This result shows that it is critical to avoid the volume expansion of the bubble, in order to utilize temperature Marangoni convection, and this design is therefore not suitable for temperature Marangoni convection. Marangoni convection, with a lower laser output, did not occur because both sides of this tiny device were not thermally insulated from each other, and the temperature difference was not realized. As for thermal insulation, the thicker middle disk, the larger hole of the middle disk, and different materials with small thermal conductivity for the device, will be the options of the design modification of the device geometry.

4.2. Concentration gradient experiment

Figure 6 is the sequential snapshots of the engine in a concentration gradient to confirm the engine movement, by injecting an acetic acid solution (50 wt%) and pure water toward the front side (the right side) and the rear side (the left side) of the hole. The hanging wire was not fixed, so as to allow engine movement in this experiment. The flow rates of acetic acid solution and pure water were 80 µL/min, and they were continuously injected during the experiment. These injections were small enough to ignore the displacement of the engine due to their flow. The PIV particle movement in Fig. 6 shows that liquid at the front side flowed into the engine hole. The flow direction of the Marangoni convection was downward because the acetic acid solution is heavier than water. The engine moved from the low concentration side (left) to the high concentration side (right). It was confirmed that the Marangoni convection successfully drove the engine. The total displacement of the engine for 28.8 seconds was 1.2 mm (the original position of the engine was shown in Fig. 6 with a dashed pink line). If the tube for acetic acid solution did not obstruct the further movement of the engine, the engine might have achieved larger displacement.

Figure 7 shows the flow field around the engine calculated by PIV analysis when the hanging wire was
fixed tightly. In this experiment, the supply of pure water and acetic acid solution of 70wt% was stopped after the injection of 8.3 mL to measure the velocity field caused by the Marangoni convection. Marangoni convection successfully sucked the acetic acid solution through the hole. As shown in Fig. 7, the direction and the magnitude of the jet flow, however, were not unidirectional and not constant. First, at $t = 1.4$ s (a), a small Marangoni convection led the acetic acid solution into the hole, and a weak downward flow ($v < 3.0$ mm/s) occurred, resulting from the density difference between acetic acid solution and pure water. Then, a strong upward jet was observed at $t = 2.9$ s (b), because the Marangoni convection at the top side of the hole was larger than the bottom side. The stable suction of acetic acid and axisymmetric concentration gradient were then realized, to generate a strong horizontal jet at $t = 4.3$ s (c). At this time, the flow rate through the hole was 10 µl/s. The strong jet involved water around the hole and the jet width became larger than the hole. Finally, at $t = 5.8$ s (d), the jet was diminished, and its direction became downward again, since the concentration gap between the front side and the rear side became small, and the Marangoni convection became weak. It was concluded that the jet flow had become weaker, since the acetic acid solution had diffused in the pool and the concentration gradient on the interface had gradually diminished.

Figure 8 shows the instantaneous profiles of the velocity magnitude of the jet at a distance of 1.0 mm from the bisector of the engine, illustrated as a dashed yellow line in Fig. 7. Black dashed lines in Fig. 8 indicate the position of the central axis of the engine hole. The profiles had a peak at the center of the jet, and the jet diameter was around 2 mm. The maximum magnitude of the profile exceeds 16 mm/s at $t = 2.9$ s and $t = 4.3$ s. The change of the jet’s direction causes the peak position to be offset by approximately 1 mm. It was concluded that the engine could generate a jet within a few seconds without the continuous supply of acetic acid, while the direction of the jet was unsteady. Buoyancy due to density distribution led to unexpected concentration distribution on the interface, resulting in unsteady and baffling jet flow. Water with surfactant can be an alternative since it has almost the same density as pure water.
4.3. Thrust force of the engine during concentration gradient experiment

The thrust force generated by the engine was calculated from the images of the concentration gradient experiment shown in Fig. 7. While Lagubeau et al. (2011) measured the force applied to a small droplet with a deflection of wire attached on the droplet, the deflection of the hanging wire of this study, however, was too small to observe its displacement. When the elastic response of the wire was less than 1 pixel in the image, the driving force of the engine was estimated below 1.3 µN. In this experiment, therefore, the force was indirectly measured from the magnitude of the flow generated by the engine.

A control volume for the calculation was a cylinder with 2.1 mm in length and 3.3 mm in diameter. The axis and the half height of the control volume were the central axis and the bisector of the device, respectively. Figure 7 shows the control volume with a white rectangle. Horizontal momentum change in the control volume resulted from the force generated by the engine. Supposing that momentum exchange due to pressure and viscosity on the surface of the control volume, $S$, are negligible, the horizontal thrust force, $F_x$, is estimated from the integral form of the conservation law of the horizontal momentum as

$$ F_x = -\rho \oint_S v_x v \cdot dS, \quad (2) $$

where $\rho$, $v_x$, $v$, and $S$ are water density, the horizontal component of the velocity, the velocity vector, and the small surface element pointing outward, respectively. The velocity field was assumed to be axisymmetric. As the acetic acid solution injected in this experiment was 6–7% heavier than water, the density in Eq. (2) must be non-uniform and must be described as the function of the space and time. In this study, there is no information about the density field. Therefore, the water density was employed to calculate a reasonable approximation. The actual density field in the pool diffused and the calculation included the same level of error at most.

Figure 9 is the time development of the horizontal thrust force. The profile was smoothed by 15 point moving average to reduce the noise due to errors in PIV. Since the direction of the jet at (b) is not horizontal, horizontal thrust was about 100 nN while the thrust of the horizontal jet at (c) was about 150 nN. Thrust after (c) was diminished because of the direction change and the decrease of flow magnitude itself. The maximum value of the thrust near (a), 270 nN, is about one three-hundredth of the force calculated from the equation (1) by using the literature values(Yamada and Ono, 2013) of the surface tensions of acetic acid solution(70wt%) and pure water. This calculation overestimated the thrust force since the actual concentration field diffused, and the surface tension difference was not large.

5. CONCLUSIONS

This study proposes a prototype of a microscale engine swimming underwater powered by Marangoni convection. The engine is a disk with a hole and holds a ring-shaped bubble in a gap on the hole. When the liquid-gas interface at the hole edge has a surface tension gradient, the engine gains the thrust force as
the reaction force of the Marangoni convection. In a temperature Marangoni convection experiment, one side of the engine was heated by a laser, to make the temperature gradient on the liquid-gas interface. It was confirmed that Marangoni convection was generated, while the expanding bubble plugged the hole, to prevent the flow penetrating through the hole. Thermal insulation inside the engine may realize larger temperature differences between both sides of the engine, with a smaller heat input, to avoid natural convection and bubble expansion, due to overheating, and to result in a jet through the hole by temperature Marangoni convection. In a concentration Marangoni convection experiment, pure water and acetic acid were injected toward the hole at each side, to make the concentration gradient. The engine successfully generated a jet-like flow through the hole to move by 1.2 mm, when the engine was allowed to move. PIV analysis visualizes the flow field around the engine and the velocity profile of the jet. The jet direction was not constant because of the non-uniformity of the concentration at the edge of the hole, and the magnitude of the jet velocity gradually diminished, with a decrease of the concentration difference between both sides of the hole. The maximum value of the thrust force was estimated as 270 nN, which was calculated from the momentum conservation equation.

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