Influencing factors of self-rotating micro device based on water droplet

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Abstract. Self-propelling micro devices, which means moving spontaneously without traditional motor, have been widely studied in recent years. We proposed a new kind of self-rotating micro device based on water droplet, which can achieve rotating without any external energy. It can transform surface energy of the water droplet into kinetic energy of the micro device. And the feasibility experiment showed that the micro device work well, the numerical analysis of the micro device about the rotating velocity varied with the different center distance and number of the inclined pores provided us an empirical equation to predict the rotating property of the micro device, and an application model in micro generator field was proposed. The self-rotating micro device is a totally original self-propelling device with a green propelling mechanism to the environment.

1. Introduction

Self-propelling micro devices, which means moving spontaneously without traditional motor, have been widely studied in recent years, due to their potential applications in reality, such as in cleaning polluted water [1], and removing floating oil [2]. The driving mechanism of self-propelling micro devices can be divided into several types, which all realize the transformation from non-traditional energy to kinetic energy. For example, some researchers paid attention to nano-motors [3], which realize the transformation from chemical energy to kinetic energy. They designed a device with microvilli formed by platinum tail, and put it on the surface of hydrogen peroxide aqueous solution, then the microvilli can decompose hydrogen peroxide into water and oxygen bubbles, which can propel their device to move. Some researchers showed great interest in Marangoni effect, which refers to that when a liquid film is partially thinned due to external disturbance (such as temperature and concentration), it will form Marangoni flow under the effect of surface tension gradient, making the liquid flow back to the thin liquid surface, so it can transform heat energy or interface energy to kinetic energy. Okawa D and his team designed a PDMS block modified by the carbon nanotube with uneven distribution [4], which can easily absorb and transfer the near-infrared laser heat energy, generate the thermal surface tension gradient when it floats on the water surface, and make the PDMS block move on the water surface. Some researchers fabricated the microboats, which loads isopropyl alcohol in the stern, floating on the water surface [5], it will cause the surface tension gradient when the isopropyl alcohol spread into the water, and move the microboat, due to the change of the surface tension by the mix of isopropyl alcohol and water. Recently, we have published a new driving mechanism, which is based on water droplet that can transform surface energy to kinetic energy [6].

In this paper, a shuttle-shaped superhydrophobic aluminum plate with central symmetrical superhydrophilic inclined pores, of which the number $n$ is even and the inclined angle with the vertical
direction is 45°, was fabricated by laser etching, laser cutting, laser drilling and low surface energy modification according to our previous method.[6] The device was floating on the water surface, and did not move directionally, instead, it had rotating motion, so it was called self-rotating micro device. The wettability of the surface of the device was superhydrophobic to decrease water resistance and increase the buoyancy of water, moreover, the superhydrophobic surface can keep the water droplet, which is put on it, staying spherical shape, and it will increase the Laplace Pressure caused by the water droplet, which can push the water in the droplet into the water below the device through the superhydrophilic inclined pores and form a jellyfish-like jet. The central symmetrical inclined jet can drive the device to rotate. The influence of the number of the inclined pore $n$ and the center distance of two symmetrical holes $d$ to the rotating distance and rotating velocity was experimented in our research, and an application model in micro generator field was proposed.

2. Materials and methods

2.1. Experimental materials

1060 aluminum plate (Al, purity > 99%) was purchased from Suzhou Metal Material Manufacturer (China). Fluoroalkysilane (FAS, C₈F₁₃H₄Si(OCH₂CH₃)₃) was purchased from Degussa Co., (Germany). All chemicals were of analytical pure and were used as received.

2.2. Fabrication of the self-rotating micro device

According to our previous study, all the fabrication processing was shown in Figure 1, the aluminum plate with the thickness of 0.59 mm was cleaned by ultrasonic with ethanol and deionized water. After that, laser etching was carried out on the upper and lower surfaces of the dried aluminum plate to form the microstructure, which will obtain the superhydrophilicity. Then, the superhydrophilic plate was cut into shuttle-shape the laser. After that, the superhydrophilic plate was immersed in 1wt% fluoroalkysilane ethanol solution for 15 minutes to reduce the surface energy. After modified, the superhydrophobic property was transformed into superhydrophilic property. Finally, the superhydrophilic inclined pores, which size is 0.55mm was drilled by laser. All laser processing was using a fiber laser marking machine (SK-CX30, Shanghai Sanke Laser Technology Co., China) at 30-50% humidity and 20-25 °C, the laser parameters were: wavelength 1064nm, pulse width 100ns, repetition frequency 20 KHz, spot size 100 μm, scanning speed 200 mm/s.

2.3. Characterization

The scanning electron microscope (SEM, SUPRA 55 SAPPHIRE, Germany) was used to get the micro structures of the surface of the micro device. The volume of water droplet, which was 9.0 μL was used to get the contact angle of the superhydrophobic surfaces with the optical contact angle meter (Krüss, DSA100, Germany). And the rotating motion of the device was recorded by the transportation processes of the water droplet on the high temperature Al surface was recorded by Camera (Nikon, D7200, Japan).
2.4. Experimental setup

The structural parameters of Al plate sample and the contact angle of the superhydrophobic surface of the self-rotating device are shown in Figure 2a and Figure 2b, respectively. Figure 3a shows the self-rotating device that we designed, of which the length is 20 mm and the width is 10 mm. In the picture, there are double central symmetrical superhydrophilic inclined pores, of which the inclined angle is 45°, and the center distance between the double pores d was set as 1.2, 2.0 and 3.0 mm to obtain the influence of the center distance on the rotating distance and rotating velocity of the device. Moreover, the experiment with four central symmetrical superhydrophilic inclined pores was done to obtain the influence of the number of the pores on the rotating distance and rotating velocity of the device. As shown in Figure 3b, the self-rotating device was floating on the surface of water that is in a water tank, the syringe pump was used to feed the water to the syringe needle with large pore size to achieve to feed large water droplet onto the self-rotating device, and the volume of the water droplet was measured as 107 μL. Firstly, the height between the needle and the device was controlled enough to make sure that the droplet can fall, then camera was used to record the process, when the device was driven by single droplet. Second, the height between the needle and the device was decrease to make sure that the droplet hanging from the needle come into contact with the device, which means the droplet was leaving between the needle and the device. Continuous rotating motion can be achieved by choosing the appropriate feed rate of syringe pump to make sure that the water droplet will not be run out, then the process of the continuous rotating motion of the device was recorded, and this water supply method was called continuous water feed system method.

![Figure 2](image1.png)

Figure 2. SEM image of superhydrophobic Al plate and the contact angle of the superhydrophobic surface of the self-rotating device. (a) SEM image of superhydrophobic Al plate. (b) The contact angle of the superhydrophobic surface of the self-rotating device.

![Figure 3](image2.png)

Figure 3. The dimension schematic of the self-rotating micro device and the schematic of experimental devices. (a) The dimension schematic of the self-rotating micro device. (b) The schematic of the experimental devices, which includes the water droplet feed system and the application environment of the micro device.
3. Results and discussion

3.1. Analysis of the feasibility experiment of the self-rotating micro device.

The rotating process of the double inclined pores, of which the center distance is 3.0 mm, driven by single water droplet is shown in Figure 4, it can be seen that the self-rotating micro device can achieve rotating motion with the reduction of the volume of the water droplet. The self-rotating micro devices with different center distance of the pores can move as well, but the rotating distance and the rotating velocity varied with the change of center distance of the pores. The feasibility experiment of the self-rotating micro device shows that the two types of the water supply methods, which includes feeding single water droplet and continuous water feed system, can both propel the micro device to rotate with different center distance and number of the inclined pores. It means that our self-rotating micro device can be a kind of self-propelled micro device.

Figure 4. The rotating process of the self-rotating micro device with double inclined pores, of which the center distance is 3.0 mm.

3.2. Analysis of the numerical relationship of center distance and number of pores on continuous rotating velocity of the micro device.

The self-rotating micro device should rotate continuously in the reality application, so the water supply of it should be the continuous water feed system or continuous water droplet feed such as the rainy environment. The value of the continuous rotating velocity should be the most important property of the micro device. The relationship between rotating distance and rotating time of the micro device with different center distance of the pores is almost growing linearly when the rotating time is after 1 s, which is shown in Figure 5a. It means that the rotating velocity of the micro device is stable to a constant, so the numerical relationship of center distance and number of pores on continuous rotating velocity of the micro device should be done to get the empirical equation of the micro device.

The fitted line between rotating distance and rotating time of the micro device was also in Figure 5a, of which the slope is the rotating velocity of the micro device. We fit the data of different rotating velocity corresponding to different center distance of the pores with quadratic polynomial, and the following equation was got:

\[ v_1 = -5.75 + 57.41d - 9.54d^2 \]  
(1)

The curve between rotating distance and rotating time of the micro device in the continuous rotating process with different number of pores was shown in Figure 5b, the rotating velocity of four pores is almost twice larger than the rotating velocity of double pores. Considering the experimental error, we can draw a conclusion that the relationship between the rotating velocity and the number of pores is a positive proportion function with coefficient 1, so for the water supply system, which is continuously water droplet feed such as the rainy environment, the equation of the continuous rotating velocity changes with the different center distance and number of the pores is shown as follows and Figure 5c:

\[ v_{\text{droplet}} = (-5.75 + 57.41d - 9.54d^2) \times n/2 \]  
(2)

For the water supply system, which is continuous water feed system, the continuous rotating velocity with double pores is 67.5 °/s, but the continuous rotating velocity with double pores driven by one water
A droplet can reach 80.6 °/s. We thought the reason is that the volume of droplet will reduce when it produces the jet, which can increase the Laplace pressure [6], but the volume of the droplet in the continuous water feed system will not change. So the continuous rotating velocity driven by single water droplet is much higher than the continuous water feed system. The continuous rotating velocity for the continuous water feed system with different center distance and number of the pores should be corrected as follows and shown in Figure 5c:

\[ v_{\text{water-feed}} = (-5.75 + 57.41d - 9.54d^2) \times \frac{67.5}{89.6} \times n/2 \]

(3)

Figure 5. Analysis of the numerical relationship of center distance and number of pores on continuous rotating velocity of the micro device. (a) The curve between rotating distance and rotating time of the micro device with different center distance of the pores when the rotating time is after 1 s. (b) The curve between rotating distance and rotating time of the micro device in the continuous rotating process with different number of pores. (c) The continuous rotating velocity of the device with the continuous water droplet feed changes with the different center distance and number of the pores. (d) The continuous rotating velocity of the device with the continuous water feed system changes with the different center distance and number of the pores.

3.3. Model design of micro generator based on the self-rotating micro device.
When a part of the conductor of the closed circuit cuts the magnetic induction line, the induced current can be generated, which is the principle of the generator. According to this principle, we designed a kind of micro generator based on self-rotating micro device, which is shown in Figure 6. There is a water tank with a size slightly larger than that of the self-rotating micro device. The induction coil was installed on the side wall of the water tank, and the micro device with strong magnetic magnets was placed on the water surface. The rotation of the micro device will occur when the water droplet falls on pores of the micro device, which can produce relative motion between the magnet and induction coil, and produce induced current.
Figure 6. The model of the micro generator based on the self-rotating micro device.

4. Conclusion
In this paper, a new kind of self-rotating micro device based on water droplet which can transform surface energy of water droplet into kinetic energy of the micro device was proposed. The propelling mechanism and the realization of rotating motion are both explained. The feasibility experiment of the self-rotating micro device proved that the device can realize rotating motion whether it is a single droplet or a continuous water feed system, and the rotating velocity increase with the increase of the center distance and the number of the inclined pores. The numerical analysis of the micro device about the rotating velocity varied with the different center distance and number of the inclined pores was done to get the empirical equation when the micro device was set in a real application environment, such as rainy weather and continuous water feed system. The final result provided us an equation to predict the rotating property of the micro device, which means the micro device can be controlled in further application. The self-rotating micro device is a special self-propelling device, which can rotate instead of forward movement, will be more suitable for some fields, for example, the micro generator that we designed. The self-rotating micro device is green to the environment without any external energy, and has huge prospect in the realistic application.

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