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Original Research Article

The study on pH gradient control in solution for driving bacteria

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ABSTRACT

Medical applications are the most impactful areas of microrobotics, such as targeting tumoral lesions for therapeutic purposes, minimally invasive surgery (MIS) and highly localized drug delivery. However, miniaturization of the power source with an effective onboard controllable propulsion system has prevented the implementation of such mobile robots. Flagellated chemotactic bacteria can be used as an effective integrated propulsion system for microrobots. In this paper, we study the pH gradients control in solution for driving bacteria. The swimming property of flagellar bacteria and mechanism of forming the pH gradient field in solution are discussed. By experiments, we found that the pH gradient field distribution in solution is mainly related to the electrode shape. And the input voltage value can control the stable time of the pH gradient field, while it has no effect on the distribution of the field. The electric potential distribution is analyzed by simulation with COMSOL Multiphysics. The simulation results are consistent with the experiment results, which indicate that the bacteria movement can be controlled by the electrodes' shape and the input voltage.

1. Introduction

Microrobots could be greatly beneficial for medical applications. Due to their small size, microrobots can currently reach to accessible areas of the human body and carry out many complex operations, such as minimally invasive surgery (MIS), highly localized drug delivery, and screening for diseases at their very early stages [1]. The study on microrobot has received wide attention in recently years. For example, Ishiyama proposed a swimming micro-machine driven by magnetic torque [2], Edd discussed microrobot driven by biomimetic propulsion [3,4]. However, the implementation of such mobile robots is prevented because of the lack of the effective propulsion system [5].

The idea of using microorganisms, particularly bacteria, to actuate microrobots is very appealing [6]. The advantage of this approach is that microorganisms can very efficiently convert chemical energy to mechanical energy. In addition, it is easy to produce microorganisms with very cheap cost [7]. Bacteria is a simple and effective organism living in low Reynolds number liquid without external energy to drive themselves [7,8], and can swim fast in low Reynolds number liquid, such as human blood. Thus, the strategy of utilizing the

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existing motor machinery within cells for actuation, cargo transport and delivery, sensing, and control could lead to the realization of next generation biohybrid devices [9–12]. Martel et al. investigated the movement of magnetotactic bacteria [13]. External magnetic field switches bacteria from Brownian movement to directional swimming. Behkam and Sitti discovered that bacteria movement can be controlled to stop or resume the motion by using copper ions (Cu^{+2}) and ethylene diamine tetraacetic acid, respectively [11]. Aranson et al. focused on interactivity between bacteria such as conglutination and volute movement after their contact [14]. Balagadd et al. and Keymer et al. found that pH affects not only flagellar bacteria survival but also their movement toward optimal pH area [15,16]. Sokolov invented a device which can adjust the pH value to control flagellar bacteria [17]. However, the movement direction of bacteria is still out of order, which makes it hard to propel microrobots.

Generally, the pH value control system is nonlinear, time-varying and operates with long time delay. In this paper, we study the pH gradients control in solution for driving bacteria. In Section 2, the swimming property of flagellar bacteria and mechanism of forming the pH gradient field in solution are discussed. In Section 3, the influencing factors of the of the pH gradient field distribution in solution are studied through experiments. In Section 4, The electric potential distribution is analyzed by simulation with COMSOL Multiphysics. Finally, the discussions and conclusions are presented in Sections 6 and 7, respectively.

2. Swimming property of bacteria

Flagellar Bacterium is a unicellular organism. The bacterial flagellar filament consists of single protein protofilament, which is called Flagellin [18]. The flagellum is a propulsive organelle that includes a reversible rotary motor embedded in the cell wall, and a filament that extends into the external medium [1,19]. The filament is long, thin and helix, and acts as screw propeller for the bacterium.

Some flagellar bacteria exhibit chemotaxis, the ability to move toward or away from the source of a diffusing chemical. Studies show that bacteria with flagella (such as *Bacillus subtilis*) will swim toward the optimal pH region in plasma solution with a pH gradient field [15–17]. The swimming direction and speed of bacterium will vary in different pH levels in the solution [20,21]. So microrobots can be driven by the embedded bacteria with high efficiency. The power supply problem of microrobots will be replaced by bacteria control. Based on this principle, it is possible to control bacteria moving direction and speed if we establish a proper pH gradient field in the solution.

3. Formation mechanism of pH gradient field

pH value is the concentration index of hydrogen ions which indicates alkalinity and acidity of solution. It represents activity of hydrogen ions and its unit is mol/L. pH is defined as the hydrogen ion concentration index. In dilute solution, hydrogen ion activity is approximately equal to concentration of hydrogen ions, and hydrogen ion concentration can be used for approximate calculation, which is given by

$$pH = -\lg a \tag{1}$$

where a is concentration of hydrogen ions. In this paper, the expected pH distribution in solution can be built using an electrolysis method. When the power source is turn on, the electrode potential will be polarized and departed from equilibrium. The process of electrolysis includes the following three steps: (1) Particles move toward the surface of the electrode, known as the liquid phase mass transfer step; (2) Particles produce the oxidation–reduction reaction on the interface between the electrode and the solution, known as the electrochemical reaction step. (3) The reaction forms some products, such as gas, called the new phase generation step. The liquid phase mass transfer must be the main step of electrode process to form pH gradient.

Once electrode process starts, liquid phase mass transfer, a very complicated process, occurs immediately. Reactive particles such as H_2O and electrons move to electrodes by the mass transfer because of their consumption in these regions. Firstly, the products of reaction move away from the electrodes and the concentration of particles is changed near the electrodes. After power on, ions migrate to the anode and the cathode respectively under the electric field along certain directions, and then the particles which are not involved in the reaction are also driven by the active ions. Secondly, density and temperature differences in the solution cause free convection, which changes the particles distribution. The direction of free convection is perpendicular to the electrodes. Lastly, particles in high concentration areas diffuse to low concentration areas automatically. When the electrochemical reaction consumes particles in the solution and produces new particles, diffusion happens accordingly. By the above analysis, the electro migration, convection and diffusion consist of the liquid phase mass transfer, which breaks the initial uniform distribution.

As a result of the liquid phase mass transfer, a pH gradient is generated and balanced temporarily in the solution. The electrolysis leads to redox reaction in the water. H^+ and O_2 are generated on the anodic surface, which can be described as Eq. (2). At the same time, OH^- and H_2 are generated on the cathodic surface, as shown in Eq. (3).

$$\text{Anode}: H_2O \leftrightarrow 2H^+ + 1/2O_2 + 2e^- \tag{2}$$

$$\text{Cathode}: 2H_2O + 2e^- \leftrightarrow 2OH^- + H_2 \tag{3}$$

Eq. (2) shows that the H^+ density in the solution increases near the anode, which leads to pH value decrease in this region according to Eq. (1). Similarly, the pH value increases near the cathode.

4. Experiments of pH gradient field control

4.1. Experiments with different electrode shapes

To study the relationship between the distribution of pH gradient field in the solution and the electrode shape, arc