KINEMATIC STUDY OF MOTILE MICROALGAE UNDER THE INFLUENCE OF LOW GRADIENT MAGNETIC FIELD

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by

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LIST OF ABBREVIATIONS

AAS	Atomic Absorption Spectrometry
AC	Alternating current
BSA	Bovine serum albumin
$CaCl_2 \cdot 2H_2O$	Calcium chloride dihydrate
$Co(NO_3)_2 \cdot 6H_2O$	Cobalt (II) nitrate hexahydrate
$CuSO_4 \cdot 5H_2O$	Copper (II) sulphate pentahydrate
DC	Direct current
dH_2O	Distilled water
$EDTA\text{-}Na_2$	Disodium ethylenediaminetetraacetic acid
Fe	Iron
$FeCl_2 \cdot 4H_2O$	Iron (II) chloride tetrahydrate
$FeCl_3$	Iron (III) chloride
$FeCl_3 \cdot 6H_2O$	Iron (III) chloride hexahydrate
Fe_3O_4	Magnetite
FFT	Fast Fourier Transform
HA	Hyaluronic acid
HCl	Hydrochloric acid
HNO_3	Nitric acid
H_3BO_3	Boric acid
IONPs	Iron oxide nanoparticles
I_2	Iodine
KH_2PO_4	Potassium dihydrogen phosphate
K_2HPO_4	Dipotassium hydrogen phosphate

KI	Potassium iodide
LEDs	Light-emitting diodes
$MgSO_4 \cdot 7H_2O$	Magnesium sulphate heptahydrate
$MnCl_2 \cdot$4H2O	Manganese (II) chloride tetrahydrate
NaCl	Sodium chloride
$Na_2MoO_4 \cdot 2H_2O$	Sodium molybdate dihydrate
$NaNO_3$	Sodium nitrate
NaOH	Sodium hydroxide
NdFeB	Neodymium boron ferrite
Ni	Nickel
$NiSO_4$	Nickel (II) sulphate
PDA	Polydopamine
PDDA	Poly(diallyldimethylammonium chloride)
PDMS	Polydimethylsiloxane
PLL	Poly-L-lysine
PNIPAM	Poly(N-isopropylacrylamide)
PPY	Polypyrrole
PS	Polystyrene
TEM	Transmission Electron Microscope
Ti	Titanium
UV	Ultraviolet
VSM	Vibrating Sample Magnetometer
$ZnSO_4 \cdot 7H_2O$	Zinc sulphate heptahydrate

LIST OF SYMBOLS

a	Semimajor axis length
$a(r)$	Acceleration as a function of r
b	Semiminor axis length
B	Magnetic field strength
B_r	Remanence field strength
$\frac{dB}{dr}$	Magnetic field gradient with respect to r
$\frac{dr}{dt}$	Rate of change of distance from tip surface
$\frac{dv}{dt}$	Rate of change of velocity
$\frac{d^2B}{dr^2}$	Derivative of magnetic field gradient with respect to r
f	Frequency
f_{inertial}	Inertial force
f_{viscous}	Viscous force
F	Applied force
F_{b}	Buoyant force
F_{drag}	Viscous drag force
$F_{\mathrm{drag},\parallel}$	Component of viscous drag force parallel to the reference axis
$F_{\mathrm{drag},\perp}$	Component of viscous drag force perpendicular to the reference axis
F_{mag}	Magnetophoretic force
F_{swim}	Swimming force
$F_{\mathrm{swim},\parallel}$	Component of swimming force parallel to the reference axis

$F_{\mathrm{swim},\perp}$	Component of swimming force perpendicular to the reference axis
F_{thrust}	Thrust force
g	Gravitational acceleration
H	Height of magnet
K	Geometric correction factor
l	Longitudinal length of synthetic cargo
ℓ	Characteristic length
L	Length of magnet
m_{m}	Mass of microbot
r	Distance from tip surface
Re	Reynolds number
R	Radius
R_{c}	Radius of microalgal cell
t	Time
v	Velocity
$v_{\parallel}$	Component of velocity parallel to the reference axis
$v_{\perp}$	Component of velocity perpendicular to the reference axis
v_{c}	Velocity of microalgal cell
v_{m}	Velocity of microbot
V	Volume
W	Width of magnet
η	Dynamic viscosity of fluid
μ	Magnetic moment
ρ	Density of object

ρ_f	Density of fluid
τ_{mag}	Magnetic torque
ω	Angular velocity
∇B	Magnetic field gradient
Ø	Diameter
–COOH	Carboxyl functional group
–OH	Hydroxyl functional group

KAJIAN KINEMATIK TERHADAP MIKROALGA MOTIL DI BAWAH PENGARUH MEDAN MAGNET BERKECERUNAN RENDAH

ABSTRAK

Mikrosfera magnet, yang terdiri daripada teras polistirena (PS), nanopartikel oksida besi (IONPs) dan polielektrolit kationik, disintesis melalui teknik penyusunan secara berlapis-lapis. IONPs disintesis melalui kaedah pemendakan bersama. Pengendapan IONPs diikuti dengan polielektrolik pada permukaan teras PS dikenal pasti melalui pemeriksaan kegerakan elektroforesis. Morfologi teras-petala mikrosfera magnet dibuktikan melalui mikrograf mikroskopi transmisi elektron manakala jisim magnet dan sifat magnetnya dikaji dengan menggunakan spektroskopi serapan atom dan magnetometer sampel bergetar. Mikro-robot magnetik buatan dibentuk dengan mengikatkan mikrosfera magnet dengan mikroalga melalui saling tindak elektrostatik. Tingkah laku kinematik mikro-robot yang membawa mikrosfera magnet dengan diameter 2 μm dan 4.5 μm telah dikaji di bawah pengaruh dan tanpa pengaruh medan magnet berkecerunan rendah ($\nabla B < 100\ \mathrm{T/m}$). Dalam keadaan tanpa pengaruh medan magnet, mikro-robot bergerak secara heliks akibat daripada salah jajaran antara daya tujah dan paksi simetri mikrosfera. Mikro-robot yang diikat dengan mikrosfera magnet yang bersaiz besar bergerak dengan halaju translasi yang tinggi tetapi berputar perlahan pada paksi putarannya. Keseimbangan antara daya kelikatan bendalir dengan daya tujah mikro-robot menyebabkan mikro-robot bergerak secara rawak dengan halaju terminal. Sebaliknya, di bawah pengaruh medan magnet berkecerunan rendah, kawalan terarah mikro-robot tercapai berdasarkan prinsip-prinsip berikut: (1) daya magnetoforesis tidak berperanan untuk mempengaruhi pergerakan seranjang mikro-robot, dan, (2) pergerakan selari mikro-robot bergantung pada kemotilan mikro-robot

and magnetoforesis, di mana kesan koperatif ini dipengaruhi oleh jarak pemisahan antara mikro-robot dengan magnet. Apabila mikro-robot mendekati magnet, penahanan daya magnetoforesis terhadap kemotilan mikro-robot diri membawa kepada pergerakan magnetotaksis positif mikro-robot ke arah sumber medan magnet. Penggunaan mikrosfera yang mempunyai jisim magnet yang tinggi boleh meningkatkan pecutan mikro-robot dan memperluas jejari pecutan. Keputusan ini menandakan kawalan magnetotaktik terhadap mikro-robot dalam medan magnet dapat dicapai dengan memanipulasikan jisim magnetnya.

KINEMATIC STUDY OF MOTILE MICROALGAE UNDER THE INFLUENCE OF LOW GRADIENT MAGNETIC FIELD

ABSTRACT

Magnetic microbead composed of a polystyrene (PS) core, iron oxide nanoparticles (IONPs) and cationic polyelectrolyte, was prepared via layer-by-layer assembly. The IONPs were synthesized by co-precipitation method. The successful deposition of IONPs followed by polyelectrolyte onto the PS bead was monitored with electrophoretic mobility measurement. The core-shell morphology of the magnetic microbead was confirmed by transmission electron microscopy technique, and its magnetic mass and magnetic property was determined by using atomic absorption spectroscopy and vibrating sample magnetometer respectively. An artificial magnetotactic microbot was created by attaching a magnetic microbead onto a microalgal cell by the means of electrostatic interaction. The kinematic behaviors of the microbots carrying magnetic microbeads of two different sizes, with diameter of 2 μm and 4.5 μm, in the absence and the presence of low gradient magnetic field ($\nabla B < 100$ T/m) were characterized. In the absence of magnetic field, the microbot exhibited a helical motion as a result of the misalignment between its thrust force and the symmetry axis after the attachment. The microbot bound with a larger magnetic microbead moved with higher translational velocity but rotated slower about its axis of rotation. The viscous force was balanced by the thrust force of the microbot, resulting in a randomized swimming behavior of the microbot at its terminal velocity. Meanwhile, under the influence of a low gradient magnetic field, the directional control of the microbot was achieved based on following the principles: (1) magnetophoretic force was insignificant on influencing its perpendicular motion, and,

(2) its parallel motion was dependent on both self-swimming and magnetophoresis, in which this cooperative effect was a function of separation distance from the magnet. As the microbot approached the magnet, the magnetophoretic force suppressed its self-swimming behavior, leading to a positive magnetotaxis of the microbot toward the source of magnetic field. The use of a high magnetic mass of microbead enhanced the acceleration of the microbot and expanded the acceleration radius, suggesting that the spatial magnetotactic control of microbot in the magnetic field can be achieved by varying its magnetic mass.

CHAPTER ONE

INTRODUCTION

1.1 Motility and biohybrid microbot

Motility is the ability of an organism to exhibit motion and to perform mechanical work using its metabolic energy (Allen, 1981). Swimming organisms range in sizes from a few micrometres as motile microorganism up to several metres as a large marine animal. However, the physics governing swimming at the micrometer length scale is completely different from the physics of swimming at the macroscopic scale (Eric and Thomas, 2009). The underlying physics are dictated by the ratio of the inertial forces to the viscous forces, which is represented by a dimensionless quantity known as Reynolds number (Chisholm et al., 2016). The fundamental differences between motion in microscale and macroscale were discussed by Edward Mills Purcell, a Nobel Laureate in Physics in his famous lecture "Life at low Reynolds number" in 1977 (Purcell, 1977). Microorganisms use cilia or flagella to swim at small characteristic length scale in the low Reynolds number regime, where viscous forces dominate inertial forces. The specific beating pattern of these appendages creates a time-irreversible deformation of the appendages for cell propulsion which later contribute to its translational (and, to some extent its rotational) motion.

The recent decades have witnessed great progress in the realization of various miniature mobile robots for potential applications in biomedicine, bioengineering and lab-on-a-chip devices. However, the key challenges in the further miniaturization of mobile robots down to micrometer scale are (1) the miniaturization of the on-board actuators and (2) power sources for the microrobotic systems (Behkam and Sitti, 2007). The capability of the highly motile microorganism to swim in low Reynolds number environment proposes that they could be a promising solution to the aforementioned challenges faced especially in overcoming miniaturization issue. In this regard, various motile microorganisms (microswimmers) such as bacteria (Akin et al., 2007; Sahari et al., 2012; Behkam and Sitti, 2008; Fernandes et al., 2011; Arabagi et al., 2011), algae (Weibel et al., 2005) or motile sperm cell (Magdanz et al., 2013) combined with synthetic functional materials for the assembly of biohybrid microbot have been studied. This approach exploits the biological cells as an efficient on-board power source for propulsion of the biohybrid microbot because they can harvest chemical energy from the surroundings and efficiently convert the chemical energy into mechanical work, provided that there are sufficient nutrient present in the working environment (Carlsen and Sitti, 2014).

Besides, biological cells not only exhibit high motility but show huge potential to serve as on-board sensors due to their intrinsic and versatile sensing abilities (Zhuang et al., 2015). Different motion control strategies have been developed, from the cell’s sensory and behavioral response to external stimuli, in order to utilize the swimming locomotion for microscale cargo transport and delivery by microbots. These control strategies include chemotaxis (Kim et al., 2012a; Zhuang and Sitti, 2016; Park et al., 2014; Uthaman et al., 2016), pH-taxis (Zhuang et al., 2015), magnetotaxis (Ma et al., 2012; Martel et al., 2006), phototaxis (Steager et al., 2007; Weibel et al., 2005), and electrotaxis (Steager et al., 2011). Among these strategies, magnetotaxis offers an attractive advantage over others in which it can be used in both homogeneous and heterogeneous environments as the magnetic fields can be generated remotely (Carlsen and Sitti, 2014). Furthermore, this method is less invasive and does not interfere with chemical and biological activities of the microorganism.

1.2 Problem statement

In general, magnetotaxis of microbots can be achieved by the integration of magnetically responsive biological components into nonbiological components, or vice versa. The primary approach is to use biological cells that are responsive to magnetic fields. Such biological cells can be either a magnetotactic bacteria (Ma et al., 2012; Martel et al., 2006) that possesses naturally occurring intracellular magnetosomes, or an artificial magnetotactic cell (Kim et al., 2010) with ingested magnetic nanoparticles. However, these approaches are either dependent on cells with magnetoception capability or cells that can remain viable after the ingestion of magnetic nanoparticles, limiting the type of cells that can be utilized (Carlsen et al., 2014).

For the latter approach which is also the most popular way to achieve magnetotaxis, it incorporates magnetic materials onto nonmagnetic biological cells, creating artificial magnetotaxis for the motion control. Magdanz et al. (2013) presented the development of a microbiorobot comprising a magnetic tube driven by a spermatozoid. In other work, Carlsen et al. (2014) described the directional magnetic steering control of a superparamagnetic bead propelled by a swarm of rod-shaped gram-negative bacteria, *Serratia marcescens*. From all these studies, the reported cell velocities driven by micron sized magnetic particle were surprisingly low and were approaching the magnetophoretic velocity (10 μm/s) of an individual iron oxide nanoparticle with diameter at ~ 35 nm (more than 100 times smaller than those microbead used) reported by Lim et al. (2011). There is a huge mismatch between the theoretical predictions of magnetophoretic velocity with recorded velocity. In most likelihood, the thrust force associated with the self-swimming has randomized or even suppressed the migration of entire microbead-microswimmer system under artificial