Surface viscosity effects on the motion of self-propelling boat in a channel

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Abstract. Self-propelled droplets have been conceived as simple chemical toy models to mimic motile biological samples such as bacteria. The motion of these droplets is believed to be due to the surface tension gradient in the boundary of the droplet. We performed experiments to look at the effect of varying the medium viscosity to the speed of a circular boat that was soaked in Pentanol. We found that the boats undergo oscillatory type of motion inside a channel. Moreover we found the maximum speed of the boat is independent on the viscosity of the medium. On the other a time scale describing the width of the velocity profile of the boat was found to increase with increasing viscosity.

1. Introduction
Motility is an essential need of biological systems that has allowed it to respond to various environmental changes [1]. For instance *Escherichia coli* (E.coli) bacteria via chemotaxis move from regions of low food to regions of higher density of food. Present understanding is that the E.coli uses complex chemical network inside its body that allows it to measure chemical gradients in the environment and as a result control the direction of rotation of the molecular motor of the E.coli. Force generation used by E. coli is through the synchronized rotation of its flagella [2]. We note that E.coli is also sensitive to the presence of temperature (called thermotaxis) and optical field (optotaxis) gradients. Aside from using flagella for motion, other bacteria use crawling mechanism, generally termed as gliding motility, wherein the propulsion is due to active actin polymerization at the cell boundaries. This is for instance used by *Anabaena sp.* a cyanobacteria of family *Nostocaceae* [3]. Understanding cell motility is an important problem with huge potential uses in both biological manipulation and in medical science. For instance understanding cell migration could help elucidate the biochemical and physical dynamics of wound healing [4]. On the physical aspect, cell motility is interesting for a physical understanding of it requires a Non-Equilibrium thermodynamics picture of the system of which the scientific community is still trying to build. An issue of interest on these studies is how the physical and chemical properties affect the dynamics of cell motility. There have been varied approaches to look on this issue. First is the development of 3D scaffolds to look at cell motility on 3D structures.
migration at 3D. Moreover, the scaffold's physical property can be changed. Another approach is to use simple models to mimic cellular motion. It was first reported in 1978 where the spontaneous motion of a surfactant in a two-phase co-existing system is similar to the behavior of an amoeba [5]. Thus the self-motion of a surfactant can be used as simple experimental models for investigating the behavior of micro-organisms.

Separation of a surfactant in a microscopic scale is one manifestation of multiple-phase coexisting systems. The self-motion of a reactive droplet is caused by an imbalance in the interfacial tension of a substrate induced by an inherent chemical effect in the moving droplet. This phenomenon is known as the Marangoni Effect [6]. Spontaneous motion of droplets driven by this effect is one good example of self-motion in physicochemical systems. In this study, a circular boat soaked in Pentanol is observed in water-glycerin aqueous solution. There had been recent studies conducted about the spontaneous motion of a Pentanol droplet driven by the Marangoni effect. Ref. [7] reported the motion of Pentanol with varying droplet size. A small droplet moves irregularly, a middle-sized droplet moves vectorially, and a large droplet splits into smaller droplets. They found out that its volume controls the droplet's type of motion. Also, in similar works in Ref. [8,9], spontaneous motion of Pentanol was found to be dependent on the temperature of the aqueous solution. These previous studies involved a two-phase coexisting system with Pentanol droplet that changes its shape as it moves similar to bacteria, and had not considered varying the viscosity of the aqueous phase.

In this paper, we report the effects of viscosity on the one-dimensional motion of boats soaked in Pentanol with the addition of Glycerin to the aqueous solution. These boats do not change in shape as it moves along the channel and during the diffusion of the pentanol it contain.

![Figure 1](image-url)

**Figure 1.** (a) Schematics of the Experimental set-up. (b) Image sequence showing the position of the boat at different time for the case of 3% glycerin concentration. (c) Trajectory of the boat in a petri dish at [Glycerin] = 0% concentration. (d) Image sequence representing the trajectories in (c). The petri dish has a diameter of 85mm.
2. Experimental design and methodology
Experiments are performed using the set-up shown in Figure 1a where 5mL of water-glycerin solution is poured on a rectangular glass channel with 75mm × 12.5mm × 12.5mm dimensions. To determine the effects of viscosity on the mode of motion of camphor boats, the concentration of the solution is varied from 0 vol. % to 21 vol. % glycerin (ρ = 1.261 g/cm³, PHILUSA Corp.). The circular boats, with a diameter of 10mm are made from filter paper. In order to clearly visualize its motion, the center of the camphor boat is inked using a small droplet of black enamel paint (Roosevelt Chemical Inc.). It is then soaked in 100% pentanol for 10 minutes before being added to the water-glycerin solution. The self-motion of the camphor boats on the aqueous solution is monitored using a video camera (Nikon Coolpix L21) at 30 frames per second. The experiments are carried out at room temperature (24°C) and are performed with five trials for each concentration. In the analysis of the movies of the boat self-motion, image sequences are exported using VirtualDub, and its location is determined per 1/30 second using a home-made particle tracking program written in IDL.

3. Results and discussion
Unlike the experiments done in Ref.[7], we used circular boats soaked in Pentanol in all our experiment. Already in our previous work we found that the circular boats undergo rich dynamics for instance circular trajectories as seen in figure 1d [10] when the boats is placed in an aqueous phase. This is very different to the irregular type of motion observe for the case of a plain active Pentanol droplet in water [7]. We take note that in all our other experiments we used a rectangular channel, Figure a, to confine the movement of the boat along one dimension.

Figure 1b shows the self-propelled motion of the boat for the case when the glycerin concentration is 0%. After being placed on the surface of the aqueous solution, the boat accelerates and then undergoes an oscillatory type of motion that is it moves back and forth along the channel. The self-propulsion is due to the surface tension gradient across the boat caused by the unequal distribution of pentanol along the boat diameter [7]. Surface tension and Pentanol concentration has a negative relation, i.e. the higher the concentration of Pentanol, the weaker is the surface tension. We take note that oscillatory type dynamics was also seen for the case of a plain reactive droplet in channels [11]. In Figure 2a we plot a sample trajectory of a boat in a water medium ([Glycerin] = 0% vol.). The trajectory clearly shows the boat moving from one side of the channel towards the other side and then back and forth although after some time we observe the boat to not be able to reach the other end of the channel before reversing its direction of motion. To investigate the effect of increasing viscosity we made use of a Glycerin/Water solution as medium. We vary the concentration of Glycerin from 0% vol to 21% vol. In figure 2a-f we plot the trajectories of the boat at 0%, 3%, 6%, 9%, 15%, and 21% glycerin concentration respectively. We found that the boat still undergoes oscillatory type of motion irrespective of the concentration of glycerin. At [Glycerin] = 100%vol concentration we found the boat not to move at all. From the particle track, we were able to calculate the particle velocity using the formula where \( x[i] \) and \( x[i-1] \) are the position of the particle at time interval \( \Delta t \). In Figure 2g, we plot the velocity for the case of 0% glycerin solution. We superimposed the particle trajectory for comparison. The velocity can be characterized by two parameters; the maximum speed \( v_{\text{max}} \) (which corresponds to the height of the peak) and the time width at half maximum, \( \tau_{\text{FWHM}} \) (corresponds to the width of the peak). In figure 3a we plot the \( \tau_{\text{FWHM}} \) values for different Glycerin concentration. It is observed that as the amount of Glycerin on the aqueous solution increases, the time width also increases linearly. On the other hand we found that \( v_{\text{max}} \) is insensitive to the Glycerin concentration.

To further gain insight to the experimental result we did numerical simulation of the motion of the boat using the model proposed in Ref.[7] where an active droplet motion is given by,

\[
\frac{d^2x}{dt^2} = -\mu \frac{dx}{dt} + F(t) + \eta(t)
\]

where \( x(t) \) is the particle position at time \( t \), \( \mu \) is the surface tension viscosity, \( F(t) \) is the force due to Marangoni effect, and \( \eta(t) \) is the thermal noise. The second term of the right-hand side (rhs) of equation(1) corresponds to the friction experienced by the particle as it moves, thus the negative sign.
The third term of the rhs corresponds to the thermal fluctuation due to constant bombardment of the solvent molecules. We numerically evaluate equation (1) to extract features of the motion of the self-propelling particle for varying medium surface viscosity. The force $F(t)$ is modelled as a Heaviside function,

$$F(t) = \begin{cases} f_0, & t > 0.3 \\ 0, & t < 0.3 \end{cases}$$

Figure 2. Trajectory plots for (a) 0%, (b) 3%, (c) 6%, (d) 9%, (e) 15%, (f) 21% solution which shows the oscillatory motion of the boat. (g) Position and velocity plot of the boat at 0% concentration. The height and the width of the peak determine $v_{max}$ and $\tau_{FWHM}$ values respectively.
and we consider the case of a noise-free scenario. We note that modelling the force by a Heaviside function simplifies the analysis of the motion of the boat. We note that modelling the force by a Heaviside function simplifies the analysis of the motion of the boat. For instance the Pentanol inside the boat could still be diffusing out of the boat during transit and thereby the force may not be considered constant. In Figure 3c we plot the computed boat velocity for varying surface viscosity. Contrary to our experimental result, numerical computations suggest that $\tau_{FWHM}$ increases with decreasing viscosity.

![Figure 3](image)

**Figure 3.** Plot of (a) $\tau_{FWHM}$ and (b) speed values for different concentrations of glycerin. (c) Numerical calculation of the speed of the boat via equation (1) for different surface viscosity.

### 4. Conclusion

In summary, we have found that Pentanol soaked circular boats exhibit oscillatory self-motion when placed on rectangular channel filled with water-glycerin solution. Oscillatory motion of the boat is seen for [Glycerin] < 21% vol. We found that the maximum velocity of the boat was found to be independent of the Glycerin concentration. Moreover the measured $\tau_{FWHM}$ was found to increase with increasing viscosity. This results is counter-intuitive, numerical calculation of a simplified model suggest that $\tau_{FWHM}$ should increase with decreasing viscosity. Future work will look on this inconsistency.
5. References

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