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Sub-millimeter thruster-in-water powered by a remote laser pulse

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ABSTRACT

Thrusters with 900–2000 μm in lengths and 340–800 μm in diameters are fabricated from glass tubes and light-absorbing graphite cores. The smallest thruster moves ~2300 μm in water powered by a remote laser beam of 1.1 W for 30 ms. The thrusters also move reliably at low Reynolds number of $\sim 10^{-4}$ in glycerol. The conversion efficiency from thermal energy of a laser pulse to kinetic energy increases significantly as the size of the thruster decreases. This simple mechanism can be utilized for the propulsion engines of a μm-sized untethered swimmer in water at low Reynolds number regime.

1. Introduction

All elemental biological components are immersed in water and the reactions between them are processed efficiently in water. Since their sizes are mostly in the range of μm-scale and below, untethered micro-swimmers capable of manipulating the biological organisms in water would be useful.

Recently various artificial swimmers have been presented to demonstrate the propulsion mechanisms in water: a cm-sized spiral wire [1] and μm-sized propellers [2,3] rotated by external magnetic field, a μm-sized beating flagellum powered by external magnetic field [4], a mm-sized diode [5] and μm-sized nanobelt [6] powered by external electric field, and a sub-mm sized resonant magnetic microactuator powered by external alternating magnetic field [7]. Since these devices are powered by external magnetic or electric fields, however, a specific swimmer cannot be pinpointed and controlled independently from others.

The light beam can be focused into a sub-μm spot to pinpoint a specific device or expanded to a broad area to irradiate multiple ones simultaneously. The light beam can also be modulated rapidly in the intensity. The light with long wavelength does not induce chemical, electric, magnetic, and other toxic effects in water. Though the light cannot be utilized directly in mechanical applications since the momentum of the light is negligibly small, it can carry a thermal energy large enough to vaporize a small amount of water and generate appreciable mechanical impacts. Hence various mechanisms of laser propulsion have been studied in aerospace applications for several decades [8–10]. If a μm-sized untethered swimmer can be propelled in water by remote laser pulses at low Reynolds number regime [11], it would become a convenient and useful tool in manipulating the biological organisms.

In this Work, handmade thrusters in mm- and sub-mm-sizes were fabricated. When the thrusters were irradiated by a remote laser beam of 1–2 W for 30–50 ms, they moved distances of 150–2300 μm in water. The thrusters could also move in glycerol at low Reynolds number of $\sim 10^{-4}$. Though the energy efficiencies of the thrusters were very low, they increased significantly as the size of the thruster decreased. This simple mechanism can be utilized for the propulsion engines of μm-sized untethered swimmers in water.

2. Experimental setup

Let's consider a simple thruster consisting of an outer transparent shell and an inner light-absorbing core as represented schematically in Fig. 1(a). When the thruster is irradiated with a light beam, the light will pass through the outer shell and be absorbed by the inner core. If the energy of the light beam is large enough and the amount of water in the shell is small, the water will boil in a short time period. Then the water vapor can fill the inner space of the shell and push out water of mass m with the velocity $\mathbf{v}_2$ as shown in Fig. 1(b). Finally the thruster of mass M will recoil in the opposite direction with the initial velocity $\mathbf{v}_1$, conserving total momentum of the system.

The thruster in this work consists of an outer glass shell and an inner graphite disk. One end of a glass tube segment is melted

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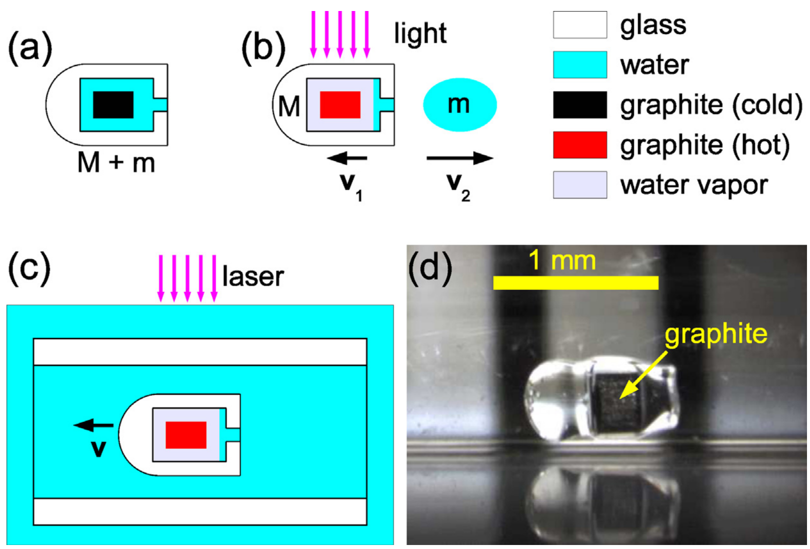

Fig. 1. (a) The thruster consists of a glass shell and a graphite core. The total mass of the thruster including water is $M+m$, (b) the graphite core is irradiated and heated by a remote laser pulse and vaporizes the nearby water. The expanded water vapor fills the inner space of the thruster and pushes out the water drop of mass m with the velocity $\mathbf{v}_2$. The thruster with mass M recoils in the opposite direction with the velocity $\mathbf{v}_1$, conserving total momentum of the system, (c) the thruster is placed in a long water-filled glass tube to be confined in one-dimensional motion and (d) the side view of a thruster in water.

and closed by a torch to form a glass shell. Thin graphite rods are used as the light-absorbing material because they are uniform black and easy to handle. Various graphite disks are prepared by cutting graphite rods in different lengths. A graphite disk is inserted into the glass shell, and the open end of the shell is narrowed to prevent the graphite disk from escaping. Though graphite is hydrophobic and repels water, the glass shell is hydrophilic and attracts water to wet the inner wall and fill the inner space. The structural parameters of the six thrusters tested in this work are listed in Table 1.

A laser diode with the wavelength of 808 nm and the maximum power of 2.1 W was used to irradiate the thrusters. The power of the laser diode was controlled by electric current and was calibrated by a power meter. The laser diode was operated in square wave shape: at low power phase the power of the laser was maintained at 1–5 mW for easy alignment, and at high power phase the power was raised to a target value and maintained for the pulse duration, and finally it was returned to the low power value. Irradiation of several weak laser pulses on the thruster at the initial stage pushes

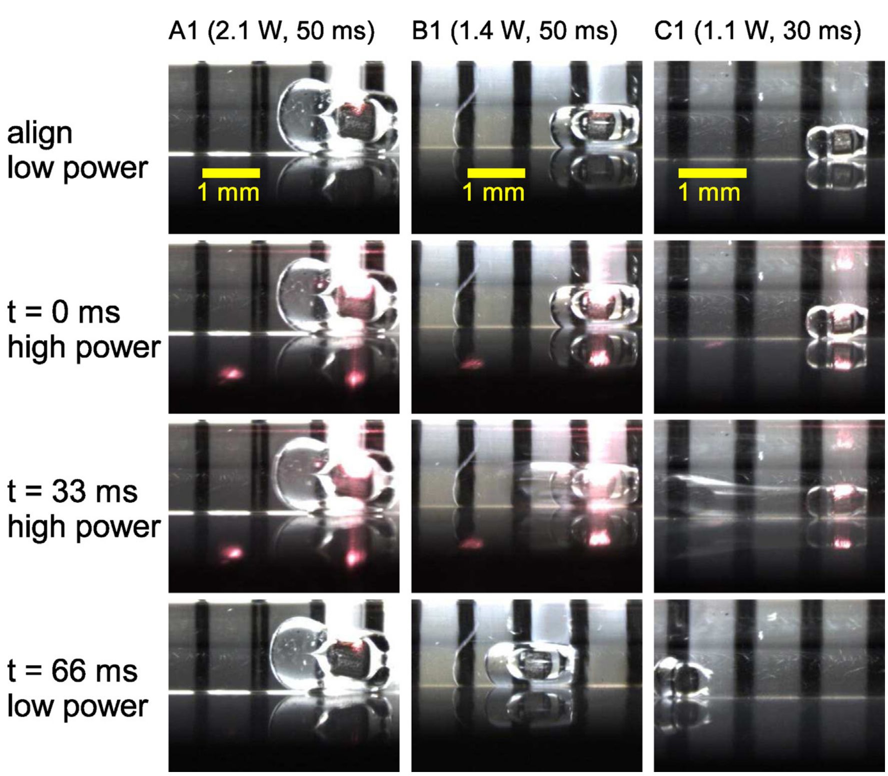

Fig. 2. Successive pictures of the three types (A1, B1, and C1) of thrusters in motion. At first the laser beam with the low power of 1–5 mW is focused on the graphite disk in the thruster. Then the power of laser is increased to 2.1 W, 1.4 W, and 1.1 W for the thrusters A1, B1, and C1, respectively. After the pulse durations of 50 ms, 50 ms, and 30 ms for A1, B1, and C1, respectively, the laser power returns to the initial low power.