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RESEARCH HIGHLIGHT

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Study on the Electric Actuation of Liquid Metal Column in Confining System

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Abstract

Research on micro-machines is becoming popular. In this paper, the electric driving behavior of liquid metal columns in confining channel was studied. When the electric field was applied, the liquid metal near the negative electrode became flat, longer. The NaOH electrolyte (1.0 mol/L) could flow from the positive electrode to the negative electrode from a small space above the liquid metal column. Besides, the length and volume of the liquid metal would affect its motion and deformation behavior. Both cylindrical liquid column ($R = 5$ mm, $L = 5$ cm) and linear liquid column ($R = 5$ mm, $L = 40$ cm) exhibit deformable movements, which are similar to the bionic movements of earthworms. The electrically driven liquid metal in closed systems could provide a theoretical basis for droplet actuation in microtubes. It has a very wide application prospect in the field of micro-drive machines.

Keywords: Liquid metal, Electric actuation, Biomimetic, Micromachines, Motion

1 Introduction

Due to the huge size, the traditional robot could not work in a tiny environment or inside the human body, which was limited to its application. Therefore, the micro-driven machine which could work in an internal environment has received much attention [1]. The micro-drive robots are composed of various materials and driven in various ways. Liquid metal (LM) was a kind of metal alloy that is a liquid state at room temperature. Owing to its excellent physical and chemical properties, such as high surface tension and good flexibility, it is both remarkably attractive and has potential in a broad range of various application fields [2, 3]. Numerous methods and strategies of actuating liquid metals have been previously proposed, including electric actuation, magnetic actuation, thermal actuation, acoustic actuation, optical actuation, etc. [4, 5]. At the same time, liquid metals could be driven by chemical reactions with other materials [6].

Nowadays, electrically driven liquid metal droplet has been reported in acidic electrolyte [7] and alkaline electrolyte [8, 9]. Notably, under the action of an electric field, liquid metal could be driven by interfacial tension [10, 11]. The surface tension would change with the distribution of surface charge. Then, the electric field forces drive the liquid metal. Meanwhile, the electric drive of liquid metal could be classified into the following categories: electric capillary drive, dielectric wetting drive, continuous electrowetting drive, and electrochemical drive. The surface tension of liquid metal changes with the changes of electrode potential. When the electrocapillarity occurs, the liquid metal could be driven. Dielectric wetting was mainly utilized in flat plates, through which the contact angle of liquid metal could be changed. The continuous electrowetting drive was an improvement based on the dielectric wetting drive. An electrochemical actuation is performed by placing liquid metal in a dielectric and applying a voltage.

However, at present, in the field of electric drive, most of the current studies on liquid metal droplets driven by electricity are open systems. In an open system, both matter and energy exchanges with the surrounding. The electric drive behavior of liquid metal in closed systems

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or micro-channel systems was rarely studied. Whereas in a confining channels or confining environment, heat exchanges with the surroundings, the quality of liquid metal and NaOH solution inside closed system is always the same. In order to achieve applications in complex environments, liquid metal microrobots usually need to move in closed systems, which is important for the precise control of their movement behavior.

Hence, there is an urgent need to explore the possible reaction and different phenomena of liquid metal in a closed system of the electric field action. In this study, the electric driving behavior of liquid metal in different lengths in closed airtight pipes was mainly studied. We found not only the movement of the liquid metal, but also the movement of the electrolyte. In addition, a clear and quantitative understanding of the deformation and movement behavior of liquid metals with different shapes in closed systems was essential. The deformation phenomena and mechanism behind them were finally investigated.

2 Results and Discussion

Two substances were first mixed with a ratio Ga: In = 75.5: 24.5, and then heated at a constant temperature of 60 ℃. After magnetic stirring of 0.5–1 h, the liquid metal was successfully configured. Add 4.0 g of solid NaOH into 100 ml of distilled water, and 1.0 mol/L NaOH solution was successfully prepared. A transparent hose (silica gel, R = 5 mm) was purchased from the GeFang Flagship store. High purity copper wire (R = 2 mm) was purchased from Luoyang Zhan Yuan Copper Co. LTD. Dc stabilized voltage power supply, model UT, was purchased from Uni-Trend Group Company.

The liquid metal droplet (19.6 or 157 mg) was firstly placed in a transparent rubber tube. A NaOH solution (1.0 mol/L) was injected into both ends of a transparent hose. Two copper wires were inserted into the NaOH solution. The voltage was applied to the closed system at room temperature of 20 ℃. After a voltage of 5 V was applied, the electric driving behaviors of liquid metals in the closed cylindrical pipe were mainly discussed: (1) electric driving behavior of liquid metal cylindrical column (dimension R=5 mm, L=5 cm); (2) electric driving behavior of liquid metal linear column (R = 5 mm, L = 40 cm). Hereinto, R represents diameter, L represents the length in the direction of the beam axis.

Liquid metal was injected into the NaOH solution to form a short cylindrical liquid metal column (R = 5 mm, L = 5 cm). No bubbles were formed in the transparent hose, which was filled with NaOH solution and liquid metal (Figure 1(a)), and a confining system that was closed from the outside environment was formed.

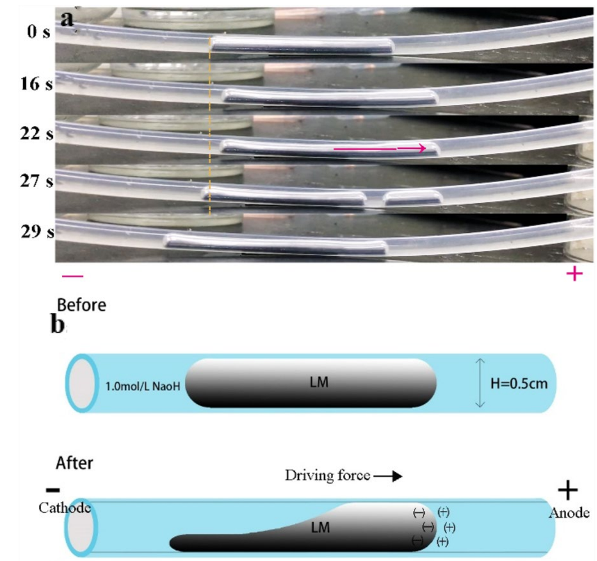

Figure 1 **a** Deformation peristaltic behavior of short liquid metal column in a closed pipeline under the voltage, **b** Deformation behavior of liquid metal column in confining channel

As illustrated in Figure 1, the copper wire inserted at the right end of this confining channel was connected to the positive electrode; on the contrary, the copper wire inserted at the left end of this confining channel was connected to the negative electrode. When a voltage of 5 V was applied, the liquid metal column was found to be moving towards the positive electrode, which was caused by an electrical double-layer phenomenon of the surface of the short cylindrical LM column [12]. The liquid metal has a negative charge near the positive end of the power supply, while it has a positive charge near the negative end of the supply. According to the Marangoni effect, the skin of a liquid metal droplet flows from a low surface tension area to a high surface tension area, which means it flows from the cathodic pole to the anodic pole. And the liquid metal droplet is propelled to move towards the anodic electrode.

Besides, the shape of this liquid metal column was also deformed. As long as the voltage was switched on for 0–29 s, the liquid metal became long and narrow at the negative end. The corresponding side image was in Figure 1(b).

Noteworthiness, it was interestingly found that the electrically actuated behavior of liquid metal column in the closed system was quite different from an open system. The liquid metal column could waddle forward in a channel. During motion, the short cylindrical liquid metal column in the closed system would undergo extrusion and deformation. As illustrated in Figure 1(a), when the electric field was applied from 0 to 27 s, the liquid metal grows closer to the positive electrode (moving speed $V = 0.591$ mm/s). It was also squeezed by the surrounding NaOH electrolyte.

To verify the motion behavior of the NaOH solution in a closed system, this solution in the positive or negative electrodes was stained by Congo red (CR) solution, respectively. As schematized in Figure 1, as the electric time was prolonged to 27 s, the anode NaOH electrolyte began to enter the closed channel inside the liquid metal column. In addition, when the liquid metal column was compressed by the electrolyte to a certain extent, it caused the liquid metal column to break (Additional file 1: Move 1). The liquid metal column was divided into two sections by the NaOH electrolyte. It is noteworthy that the NaOH electrolyte squeezed the liquid metal column at the negative end. Finally, through the extrusion deformation of the liquid metal column, the electrolyte entered the negative pole.

Double electric layer effect is formed on the interface between liquid metal and NaOH electrolytes [13]. Based on electric field control, liquid metal could easily induce vortex pairs in the surrounding solution. As the liquid metal moves toward the anode, it pushes the NaOH solution around the liquid metal toward the cathode. However, in an open system, the liquid metal has not undergone compression.

As illustrated in Figure 2(a), the liquid metal (R = 5 mm, L = 40 cm, aspect ratio of 80:1) was injected into a transparent hose (R = 5 mm, L=60 cm). The positive electrode of the power supply was connected to the lower end of the confining channel, and the negative electrode was connected to the upper end of the confining channel.

When the electric field was applied, in the closed system, an electric double layer phenomenon was formed in the liquid metal column [12]. Near the negative electrode, the liquid metal has a positive charge; Near the positive electrode, the liquid metal was negatively charged. In addition, it was found that the liquid metal linear column creeps from cathode electrode to anode electrode (moving speed V = 4.5 mm/s). The liquid metal near the cathode was found to be under pressure and eventually fractured several times. Because of the long length of the liquid metal column, the fracture occurred. As time goes on, the liquid metal fault grew larger and larger.

Figure 2 **a** Compression of LM occurred at one end of the cathode, **b** The time-lapse images of formation and expansion of the fracture layer of LM

Obviously, it could be found that the NaOH electrolytic solution also carried on the related movement in the closed channel at the same time. As schematized in Figure 2(b), as time goes on, when the NaOH electrolyte entered the central part of the liquid metal linear column, multiple fractures have occurred in the liquid metal column. This experimental phenomenon was different from that of a short column of liquid metal. The fracture layer which is composed of NaOH electrolyte solution was formed and gradually increased with time.

Subsequently, when the electrode touched the liquid metal, it was found that an electrolytic cell was formed in the area of the fractured layer, and hydrogen (H_2) was formed. At the same time, the electrolytic solution near the cathode electrode also formed hydrogen. See Eqs. (1) and (2):

$$\mathrm{Ga} - 3\mathrm{e}^{-} = \mathrm{Ga}^{3+}, \tag{1}$$

$$2\mathrm{H_2O} + 2\mathrm{e}^{-} = \mathrm{H_2} + 2\mathrm{OH}^{-}. \tag{2}$$

To further investigate the motion behavior of the NaOH solution in this system, the NaOH solution in the positive or negative electrodes was stained by Congo red (CR) (Additional file 1: Move 2, 3). When part of the NaOH electrolyte was stained, the experimental phenomenon was more obvious. After the liquid metal peristalsis, it is noteworthy that the colored NaOH electrolyte at one end

Figure 3 The electric actuation of liquid metal column, which like bionic earthworm movement

of the anode electrode could slowly enter the middle of the liquid metal column (Figure 3). These results demonstrate that the NaOH electrolyte moves from an anode to a cathode. Therefore, in a closed system, the liquid metal crawled toward the anode, and the electrolyte moved toward the cathode. Thus, the denaturation peristalsis of liquid metal was closely related to the movement of the solution.

3 Conclusions

In summary, herein the electric driving behavior of liquid metal column in a confining channel was studied. It was found that the length and volume of the liquid metal would affect its motion and deformation behavior.

(1) The cylindrical liquid metal ($R = 5$ mm, $L = 5$ cm) is placed in an electrolytic solution. By applying an electric field, the liquid metal moved to the anode electrode, and the NaOH electrolyte moved toward the cathode electrode, which was obviously different from the open system.
(2) The linear liquid metal ($R = 5$ mm, $L = 40$ cm) is placed in an electrolytic solution. By applying an electric field, the cathode of the liquid metal is compressed, broken several times, and hydrogen is formed from the electrolyte solution at the cathode.

The electrically driven liquid metal in closed systems could provide a theoretical basis for droplet actuation in microtubes.

Supplementary Information

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Additional file 1. Experimental conditions that would affect the deformation behavior of liquid metal (PDF), Electric driving behavior of liquid metal cylindrical column ($R = 5$ mm, $L = 5$ cm) (MP4), Electric driving behavior of liquid metal linear column ($R = 5$ mm, $L = 40$ cm)--the anode dyeing (MP4), Electric driving behavior of liquid metal linear column ($R = 5$ mm, $L = 40$ cm)–the cathode dyeing (MP4), Electric driving behavior of liquid metal column ($R = 5$ mm, $L = 3$ cm) (MP4)

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Author contributions
SL was in charge of the whole trial, and wrote the manuscript; ZW wrote part of the manuscript; FL, MH, and GD assisted with sampling and laboratory analyses. All authors read and approved the final manuscript.

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Competing interests
The authors declare no competing financial interests.

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