Toward Colloidal Motors

Miklós Zrinyi[1,2*], Masami Nakano[3]

Abstract

We have presented the first direct observation of electric field induced rotation of epoxy based polymer rotors. Polymer disks and gears were prepared in few micrometer dimensions as rotors. Electrorotation of these sub-millimeter sized tools was studied under uniform DC electric field. The rotational speed of micron-sized polymer rotors can be conveniently tuned in wide range (between 300 – 3000 rpm) by the DC electric field intensity, opening new perspectives for their use in micro electric motor applications.

[1] Department of Biophysics and Radiation Biology, Laboratory of Nanochemistry, Faculty of Medicine, Semmelweis University, H-1089 Budapest, Nagyvarad ter 4., Hungary

[2] MTA-SE Molecular Biophysics Research Group, Semmelweis University, H-1089 Budapest, Nagyvarad ter 4., Hungary

[3] Intelligent Fluid Control Pystems Laboratory, Institute of Fluid Science, Tohoku University, 2-1-1 Katahira, Aoba-ku, Sendai, 980-8577, Japan

* Corresponding author, e-mail: mikloszrinyi@gmail.com

1 Introduction

All neutral materials experience forces and torques when subjected to high electric field. These interactions can be utilized in several mechanisms from electrostatic spraying to electrospinning. It also provides innovative solutions for preparing novel smart materials which can adaptively change their physical properties in external electric field. Discovery of electrorotation phenomena has initiated us to the construction of novel polymer based micro sized motors with tunable angular frequency [1].

The first impulse to build micro- or nanomotor was given by R.P. Feynman in 1959 [2]. Since then the micro-electromechanical (MEMS) field has grown enormously in the past decades. Despite the rapid development, very little was done at sizes below ten micrometer. It is a challenging task to build device and study the rotary behavior. The early attempts to miniaturize the electromotors were achieved by making a scale reduction of existing motor parts. On the basis of this technique the first micromotor was developed by L.S Fan and Y.C. Tang in 1988 [3]. Their electrostatic driven motor had a diameter of 120 μm and the rotation speed of 500 rpm with a torque of some pNm. Due to their complicated construction, the coils of traditional electromagnetic motor are rather difficult to miniaturize. Despite several works have been devoted to develop and manufacture micromotors, there are only few studies available in literature about their design and performance [3-7].

In our previous work, we have reported the development of micron-sized polymer composites disks that showed electrorotation in uniform DC electric field [8-11]. Here we report that a novel polymer has been used for realization of a rotor part of side drive micromotor, based on the electrorotation phenomena [1].

2 Interaction of colloidal particles with external electric fields

Electrorotation or Quincke rotation is the circular movement of an electrically polarized micron sized particle or material in dielectric liquids [1]. The basic theoretical approach of the Quincke rotation, for rigid spherical particles, was provided by several authors [12, 13]. These approaches are based on the

assumption, that free charges which are present in the liquid and in the particle, accumulate at the surface of the particle, inducing dipole moment, P. Depending on the relative magnitude of the charge relaxation times in the liquid and in the particle, the induced dipole is either in the direction or opposite of the field. If the charge relaxation time of the liquid is shorter than that of the solid, the direction of induced dipole is antiparallel to the direction of the electric field. This configuration is unstable and the particle begins to rotate in order to flip its dipole moment. The particle rotation reaches a stationary state where the electric torque is balanced by the viscous one. The rotational axis is perpendicular to the electrostatic field. The conditions of spontaneous rotation can be expressed by the permittivity, and conductivity, data: where the subscripts 1 and 2 refer to the liquid and the dispersed particle, respectively.

The angular velocity, ω as a function of the applied field, E for spherical particles can be given as [12, 13]:

$$\omega(E) = \pm \frac{1}{\tau_{MW}} \sqrt{\frac{E^2}{E_{cr}^2} - 1} \qquad E > E_{cr} \qquad (1)$$

where τ_{MW} is the Maxwell-Wagner interfacial polarization relaxation time for spheres defined as

$$\tau_{MW} = (2\varepsilon_1 + \varepsilon_2)/(2\sigma_1 + \sigma_2) \qquad (2)$$

The threshold electric field strength, E_{cr} at which the solid particles begin to rotate is independent of the size of the dispersed particle and depends on the electric properties of particles and the viscosity of the medium. Equation (1) refers to solid monolith particles with size between 1-500 μm. The ± sign stands for the two possible directions of rotation around the axis that perpendicular to the direction of applied electric field. It must be mentioned that until now, a few theoretical description has been worked out for electrorotation of other geometry, than sphere. It must be mentioned that F. Peters, L. Lobry, A. Khayari, and E. Lemaire have studied the electro-rotation of spherical and infinite insulating cylinder [14, 15]. They found for spherical particles that if the rotor size is much larger than the characteristic ion layer thickness around the particles the angular velocity does not depend on the rotor size. Theories, which consider neutral polymers as rotors best of our knowledge are missing.

3 Materials

The SU8 2075 photoresists and SU8 developer (mr-Dev 600) were purchased from Micro Resist Technology (Germany). Microscope glass slides were purchased from Menzel Glaser (Germany). The SU8 disks were made of SU8 2075 at two different thicknesses and four different diameters. The diameter was varied between 100 to 500 microns with heights of 20 - 40 microns. Disk, hollow cylinders and gear with asymmetric teeth of different size as prototypes were successfully manufactured

by mask lithography technique [10]. The polymer hardens in a pre-defined 3D shape upon illumination with focused laser light. The detailed description of the experimental procedure can be found our other paper [11]. Electrorotation was studied in oil mixture containing substantial amount of triglicerid of oleic-, palmitic-, and linoleic acids.

4 Methods

We have studied the effect of DC electric field intensity on the speed of rotation. Uniform DC electric field was applied perpendicularly to the axis of the disk. Figure 1 shows an experimental device to apply electric field to the disk shaped polymer rotor. The gap distance between the electrodes was 3 mm. The space between the electrodes was filled up with the mentioned oil. The electric field was supplied by a high voltage DC power supply (TREC, USA). We have increased the electric field intensity step by step up to 2.2 kV/mm. The rotation was followed by optical microscope (OLYMPUS, Japan) equipped by a high speed camera (Photron, Japan). In order to visualize the rotation and to determine the angular frequency, a visible sign close to the edge of the disk was used. The angular frequency of the rotation was determined by recording the spinning motion of the disk.
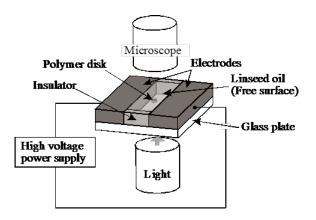

Fig. 1 Experimental set up to determine the dependence of rotational speed on the DC field intensity.

The rotation of floating micro-disk in the oil was followed by optical microscope and monitored by high speed camera. The angular frequency of the rotation at all adjusted electric field intensity was determined by the aid of the video of spinning. Not only disks, but also gear wheels have been prepared as shown in Fig. 4.

5 Results and Discussion

We have observed that that in uniform electric field no force, but torque acts upon the disks. As a result the sub-millimeter sized polymer rotors perform rotation at constant position of the axis which is perpendicular to the plane of electric field. We have studied the dependence of spinning rate on the electric field intensity. It was concluded that the dynamics is electrorotation

of disks is rather complex. If the strength of static DC field is accounted for, three regimes have been observed.

1. Far below a threshold value, E_{cr} of the electric field, the disk does not show any motion.
2. Close to the threshold value and slightly above, the disk begin to move, but the angular displacement is less than 2π.
3. At DC field intensities higher than the threshold value, continuous rotation is observed. The direction of rotation for perfect polymer disks seems to be randomly selected with the same probability, occurring either in clockwise or counter-clockwise.

Figure 2(a) shows that with increasing electric field intensity, the rate of spinning significantly increases and within the experimental accuracy the dependence is linear. It is also seen that the threshold value E_{cr} of the static electric field is close to 0.6 kV/mm. Figure 2 also indicates that there is a significant size effect on the speed of rotation. At the same electric field intensity, the smallest disk (100 micron) performs the most intensive rotary motion. The opposite effect was found for the disk thickness, as seen in Fig. 2(b). At the same electric field intensity, the rotation speed of the thicker disk (38 micron) is higher. The highest rotation speed that we were able to monitor was around 3000 rpm which significantly exceeds the rotation speed of first electrostatic driven motor [3].
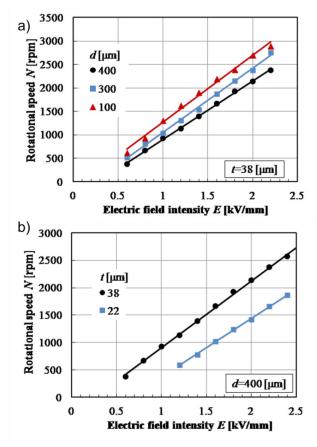

Fig. 2 Dependences of rotational speed N on the diameter d (a) and thickness (b) of polymer disks.

The sub-millimeter sized rotors perform very intensive rotation in uniform DC electric field. In our work the diameter of the smallest rotor was 100 μm with a thickness of 22 μm. This is far above the nano-sized range. This work clearly indicates that decreasing the size of the rotor, the speed of rotation increases as shown in Fig. 3. It would be a great challenge to move into the nano-meter range (denoted by question mark in Fig. 3), with the disk diameter, but in vain if we were able to prepare such a disk size, we could not observe the rotary motion with traditional light microscopy.

Despite this is holding a great promise to construct motors of even several micrometers diameter that can rotate even faster than presented here.
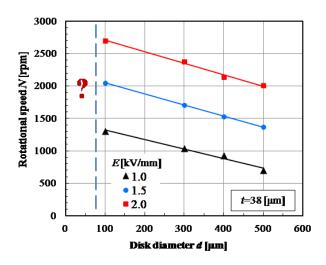

Fig. 3 Dependences of rotational speed N on the diameter d polymer disks

For any technical application, it is important to control the direction of the rotation. For perfects disks the direction clockwise and anti-clockwise spinning is equally possible. In order to generate controlled rotation direction, we have to break the symmetry of the rotor geometry. This can be achieved by using gears with asymmetric teeth. The asymmetric teeth were shaped using different angles on the drive side and coast side of the teeth (see Fig. 4). Due to the presence of asymmetric rotor teeth, we have always observed directed rotation.
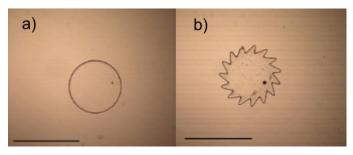

Fig. 4 Polymer rotor prepared from epoxy based polymer. (a) disk, (b) gearwheel. The bar indicates 500 microns. The dot close to the edge of the micro tools was used to determine the speed of rotation.

Figure 5 indicates that in case of gearwheel we have also observed significant size effect on the speed of rotation. At the same electric field intensity, the smaller gear (300 micron) performs more intensive rotary motion. It is also seen that the linear dependence of the rate on the electric field intensity remained as well.
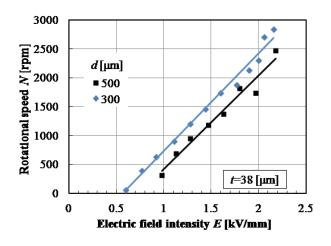

Fig. 5 Dependence of rotational speed N of polymer gear wheels as a function of electric field intensity E on the diameter d. The thickness of the gears is t=38 μm.

6 Summary and Conclusions

In this paper we reported experimental evidence on the electrorotation of polymer disks submitted to DC electric field. The angular motion of insulating polymer composite disk, immersed in slightly conducting oil, was studied as a function of DC field intensities.

It was found that above a critical value of electric field, the disk begins to rotate at a constant rate. This rate is sensitive to the field intensity. With increasing field intensities, the angular velocity of rotating disk increases. At this point, we are not able to provide a theoretical background to interpret the complexity of the electrorotation phenomena. All these measurements provide fundamental information on micro-motor characteristics which is important for further micro-engineering development. A microscopic electric motor of which operation is based on the principle of electrorotation is just one step away.

Acknowledgement

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