Vapor Marangoni driven self-propelling water walking actuator

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ABSTRACT

The propulsion mechanisms of water-walking insects, such as water striders, have long fascinated researchers, leading to the development of various bioinspired actuators. However, many of these actuators involve complex structural designs. In our study, we sought simpler yet effective models and turned our focus to the unique abilities of *Microvelia*, a species of water strider that uses the Marangoni effect to propel itself. This effect arises from a surface tension gradient created by a mix of low-tension body secretions and the high surface tension of water. Inspired by this mechanism, we developed novel Marangoni actuators powered by vapor, in contrast to conventional liquid or solid fuels. Our vapor-driven approach provides more sustained and controlled actuation, allowing for longer operation. We further refined this approach by modeling the vapor diffusion profile, enabling us to predict actuator velocity accurately, which was subsequently validated by experimental results. Potential applications for these actuators, such as directional control and micromixing, were also explored in this study, underscoring the versatility of this bioinspired design.

KEY WORDS

Marangoni effect, Bio-mimic, Self-propulsion

1. INTRODUCTION

Our research to advance small aquatic robots has driven researchers toward bioinspired technologies that replicate the movement of insects skimming across the water's surface. Microvelia, a particularly remarkable insect, utilizes a unique propulsion mechanism [1], making it a focal point for such designs. When facing strong water currents or predators, Microvelia releases a specialized, low-surface-tension fluid from its rostrum, reducing the water's surface tension directly behind it. This creates a surface tension imbalance between the front and back of the insect, resulting in a forward-driving force—a phenomenon known as the Marangoni effect.

Through Marangoni propulsion, Microvelia can reach speeds of approximately 15 cm/s with a single leg movement, surpassing its typical walking speed, which involves multiple leg strokes to achieve just 4 cm/s [2]. This swift movement stems from the contrast in surface tension as liquids with differing properties mix. However, conventional systems attempting to imitate this effect often use bulk mixing, where the fuel

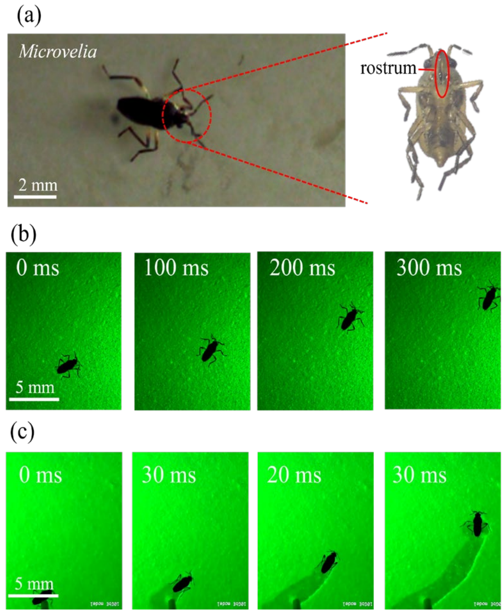

Figure 1 (a) Image of a Microvelia (right) illustrating the use of its rostrum to release a liquid with low surface tension, generating Marangoni propulsion (left). (b) Time-sequence snapshots capturing the transition between running motion and propulsion driven by the Marangoni effect.

directly contacts the
water surface, leading to rapid consumption and limiting sustained motion [3].

To address these constraints and better mimic Microvelia's prolonged movement across water, our research employs a vapor-mediated approach to the Marangoni effect. By utilizing vapor from volatile alcohols, only the vapor interacts with the water's surface, creating a controlled and efficient surface tension gradient. This approach enabled us to develop a vapor-driven actuator, supported by a theoretical model that accounts for surface tension gradients and viscous forces. Our predictions for the actuator's movement were successfully confirmed through experimental testing.

2. Experiment

Isopropyl alcohol (IPA) vapor was applied as a] catalyst to achieve a reduction in surface tension in our actuator model. Due to its high vapor pressure, IPA efficiently lowers the surface tension of water from 72 mN/m down to 27 mN/m, making it ideal for this purpose. Fuel was stored using square

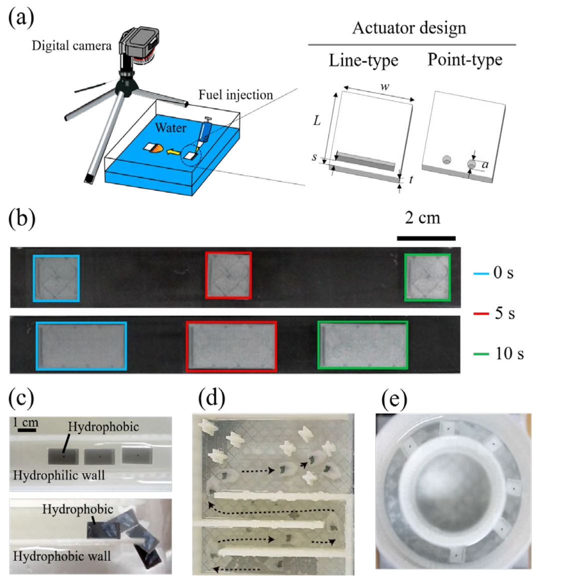

Figure 1 (a) Illustration depicting the experimental configuration on the left side, alongside a detailed view of the actuators on the right. (b) Comparative analysis of velocity for bodies measuring 2 cm and 4 cm in length. (c) Demonstration of the Cheerios effect, which is applied for (d) navigation through a maze and (e) enhancement in micromixing..

plates created through 3D printing, and two reservoir designs—one line-shaped and the other point-shaped (Shown in fig. 1(a))—were used to test various diffusion effects.

In designing the initial actuator, we took into account both the buoyant force needed to hold up the actuator and the capillary force arising from surface tension. We measured the deflection angle to gauge the buoyancy of each structure, ensuring the actuator's ability to remain buoyant and functional.

Afterwards, as depicted in fig. 1 (b), we examined the actuator’s linear motion and compared it against a theoretical framework that factored in both the Marangoni force and viscous drag. These forces fluctuate based on shifts in surface tension, and our model explored how they affect movement. Given the actuator’s low Reynolds number, we assumed that the boundary layer thickness evolves over time, enabling us to establish an expression for velocity derived from balancing these forces.

A significant challenge involved determining vapor concentration at the solid-liquid-gas interface contact line. We approached this using the Peclet number, which relates the rates of mass diffusion to advection. Given the small Peclet number in our system, we assumed diffusion as the primary mechanism. Using a simplified diffusion model, we derived the concentration profile for both line-shaped and point-shaped reservoirs, which provided predictions on how IPA vapor spreads across the surface. Assuming a linear relationship between surface tension and vapor concentration, we calculated the contact line surface tension.

To validate this analytical approach, we used Ansys Fluent, a computational simulation tool, to compare theoretical results with numerical data. This verification allowed us to accurately calculate the Marangoni force, predicting the actuator’s speed, which we then confirmed through experimental tests.

In our experiments, we measured the speed of the actuator while varying key parameters such as length, width, reservoir shape, and position. This allowed us to observe how each factor affects the actuator's propulsion.

As shown in fig. 1 (d-e) we applied our research in a variety of methods. To explore directional control, we investigated the influence of the water interface shape and nearby surfaces’ wettability on movement. When two surfaces shared similar wettability and shape, they attracted each other, while contrasting surfaces exhibited repulsion—an effect known as the Cheerios phenomenon. Leveraging these interactions, we developed a model that enables the actuator to follow complex pathways and avoid collisions with surrounding obstacles.

3. Conclusion

The speed of the actuator is influenced by factors such as the length of the craft, the shape and placement of the fuel reservoir, and the resulting variations in surface tension and viscous drag. A comparison of theoretical predictions with experimental data supported the accuracy of our model.

Future studies are essential to advance steering mechanisms and passive speed control solutions, which pose challenges due to the absence of established theoretical models for these systems. We plan to investigate the Cheerios effect as a potential approach for direction control in upcoming research.

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