Locomotion of Catalytic Nanomotors

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Abstract:

Bimetallic nanomotors propel themselves autonomously in solutions of hydrogen peroxide (H_2O_2). The asymmetric catalytic decomposition of H_2O_2 at the nanomotor surface creates a proton imbalance and self-generated electric field, driving fluid from the anode to the cathode, through a method known as Reaction Induced Charge Auto-Electrophoresis [1]. The nanomotors' velocities have been shown to vary directly with the concentration of H_2O_2 in solution. The effective diffusivity of the nanomotors is controlled by the coupling of the nanomotors' thermal, rotational, and translational diffusivities, as well as their advective velocities. We quantify the effective diffusivities of spherical bimetallic nanomotors by tracking their positions over long times (> 30 minutes) and calculating the root mean square displacement. We find that a motor's effective diffusivity depends on its diameter as well as the local fuel concentration.

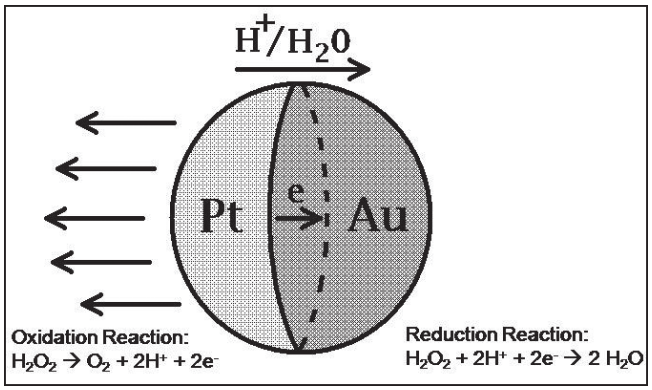

Figure 1: Depiction of propulsion mechanism.

Introduction:

The study of nanomotors has recently become one of the great foci in nanotechnology. Bimetallic nanomotors, which are Janus nanoparticles composed of two different metals, have been shown to spontaneously propel themselves when in solutions of hydrogen peroxide (H_2O_2). This phenomenon was first demonstrated by Paxton, et al. [2]. Figure 1 shows the net reaction proposed by Paxton, et al. [3]. Later, Moran, et al. suggested that the nanomotors move by a mechanism called Reaction Induced Charge Auto-Electrophoresis [1]. Consuming the peroxide as fuel, these nanomotors have been used to pick up, transfer, and deposit cargo particles.

During this project, we sought to: 1. Determine the relationships between the nanomotor's velocity, diffusivity, and local H_2O_2 concentration; 2. Quantify the nanomotors' effective diffusivities; and 3. Understand their underlying behavior by decoupling their thermal, rotational, and translational diffusivities from their effective diffusivities.

Self-propelled nanomotors offer the possibility for controlled drug delivery in the body and the mimicry of biological systems on the nanoscale.

Experimental Procedure:

Our nanomotors were created using the multi-stage deposition coating method of Wheat, et al. [4]. As can be seen in Figure 2, 3 μm diameter polystyrene spheres were

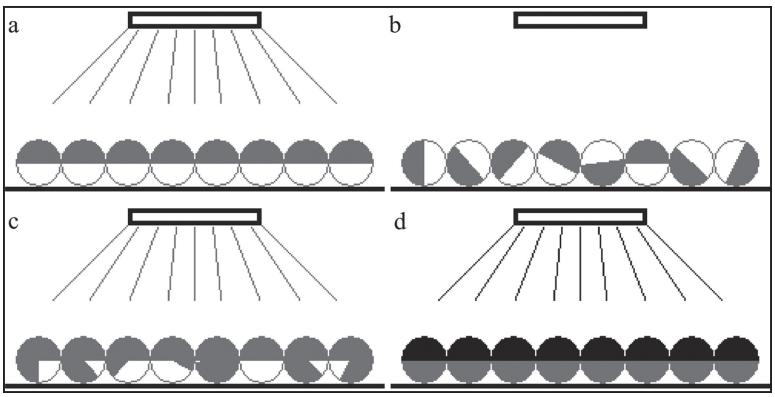

Figure 2: Experimental setup as devised by Wheat, et al. [4].

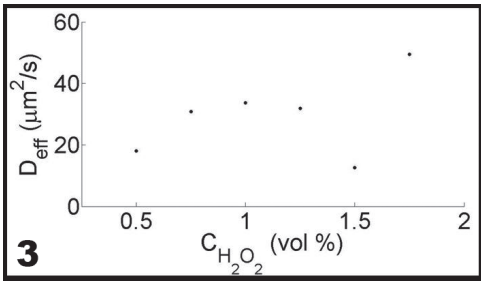

Figure 3: Nanomotor effective diffusivity.

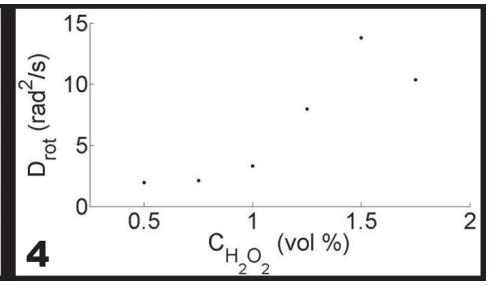

Figure 4: Nanomotor rotational diffusivity.

deposited on a glass substrate and half-coated with gold. The spheres were then resuspended and deposited with random orientations. The new exposed face was then plated with gold. Repeating this process for several cycles, fully coated the spheres in gold. Finally, they were plated with a single coating of platinum. Solutions of these nanomotors were diluted to approximately 10-20 spheres per mL. 30% H_2O_2 was then added to this solution to obtain the desired fuel concentration. 750 mL of this solution were placed in a microfluidic channel, and individual nanomotors were then located using a microscope under 20X magnification.

The motion of the nanomotors was then recorded using image capture software and analyzed using MATLAB. After tracking each nanomotor for long time periods (> 30 minutes), the effective diffusivities of the nanomotors were quantified by calculating the root mean square displacements of the particles. This method was used for a range of 0.25% - 2.00% hydrogen peroxide fuel concentrations.

Results and Conclusions:

Our preliminary data suggested a nearly linear relationship between the nanomotors' velocities and the local peroxide concentrations, a relationship that has been shown by Paxton, et al. [3]. This evidence gave initial confidence in the functionality of the motors. Due to the increase in velocity with peroxide concentration, we expect the effective diffusivity to increase with concentration as well. However, Figure 3 shows that the effective diffusivity increases and then decreases with peroxide concentration. The effective diffusivity decreases at high peroxide concentration because, as Figure 3 shows, the rotational diffusivity tends to increase with increasing peroxide concentration. When a nanomotor's rotational diffusivity is high, the increased rotation tends to prevent the motor from translating an appreciable distance from the motor's origin, despite the increased translational velocity.

These results indicate that the interplay between nanomotor velocity, rotational diffusivity, and effective diffusivity may govern the motion of these bimetallic spheres. In addition, by calculating the Brownian diffusivity for a 3 μm sphere in water, and comparing this value to experimental values of effective diffusivity, we have shown that our measured diffusivities are two orders of magnitude higher than the calculated thermal diffusivity of 0.143 μm^2/s. This demonstrates that the diffusivity of the nanomotors is greatly enhanced due to the locomotion.

Future Work:

We have shown that the effective diffusivity of bimetallic spherical motors is limited by their rotational diffusivity. However, we have not established how these two properties relate to each other, and how the velocity affects this relationship. Nor have the reasons for the spheres' increase in rotational diffusivity with peroxide concentration been established.

The experimental methods performed in this study were preliminary, and much additional experimentation will be required to determine the precise relationship between the motor velocity, effective diffusivity and rotational diffusivity. In addition, the more far-reaching long-term goal for this research is to design motors capable of autonomous but predetermined motion. This would allow for the statistically controlled delivery of cargo by the nanomotors through knowledge of the motors' swimming tendencies.

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References:

[1] Moran, J.L.; Wheat, P.M.; Posner, J.D. "Locomotion of Electrocatalytic Nanomotors due to Reaction Induced Charge Auto-Electrophoresis." Phys. Rev. E 81, 065302(R) (2010).

[2] Paxton, W.F. et al. "Catalytic Nanomotors: Autonomous Movement of Striped Nanorods." J. Am. Chem. Soc. 126, 13424-13431 (2004).

[3] Paxton, W.F.; Mallouk, T.E.; Sen, A. "Motility of Catalytic Nanoparticles Through Self-Generated Forces." Chem. Eur. J. 11, 6462-6470 (2005).

[4] Wheat, P.M.; Marine, N.A.; Moran, J.L.; Posner, J.D. "Rapid Fabrication of Bimetallic Spherical Nanomotors." Langmuir Letter DOI: 10.1021/la102218w