

Swimming at low Reynolds numbers—motility of micro-organisms

This article has been downloaded from IOPscience. Please scroll down to see the full text article.

2009 J. Phys.: Condens. Matter 21 200301

(<http://iopscience.iop.org/0953-8984/21/20/200301>)

View [the table of contents for this issue](#), or go to the [journal homepage](#) for more

Download details:

IP Address: 129.252.86.83

The article was downloaded on 29/05/2010 at 19:38

Please note that [terms and conditions apply](#).

PREFACE

Swimming at low Reynolds numbers—motility of micro-organisms

Guest Editors

Piotr Garstecki

*Institute of Physical Chemistry,
Polish Academy of Sciences,
Kasprzaka 44/52, 01-224
Warsaw, Poland*

Marek Cieplak

*Institute of Physics,
Polish Academy of Sciences,
Aleja Lotników 32/46, 02-668
Warsaw, Poland*

Microbes are important: their lives are intimately (both symbiotically and hostilely) intertwined with the lives of humans. Microbes are the tiniest organisms that we know of; although they inhabit largely the same environment as humans, their world is strange to us. This is because we cannot see them with a bare eye and because the different length scales select different rules of physics to be important. As the microbes affect us, we devote significant activity to control them. This goal obviously challenges our comprehension of ‘how the microbes work’. There are at least two strategies to accumulate this understanding. One is to simply ‘look’, classify their type and behavior and make reason out of these observations. This approach is fathered by Antonie van Leeuwenhoek, the inventor and constructor of the famous single lens microscope. A second strategy is to create models that are either analytically or experimentally tractable, and to take advantage of this tractability to analyze the models thoroughly and then relate the findings to the actual biological problem. This second strategy is naturally the domain of physics. Especially, when it comes down to one of the more mechanical aspects of microbial biology—motility.

As pointed out in the seminal works of Taylor [1] and Purcell [2] the physics of swimming at the length scales of single micrometers is very different from our common macro-scale experience. The most important difference is reflected by the low value of the Reynolds number—the ratio yielding the relative importance of inertial and viscous forces. At the microscale, inertia is not important and macro-scale mechanisms of swimming simply do not work. This was clearly discussed by Purcell [2] and is encapsulated by the dogma known as Purcell’s scallop theorem. It implies that because of the linearity of the equations of flow at low Reynolds numbers (that is within the Stokes approximation) that any periodic and reciprocal motion cannot lead to a net displacement nor a rectified speed. This rule forced various strategies of swimming that all break the reciprocity of motion of the organelles of the swimmers. The most common—and most commonly known—of these are rotating a helical flagella, as utilized by e.g. the bacterium *E. coli* [3], or performing asymmetric power and recovery strokes, as done by e.g. the green algae *Chlamydomonas reinhardtii* [4]. There are however other strategies, such as sending periodic waves over the cilia that cover the whole surface of the cell. This mechanism is discussed on the grounds of a physical model by Downton and Stark in this issue [5]. Ekiel-Jeżewska and Wajnryb [6] discuss yet another physical model of a swimmer comprised of two arms that can spin along their axes. They show that this spinning can significantly affect sedimentation, a result that could lead to insights into the behavior of gravitactic micro-organisms.

Although the scallop theorem holds, it allows for refinement. For example, in this issue, Gonzalez-Rodriguez and Lauga show several models of swimmers that can utilize the inertia of their bodies (as opposed to the inertia of the fluid in which they swim) by performing reciprocal strokes to move [7]. Golestanian and Ajdari discuss another strategy that can avoid a non-reciprocal force resulting in net motion [8]. At small scales, thermal fluctuations become important and

Golestanian and Ajdari show a *swimming ratchet*: they demonstrate that an appropriate design of the geometry of the swimmer can yield a net speed as a result of thermal fluctuations. Wilson *et al* [9] utilize the concept of the Lyapunov exponent calculated for the trajectories of elements of fluid to show how micro-organisms manage fluctuations in flow, and how the exact mechanics of swimming creates flow barriers between the fluid that is expelled during the power stroke and the fluid that returns during the recovery stroke of an organism.

Besides the insignificance of inertia, there is another striking feature of the microbial motility—at low values of the Reynolds number the hydrodynamic interactions are long range on the scale of the swimmer. This leads to conditions that are surprising for a macroswimmer—nobody swimming in a pool expects to be affected by the activity of another swimmer separated by a distance of, say, 30 lengths of a typical body (50 meters for humans). Yet at the microscale this is exactly what happens, and this feature leads to very interesting effects of interaction between swimmers, and between swimmers and solid walls. Felderhof [10] discusses the hydrodynamic interactions of a ‘peristaltic sheet’ with the proximate walls or with a second sheet, while Hernandez-Ortiz *et al* elaborate on the physical mechanisms behind one of the most fascinating behaviors of micro-organisms—collective swimming [11].

Recently, new stimuli in the research of motility of micro-organisms came from the experimental realizations of motile microstructures—artificial microswimmers. An important contribution here comes from Dreyfus *et al* who showed a micro-scale swimmer comprised of elastically linked colloidal particles [12]. In this issue, Alexander *et al* [13] discuss a similar model of Najafi and Golestanian [14] and analyze the interactions between such swimmers. Coq *et al* [15] investigate a different mechanism of swimming and report on the most important ‘organelle’ of structures that propel by rotating a helical element—they discuss the mechanics of a rotated elastic rod. Depending on the type of forcing, the rod, when subject to an increasing torque, either smoothly transforms into an increasingly deformed helical shape providing growing net flow in the direction of rotation, or shows a discontinuous transition of the shape with a sudden change in the efficiency of propulsion. Finally, Garstecki *et al* [16] demonstrate experimentally elastic artificial microswimmers powered by an external rotating magnetic field. They show that in order to design a helical swimmer one does not have to fabricate the complicated three-dimensional structure, but can use the deformation of an originally planar swimmer into a helical shape when it is subject to the opposing magnetic and viscous torques.

Certainly, this issue is not intended to cover the vast subject of micro-scale motility to any significant length. However, we hope that this collection of articles will bring the fascinating field of low Reynolds number swimming closer to a wide community of physicists and that this issue will stimulate further discussion of the highly non-intuitional world of motility at the microscale.

References

- [1] Taylor G I 1951 *Proc. R. Soc. A* **209** 447
Taylor G I 1952 *Proc. R. Soc. A* **211** 225
- [2] Purcell E M 1977 *Am. J. Phys.* **45** 3
- [3] Lighthill J 1976 *SIAM Rev.* **18** 161
- [4] Foster K W and Smyth R D 1980 *Microbiol. Rev.* **44** 572
- [5] Downton M T and Stark H 2009 *J. Phys.: Condens. Matter* **21** 204101
- [6] Ekiel-Jeżewska M L and Wajnryb E 2009 *J. Phys.: Condens. Matter* **21** 204102
- [7] Gonzalez-Rodriguez D and Lauga E 2009 *J. Phys.: Condens. Matter* **21** 204103
- [8] Golestanian R and Ajdari A 2009 *J. Phys.: Condens. Matter* **21** 204104
- [9] Wilson M M, Peng J, Dabiri J O and Eldredge J D 2009 *J. Phys.: Condens. Matter* **21** 204105

- [10] Felderhof B U 2009 *J. Phys.: Condens. Matter* **21** 204106
- [11] Hernandez-Ortiz J P, Underhill P T and Graham M D 2009 *J. Phys.: Condens. Matter* **21** 204107
- [12] Dreyfus R, Baudry J, Roper M L, Fermigier M, Stone H A and Bibette J 2005 *Nature* **437** 862
- [13] Alexander G P, Pooley C M and Yeomans J M 2009 *J. Phys.: Condens. Matter* **21** 204108
- [14] Najafi A and Golestanian R 2005 *Phys. Rev. E* **69** 062901
- [15] Coq N, du Roure O, Fermigier M and Bartolo D 2009 *J. Phys.: Condens. Matter* **21** 204109
- [16] Garstecki P, Tierno P, Weibel D B, Sagués F and Whitesides G M 2009 *J. Phys.: Condens. Matter* **21** 204110