博士学位論文審査要旨

２０２１年7月３日

論文題目：Quantification of Energy Conversion Efficiency of a Micromotor System and Its Applications
（マイクロモーターシステムのエネルギー変換効率の定量化とその応用）

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要　　旨：

微小流路系を利用して反応，分析などを行う微小化学システムの研究が近年注目を集めている。微小流路系内で流動状態を発生，維持させるため大きなポンプを利用することは装置系のエネルギー効率等から見て好ましいとは言えない。このため，流路系内部で動力を発生する液相マイクロモーターの研究が必要となる。本論文では，Introduction において，このような液相マイクロモーターとして応用可能な微小運動物体のこれまでの研究をレビューすることにより，異なる原理や系で作動するマイクロモーターの性能を比較することが困難であることを指摘している。第２章，３章において，シリコンオイル中に差し込んだ針状電極の間に印加した直流電圧下で発生する液滴と固体粒子の運動を観察し，入力エネルギーと物体の運動によるエネルギー散逸の比（変換効率）を測定し，これがマイクロモーターの性能を判断する指標となることを指摘している。このために本論文では，電気伝導度の極めて小さい液体中の電流の時間変化を精密に測定するとともに，自転，公転運動を行う物体のエネルギー散逸を画像解析から評価している。運動物体として液滴を用いた場合，電極表面での電気化学的反応を避けることが困難であるが，これによる変換効率の低下は６桁に及ぶことを見出している。第４章では，運動物体が分散する溶液の性質に着目し同様に変換効率を測定し，溶液の電気伝導度を上げると，同じ電圧でも粒子の運動性が向上しモーター出力が増大するが，入力の電気的仕事も大きくなり変換効率は逆に下がることを示し，液相マイクロモーターの性能評価の複雑さを明らかとしている。さらに，第５章では，マイクロモーターとしてのさらなる発展を目指して，固体粒子の形状や電極の正負極の配置を様々に変化させ，この系のマイクロモーターとしての可能性を示している。

以上，本論文では，液相直流電場下での微小物体の運動効率を評価するために，エネルギー変換効率を用いることの重要性と，それだけで論じきれない限界があることを明らかとし，液相マイクロモーターの工学的基礎を明らかとしている。よって，本論文は，博士（工学）（同志社大学）の学位を授与するにふさわしいものであると認められる。

総合試験結果の要旨

２０２１年7月３日

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要　　旨：
論文提出者は，現在，本学大学院理工学研究科応用化学専攻博士課程（後期課程）に在学中である。本論文の主たる内容は，Colloids and Surfaces A, vol. 607 (2020) 125496, Chemistry Letters 50, 661–663 (2021)に既に掲載されており十分な評価を得ている。2021 年 7 月 3 日午前 10 時 00 分より約２時間にわたって，提出論文に対する学術講演会（博士論文公聴会）が開催され活発な質疑応答がなされたが，提出者の説明により十分な理解が得られた。さらに講演終了後，審査委員により論文に関する諸問題につき口頭試問をした結果，いずれも十分な能力を有することが確認できた。論文提出者は国際科学技術コースに在籍し，学会発表，論文発表もすべて英語で行っており，語学についても十分な能力を有する。よって総合試験の結果は合格であると認める。

博 士 学 位 論 文 要 旨

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要 旨：

The study of nano- and micromotors has developed rapidly over the past decade for the microelectromechanical system (MEMS). A micromotor is a particle or droplet at the nano- or micrometre scales with mobility under certain conditions. These micromotor systems can be applied to microdevices in various field such as cargo and drug delivery for medical purposes and pollution detection for environmental protection purposes. However, the MEMS's or related microsystems are often submerged in liquid, which means that the Reynolds' number for the motor particles is extremely low (Re<<1). In such cases, the viscous effect is dominated, and the traditional motor would have low efficiency due to its inertia-dependent nature. Therefore, a continuous source of energy is required to maintain the motion of the micromotor. There are various methods to provide energy to the micromotor systems, using such as chemical reactions, magnetic fields, optical light directly or indirectly, and ultrasound. In this thesis, the micromotor system that was powered by an electric field is studied.

To increase the mobility of the micromotor, being particles or droplets, is crucial to develop the micromotor system. The mobility is frequently represented by the micromotor's velocity, angular velocity or motion frequency, and has been discussed with these parameters. Until now, studies on micromotors have been individually developed by different research groups. However, the performance of the micromotors in different experimental conditions are difficult to compare.

In this study, a quantification method for the energy conversion efficiency of micromotor system is developed. The comparisons between different micromotors (liquid vs. solid), different solution conditions (surfactant concentration, additional solvent) are discussed as one of the application of this methodology. Moreover, for the future application of micromotor systems, one of the possible applications is to the microfluidic devices, such as the "lab-on-chips" technology. In this study, a 4-pin microelectrode system and a ratchet-shaped micromotor were designed and manufactured with helps from Takinoue Lab., Tokyo Institute of Technology. The 4-pin microelectrode system was printed on a glass slide with thickness less than 10 μm, where four needle-shaped electrodes point towards a central spot in the arrangement like "X".

Two types of micromotor system were used in this study: a two needle-shaped electrode system with three dimensional form and a 4-pin microelectrode system. In the two needle-shaped electrode system, two needle-shaped electrodes that were controlled by manipulators was connected with a power amplifier and an ammeter in a closed circuit. An electromagnetic shield contained the whole system to block external noise. The 4-pin microelectrode system was connected to the circuit, replacing the two needle-shaped electrode system when needed. The whole experimental setup was set to ground level. Three types of micromotors were studied: water microdroplet, low density polyethylene microparticle and metallic ratchet-shaped microparticle.

When a microdroplet was used in the two needle-shaped electrode system, two types of back-and-forth motion were observed: oscillating and bouncing motions. Oscillating motion means the micromotor reached both ends of the electrodes while moving, whereas bouncing motion means the micromotor only moved back-and-forth at one end of the electrode. When the diameter of the droplet was larger than 20% of electrodes distance, the oscillating motion, otherwise, bouncing motion was observed. During the back-and-forth motion of the droplet, the acceleration increased when the droplet moved near the anode/cathode. The volume of the droplet was found to decrease with time due to electrolysis. A quantification method was proposed to calculated the kinetic energy output of the droplet from Stokes' drag equation, and the energy conversion efficiency was thus quantified. The result shows that the efficiency was significantly small. This is attributable to the electrochemical process of electrolysis.

To increase the efficiency, a chemically inert, solid micromotor made from low density polyethylene was used in the two needle-shaped electrode system. Revolving and spinning motions were observed for this micromotor. The output power of the revolving and spinning motions was calculated based on viscous drag and viscous torque, respectively. The total output power of a spherical micromotor was assumed to be the sum of these two output powers. The dependency of the output power on the surfactant concentration was also studied. The calculated energy conversion efficiency of solid microparticle was greater than that of microdroplet.

Then, the effect of additional solvent, ethanol, on the micromotor was examined. The solution mixture with ethanol was used in the solid microparticle micromotor system with two needle-shaped electrode system. Both revolving and spinning motions were observed. The output power of the microparticle in the ethanol-added system increased compared to that in the ethanol-free system. However, as the electric current increased, the energy conversion efficiency was lower.

This quantification enables the comparison between micromotor systems on energy levels, irrespective of the size, velocity, angular velocity of the micromotors, viscosity of the solution, or types of input energy to the system. It was difficult to compare abovementioned three micromotor systems but now they can be compared by their system efficiency. With this quantification method, the microdroplet and ethanol-added microparticle system had higher output power than the ethanol-free microparticle system. However, the ethanol-free micromotor system had higher energy conversion efficiency due to the chemically inert micromotor and low conductivity of solution. This result suggests that lower energy conversion efficiency did not necessarily correspond to lower system performance.

When a spherical microparticle was used in a 4-pin microelectrode system, revolving motion was observed but its revolving motion radius was bigger than that in two needle-shaped electrode system. which suggests that the motion occurred in low electric field intensity region. The output power of the 4-pin this system is expected to be higher than that of two needle-shaped electrodes system under the same voltage, if the micromotor motion can be restricted in high electric field region which is near the center of the electrodes. The ratchet-shaped microparticle showed three types of motions in the two needle-shaped electrodes system: suspending state, oscillating and spinning motion.

For future application, to place the ratchet-shaped microparticle at the center of the 4-pin microelectrode system may lead to a rapid spinning motion. This rapid motion can be applied to micro-mixing or micro-pump in the microdevices.