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Self-Steerable Propulsion of Disk-Like Micro-Craft with Dual Off-Center Nanoengines

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ABSTRACT

This paper reports a novel disk-like micro-craft with dual off-center nozzle nanoengines, consisting of three different metals: gold, nickel, and platinum. A bubble propulsion mechanism originating from momentum change induced by the detachment of oxygen bubbles is proposed to elaborate the self-steerable propulsion of the disk-like gold-nickel-platinum micro-craft. The as-proposed micro-craft is fabricated by a layer-by-layer deposition method based on the micro-electro-mechanical systems technology. Herein, the self-steerable propulsion of the fabricated micro-craft dispersed in deionized water with different hydrogen peroxide concentrations is characterized. As a consequence, the speed of the micro-craft is increased with the increment of hydrogen peroxide concentration. In addition, the micro-craft can always move forward linearly.

KEYWORDS: *self-steerable propulsion, disk-like micro-craft, dual off-center nanoengines, layer-by-layer, oxygen bubbles, hydrogen peroxide*

INTRODUCTION

In nature, living organisms are decorated with intelligent and efficient biomolecular motor proteins through millions of years of evolution [1]. For instance, bacteria can propel forward with the aid of the rotational flagellar motors, which are capable of transforming ion motive force (IMF) to rotary movement [2]. In particular, linear motor proteins (kinesin, myosin and dynein) possess fascinating abilities to harvest energy through hydrolyzing adenosine triphosphate (ATP) molecules for lateral movement along the corresponding tracts (microtubule and actin filaments) *in vivo* [3].

Evolution bestows biomolecular motor proteins with extremely powerful abilities to harvest energy from surrounding environments for various functions in cells. Inspired by naturally occurring motor proteins, researchers extensively devoted great efforts into artificial micro/nanodevices in the past two decades. They attempted to develop devices which were capable of moving forward autonomously via catalyzing the decomposition of chemicals. In special, micro/nanodevices could propel forward, drawing thrust from the detachment of oxygen (O_2) bubbles generated from the decomposition of hydrogen peroxide (H_2O_2). For instance, Sanchez *et al.* developed a tubular jet engine using rolled-up nanotech [4, 5]. Meanwhile, Zhao *et al.* reported bimetallic nanojets fabricated by template-assisted electro-chemical deposition [6, 7].

In the aforementioned reports, micro/nanodevices are designed as horizontally symmetric tubular either cones or cylinders [4-7]. Nevertheless, these micro/nanodevices could not realize self-steerable propulsion without the aid of an external control source (electric, magnetic, *etc.*). On the other hand, rolled-up and electrochemical deposition used to fabricate micro/nanodevices are sophisticated techniques which need higher skills to operate. Hence, this work attempts to develop and fabricate micro/nanodevices in a simplified method with high-efficiency.

In this paper, a tiny disk-like micro-craft with dual nozzle nanoengines comprising of three different metals: gold (Au), nickel (Ni), and platinum (Pt) is designed. A self-steerable propulsion mechanism is proposed to investigate the linear propulsion of the Au-Ni-Pt micro-craft. This novel micro-craft is fabricated by a layer-by-layer (LbL) deposition method based on the micro-electro-mechanical systems (MEMS) technology, whereby Pt functions as a chemical catalyst prompting the decomposition of H_2O_2 to produce O_2 bubbles detaching from its surface, which in turn generates a recoil force to thrust the self-steerable propulsion of the micro-craft. Herein, the self-steerable trajectory of the micro-craft immersed in deionized (DI) water with different H_2O_2 concentrations is characterized. Experimental results reveal that the speed of the micro-craft is increased with the increment of H_2O_2 concentration. In addition, the micro-craft can move forward linearly.

SELF-STEERABLE PROPULSION MECHANISM

It is well known that an aircraft can orbit around Earth and steer the trajectory using self-equipped jet engines in Space. Inspired by the aircraft, a novel disk-like micro-craft with dual off-center nozzle nanoengines is proposed, as shown in Figure 1. The micro-craft has a form of a disk, consisting of three different metals: non-catalytic Au, magnetic Ni, and catalytic Pt.

The Au-Ni-Pt micro-craft suspended in DI water without the presence of H_2O_2 is stationary. Once H_2O_2 is added into DI water, O_2 bubbles are firstly generated at the surface of the off-center nanoengines of the micro-craft, in which the micro-craft and O_2 bubbles have a joint velocity of v_1 . Afterwards, the generated O_2 bubbles grow bigger and bigger (growing state in Figure 2(a)). When O_2 bubbles reach a certain of diameters, they detach from the micro-craft (detaching state in Figure 2(a)). The micro-craft and O_2 bubbles have a same velocity of v_2 at the detaching moment. After the detachment of O_2 bubbles, the craft continues to propel forward with a velocity

of v_3 , while the detached bubbles have a different velocity of v_0 . The H_2O_2 decomposition in general can be described as

where, Pt denotes the catalyst platinum [8].

The self-steerable propulsion of the micro-craft is produced by the detachment of O_2 bubbles from the surface of Pt, as shown in Figure 2(a). According to the Momentum Conservation Law and the Momentum Theorem, a recoil force F'_{drive} will be generated to thrust the micro-craft's propulsion (see supporting information, Figure S1). In principle, the dual off-center nanoengines are symmetrically located on the disk-plate of the micro-craft, thus O_2 bubbles are identically generated and detached from the micro-craft. In turn, the total recoil force F_{drive} is aligned with the drag force F_{drag} , as shown in Figure 2(b). Hence, the micro-craft is capable of propelling forward linearly. At steady state, the values of F_{drive} and F_{drag} are equal, thus the micro-craft reaches a constant velocity of v .

EXPERIMENTAL SECTION

Fabrication of micro-craft with dual off-center nanoengines. The schematic, material compositions, and size of the proposed micro-craft with dual off-center nanoengines are shown in Figure 1. The micro-craft consists of three parts: non-catalytic Au, magnetic Ni, and catalytic Pt. Au and Ni are shaped as a concentric disk with 12.0 μm in diameter. The thicknesses of Au- and Ni-disks are 0.2 and 0.1 μm , respectively. Two identical off-center Pt nozzle nanoengines form hollow cylinders and are symmetrically located on the plate of the Au-Ni disk. The diameter, bottom-thickness, wall-height and wall-thickness of the Pt nanoengines are about 3.0, 0.3, 1.5, 0.3 μm , respectively. Au functions as a non-catalyst and is purposely used to build asymmetric structure for ensuring the autonomous propulsion in micro and nanoscale regime [9]. Ni is a

paramagnetic material, and the orientation of the magnetic material will be directed by magnetic field [10]. Thus, the propulsion direction of the micro-craft can be steered and controlled by external magnetic field in future work. Pt acts as a chemical catalyst to prompt the decomposition of H_2O_2 into H_2O and O_2 bubbles [11-14]. Micro-crafts were fabricated using the mature MEMS technology developed in Micromachines Lab, School of Mechanical and Aerospace Engineering at Nanyang Technological University, Singapore [15-18].

The micro-craft is fabricated by the LbL deposition method based on the MEMS technology (see supporting information, Figure S2). The scanning electron microscopy (SEM) top-down and side views of the fabricated micro-craft are shown in Figures 3(a) and (b), respectively. In order to confirm the material compositions of the micro-craft, energy dispersive spectrometry (EDS) analysis was conducted (see supporting information, Figure S4).

Oxygen bubble generation. The fabricated Au-Ni-Pt micro-crafts (see supporting information, Figures S3) were dispersed into H_2O_2 solution to study the generation of O_2 bubbles (see supporting information, Figure S5). The generation and detachment of O_2 bubbles associated with the propulsion of the micro-craft were characterized and captured by a camera installed onto an optical microscope. The results were recorded by a computer installed with a video recording software. It could be observed that the micro-craft was stationary in DI water without the presence of H_2O_2 , and no O_2 bubbles were generated. After the addition of H_2O_2 into DI water, O_2 bubbles were initially generated at the Pt-surface. Thereafter, the generated O_2 bubbles grew bigger and bigger. Finally, O_2 bubbles were detached from the micro-craft and next O_2 bubbles were generated and grew, as shown in Figure 4. The diameters of the detaching O_2 bubbles from the micro-craft immersed in 5% H_2O_2 solution were approximated to be 20 μm (Figure 4(a)). The results were consistent with those reported by Wang and Wu [19].

Characterization on the self-steerable propulsion of micro-craft in hydrogen peroxide solution. The fabricated micro-craft with dual off-center nanoengines was immersed into three different concentrated H_2O_2 solutions to investigate the self-steerable propulsion. The micro-craft propelled forward linearly, as shown in Figure 4. The corresponding trajectories of the micro-craft are shown in Figure 5.

RESULTS AND DISCUSSION

The data obtained in this work revealed that H_2O_2 catalyzed by Pt is decomposed into H_2O and O_2 bubbles. The detached O_2 bubbles from the dual off-center nanoengines generated a recoil force to thrust the self-steerable propulsion of the micro-craft in H_2O_2 solution.

Self-steerable propulsion speed of micro-craft in hydrogen peroxide solution. The “ImageJ” software was employed to process the recorded data, and the corresponding trajectories of the micro-craft in three different concentrated H_2O_2 solutions are shown in Figure 5. From the aforementioned experimental results, the elapsed time t (unit in s), as shown in Figure 4, and the corresponding traversed distance l (unit in μm) of the micro-craft, as shown in Figure 5, can be obtained. Hence, the speed v (unit in $\mu\text{m/s}$) of the micro-craft can be expressed as [20]

$$v = l/t \quad (2)$$

The self-steerable propulsion of the micro-craft was investigated in DI water with three different H_2O_2 concentrations, whereby H_2O_2 concentration was the ratio of the pure H_2O_2 volume to the DI water volume. The lowest H_2O_2 concentration was 5%, the medium one was 10%, and the highest one was 20%, respectively. Using equation (2), the corresponding propulsion speeds of the micro-craft at these three different concentrations were about 30, 75, and 135 $\mu\text{m/s}$, as shown in Figure 6. In general, the speeds of the micro-craft are increased with the increment of H_2O_2 concentration, in consistency with the theoretical derivation [21].

In micro and nano realm, the micro-craft in DI water without the presence of the fuel H_2O_2 can undergo thermal fluctuation motion, called Brownian motion (see supporting information). In such a case, no O_2 bubbles are generated, and the micro-craft moves forward very slowly and randomly. As seen, the steerable propulsion speeds of Au-Ni-Pt micro-craft are much larger than Brownian motion speed [22]. Hence, the Brownian motion speed is smaller and can be negligible.

Self-steerable trajectory of micro-craft in hydrogen peroxide solution. The micro-craft with dual off-center nozzle nanoengines was immersed into DI water with three different H_2O_2 concentrations to study the self-steerable propulsion. The time lapses of the self-steerable propulsion of the micro-craft in these H_2O_2 solutions are characterized, as shown in Figure 4. The instantaneous locations of the micro-craft in 5%, 10% and 20% H_2O_2 solutions are presented in Figures 4(a), (b) and (c), respectively. The corresponding trajectories of the micro-craft for these three different concentrations are presented in Figures 5(a), (b) and (c), respectively. As can be seen, the micro-craft generated multiple beams of O_2 bubbles detaching from the surface of the dual off-center nanoengines. After the detachment of O_2 bubbles, a total recoil force was generated to thrust the micro-craft propelling forward linearly, resulting from the generated O_2 bubbles which were identically and symmetrically distributed on both sides of the micro-craft and the total recoil force was well aligned with the drag force.

Discussion on the self-steerable propulsion of micro-craft. The material composition and the shapes of the fabricated micro-craft are significantly different from those studied by other researchers [4-7, 21, 23], The propulsion speeds in our results are smaller than those published in reference 4, 5, 6 and 7, while they are much larger than those reported in 21 and 23. The differences between them are derived from the different structures and material compositions of particles. One can learn the reasons from the reference 21. In fact, the propulsion speed of the micro-craft is

affected by some factors, such as the size of the micro-craft, the temperature of solution, *etc.* giving us the guidance that how to design and characterize the micro-craft in future.

As observed in our experiments (Figure 4), the generation rate and the detachment rate of O₂ bubbles from the nozzle nanoengines at higher concentrations are larger than those at lower ones, resulting from the fact that more H₂O₂ molecules at higher concentrations are decomposed to generate more O₂ bubbles at a certain of time. Hence, a larger recoil force is generated, which propels the micro-craft forward faster. In the experimental results, the propulsion speeds of the micro-craft at higher concentrations are larger, which are consistent with the physical phenomenon. The experimental results are in good agreement with our theoretical analysis, thus our model and theory are verified.

CONCLUSIONS

A bubble propulsion mechanism was proposed to investigate the linear propulsion of the disk-like Au-Ni-Pt micro-craft with dual off-center nanoengines in diluted H₂O₂ solution. A high-efficiency LbL deposition method based on the MEMS technology was employed to fabricate the novel micro-craft. The self-steerable propulsion of the micro-craft was characterized in DI water with three different H₂O₂ concentrations. The results revealed that more O₂ bubbles were generated at higher H₂O₂ concentrations, thus the micro-craft moved forward faster. In addition, the micro-craft with dual off-center nozzle nanoengines propelled forward linearly. The results of this research will encourage further studies, such as the exploration of the self-steerable propulsion of the micro-craft via the design of the off-center nanoengine [11, 24], the propulsion characterization of the micro-craft in the microfluidic channel [10, 25] and the propulsion controlling by external magnetic field [26, 27]. Such micro-crafts may be useful for cargo delivery and other applications [28-32].

ABBREVIATION

Au, gold; Ni, nickel; Pt, platinum; LbL: layer-by-layer; MEMS, micro-electro-mechanical systems; H₂O₂, hydrogen peroxide; O₂, oxygen; IMF, ion motive force; ATP, adenosine triphosphate; DI, deionized; H₂O, water; SEM, scanning electron microscopy; EDS, energy dispersive spectrometry; Si, silicon.

ASSOCIATED CONTENT

Supporting Information Available: The equipment, materials, and software used; the derivation of driving force, fabrication details, EDS analysis, experimental set-up, and Brownian motion speed of Au-Ni-Pt micro-craft with dual off-center nanoengines, videos of the microcraft's propulsion at different H₂O₂ concentrations. This information is available free of charge via the Internet at <http://pubs.acs.org>.

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Notes

The authors declare no competing financial interest.

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Figure 1. Schematic diagram of the structure, material compositions and size of the disk-like micro-craft with dual off-center nanoengines. The micro-craft is composed of three different metals: Au, Ni, and Pt. Au and Ni are concentric disks, two identical off-center nozzle nanoengines Pt are shaped as hollow cylinders and symmetrically located on the plate of the Au-Ni disk.

Figure 2. Schematic diagram of the self-steerable propulsion of the proposed micro-craft with dual off-center nozzle nanoengines. (a) Illustration of the propulsion of the micro-craft originated from the detachment of O_2 bubbles from the dual off-center nanoengines Pt catalyzing the decomposition of H_2O_2 . During the growth of O_2 bubbles, the micro-craft and growing O_2 bubbles have a joint velocity of v_1 ; at the detaching moment, the micro-craft and detaching bubbles have a same velocity of v_2 ; after the detachment of O_2 bubbles, the micro-craft moves forward with a velocity of v_3 , while the detached O_2 bubbles have a different velocity of v_0 . (b) Demonstration of the linearly self-steerable propulsion of the micro-craft in H_2O_2 solution. The recoil force F_{drive} is well aligned with the drag force F_{drag} , thus the micro-craft moves forward linearly. At steady state, the micro-craft move forward linearly with a speed of v .

Figure 3. SEM images of the Au-Ni-Pt micro-craft with dual off-center nozzle nanoengines. SEM top-down (a) and side (b) views of single micro-craft on the surface of silicon (Si) wafer, respectively.

Figure 4. Time lapses of the self-steerable propulsion of the micro-craft in different concentrated H_2O_2 solutions. The instantaneous locations of the micro-craft are shown in 5% (a), 10% (b), and 20% (c) H_2O_2 solutions, respectively.

Figure 5. Trajectories of the micro-craft with dual off-center nozzle nanoengines in different concentrated H_2O_2 solutions. The corresponding trajectories of the micro-craft in 5% (a), 10% (b), and 20% (c) H_2O_2 solutions.

Figure 6. Summary of the micro-craft's propulsion speeds in three different concentrated H_2O_2 solutions.

TOC Graphic