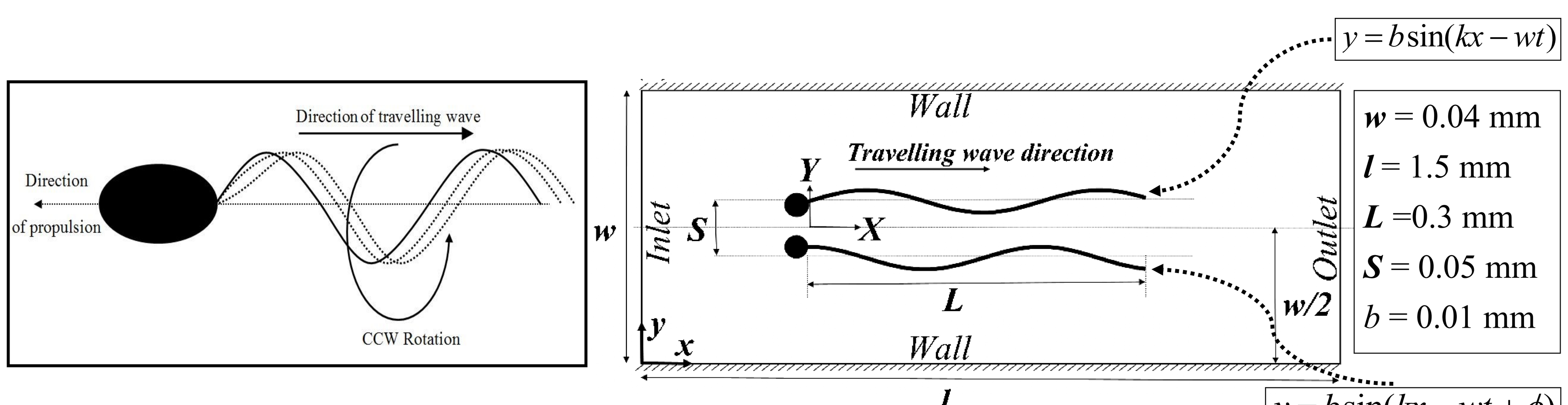
Numerical Simulation of Auto-Propulsion Mechanism of Microorganism inside a Microchannel

S. Patra[1], S. Shah[2], G. Biswas[1], A. Dalal[1], D. Bandyopadhyay[3]

[1] Indian Institute of Technology Guwahati, Department of Mechanical Engineering, Assam, India
[2] Indian Institute of Technology Bhubaneswar, Department of Mechanical Engineering, Odisha, India
[3] Indian Institute of Technology Guwahati, Department of Chemical Engineering, Assam, India

INTRODUCTION

- The maneuver of appendage enabled locomotion of bacteria and the resulting intriguing fluid dynamic behavior has fascinated the research community over the years.
- Stepping ahead, the present study manifests about the several ground breaking flow phenomena arising out of hydrodynamic interaction between two swimming bacteria in side a micro capillary at close proximity.
- Initially the waving sheet problem is validated with the Taylor's analytical solution. Henceforth the model is extended to design a single flagellated microorganism swimming inside microorganism.
- The planner beating pattern is considered as swimming mechanism of single flagellated bacteria. The net propulsion is obtained by passing lateral waves through the tail as shown in the Fig. 1(a).



(a) (b)

Figure 1: (a) Diagram of mechanism of propulsion (b) Schematic diagram of computational domain used for numerical simulation

GOVERNING EQUATIONS

- Continuity Equation : $\nabla \cdot \mathbf{u}^f = 0$ (1)
- Momentum Equation: $\rho^f \left(\frac{\partial \mathbf{u}^f}{\partial t} + (\mathbf{u}^f \cdot \nabla)\mathbf{u}^f\right) - \nabla \cdot \boldsymbol{\sigma}^f = \rho^f \mathbf{f}^f$ (2)
- Equilibrium Equation: $\rho^s \frac{d\mathbf{u}^s}{dt} = \nabla \cdot \boldsymbol{\sigma}^s + \rho^s \mathbf{f}^s$ (3)
- Geometrical Compatibility Condition: $\mathbf{u}^s - \mathbf{u}^f = 0$ (4)
- Force Equilibrium Condition : $\boldsymbol{\sigma}^s n^s - \boldsymbol{\sigma}^f n^f = 0$ (5)

BOUNDARY CONDITIONS

- On sheet: $u(X,t) = 0,$
  $v(X,t) = -b\omega\cos(kX - \omega t)\min(t,T) + b\sin(kX - \omega t)\frac{\partial(\min(t,T))}{\partial t}$ (6)

SOLUTION METHODOLOGY

- Finite element based commercial software COMSOL Multiphysics is used, in which the motion of the fluid (solid) is modeled in Eulerian (Lagrangian) framework with the help of Fluid-Structure interaction module (FSI).
- The incompressible governing equation (Eq. 2) subjected to incompressibility (Eq.1) is solved using PARDISO solver with suitable boundary condition (Eq. 6).
- Second accurate BDF solver is used for time marching with back ward Euler consistent initialization.
- The mesh velocity is obtained by using Laplace equation.
- The time step size of 10^{-3}-10^{-4} is found to be suitable for convergence.

PARAMETERS USED FOR SIMULATION

Amplitude (b)	**Density (ρ)**	**Flagellum length (L)**
0.01 mm	1000 kg.m^{-3}	0.3 mm
Proximity (S)	**Time period (T)**	**Wavelength (λ)**
0.05 mm	0.1 s	0.2 mm

VALIDATIONS

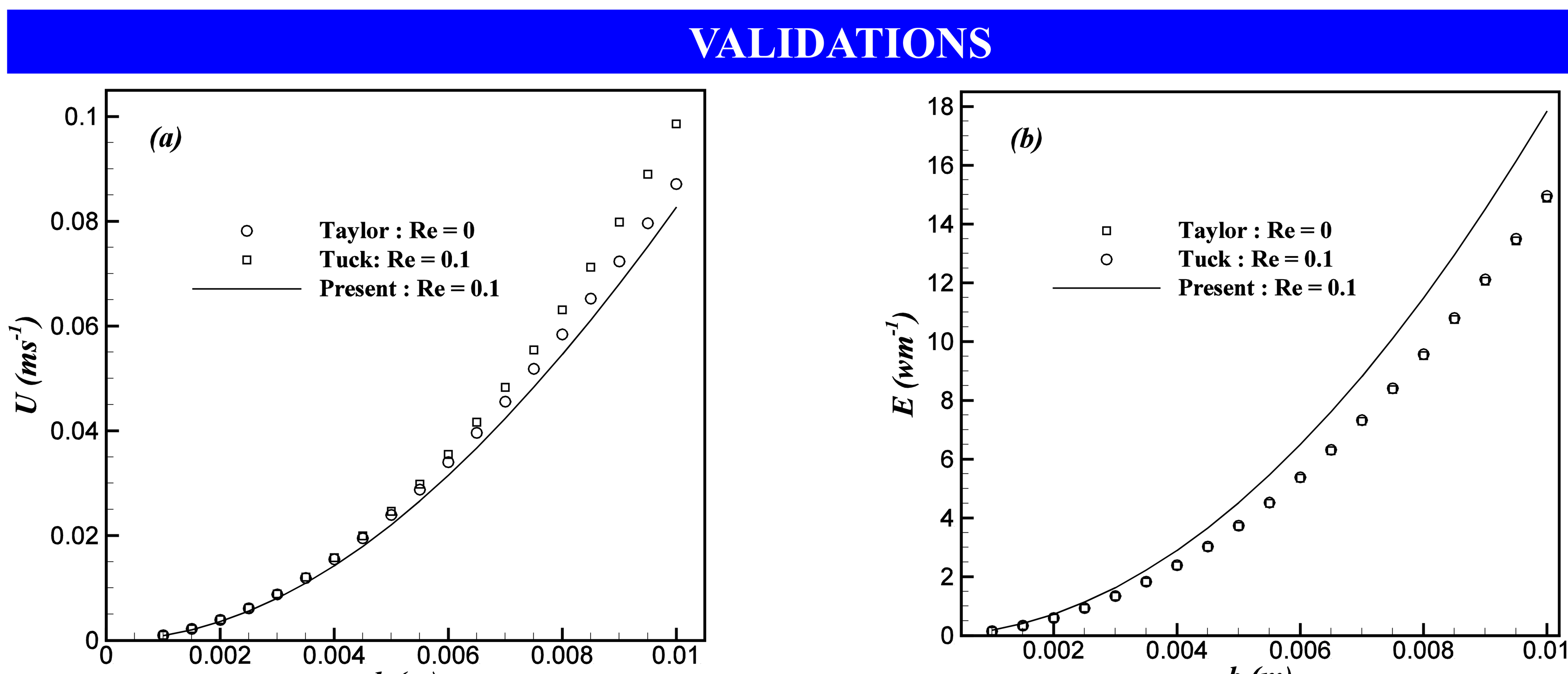


Figure 2: Variation of (a) swimming speed (U) (b) Rate of dissipation of energy (E) with amplitude (b)

RESULTS

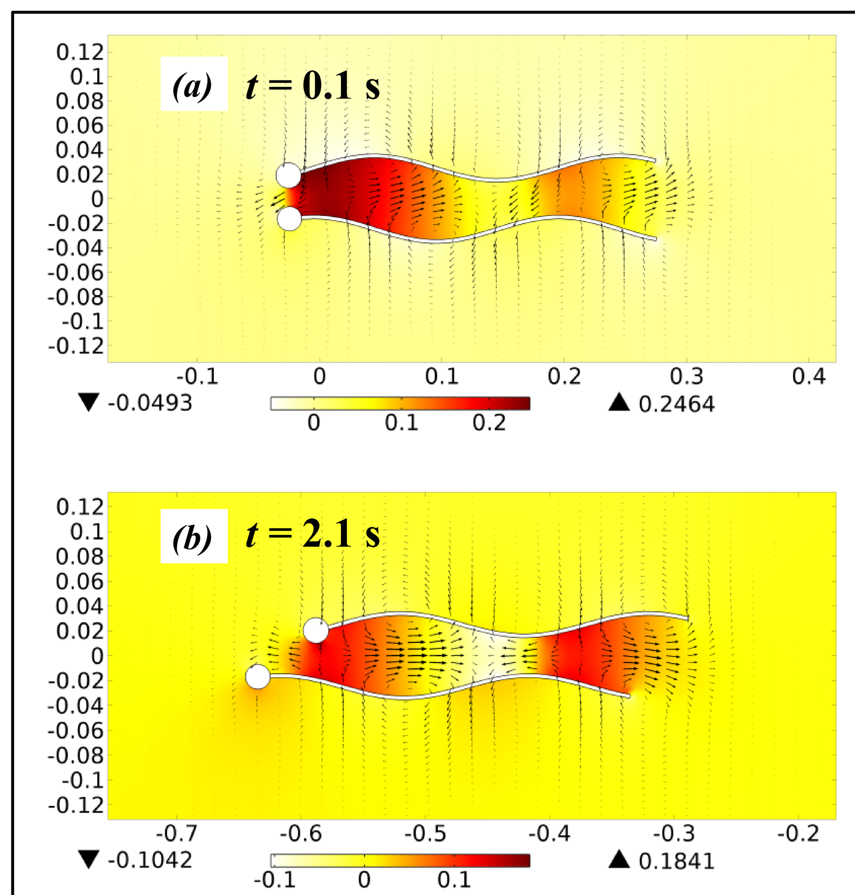


Figure 3. Anti-phase lock configuration achieved between microorganisms swimming at $Re = 0.13$, where contour shows the magnitude of pressure

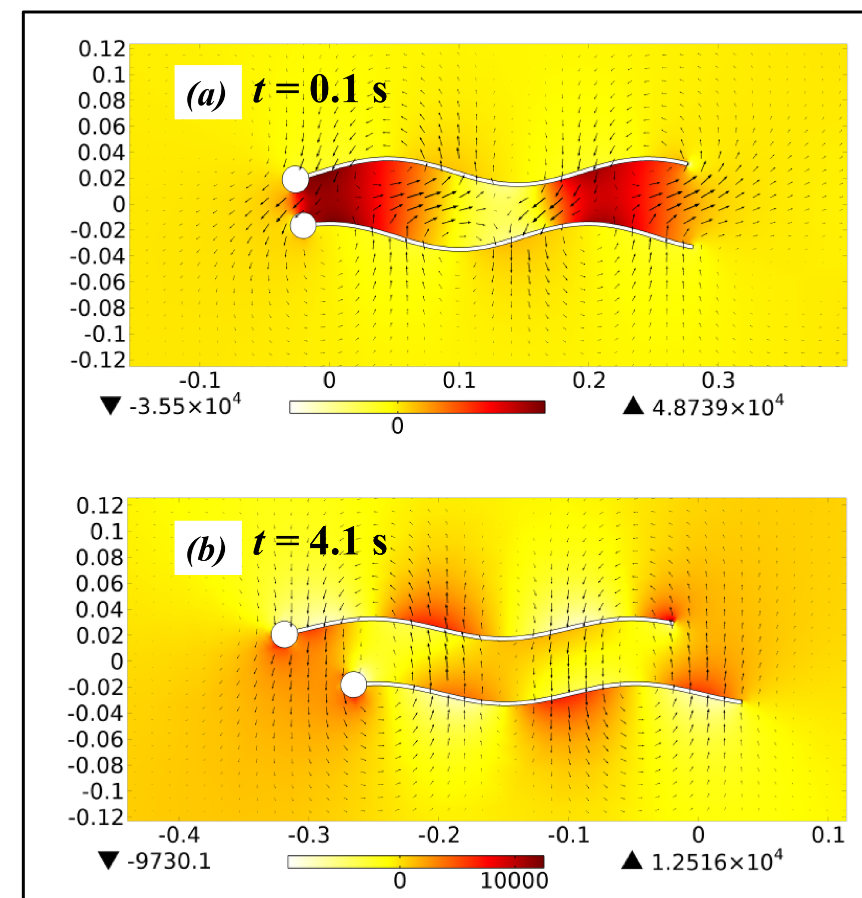


Figure 4. In-phase lock configuration achieved between microorganisms swimming at $Re = 0.0003$, where contour shows the magnitude of pressure

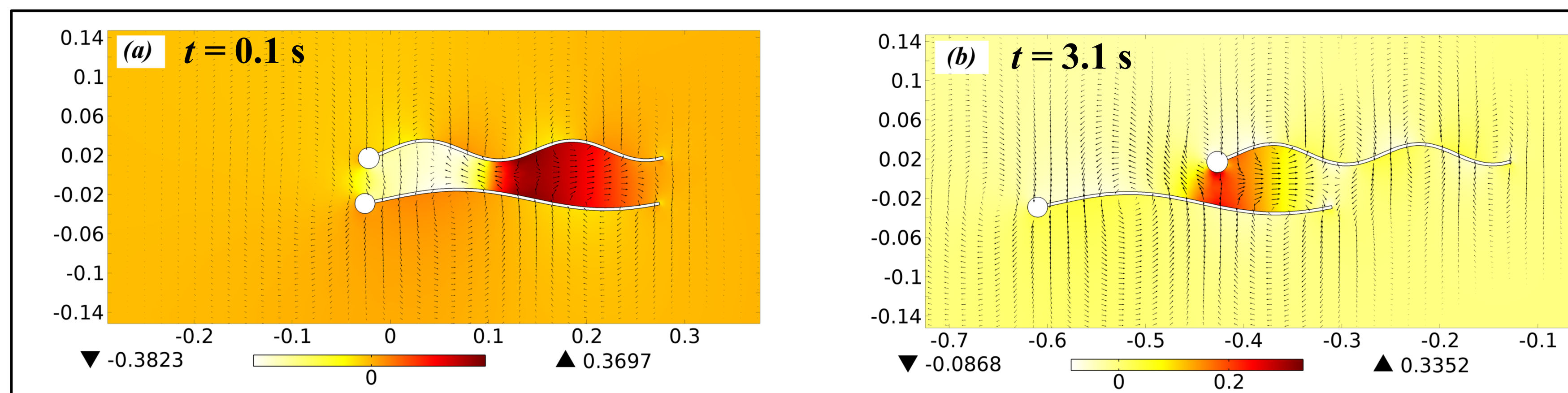


Figure 5. Anti-phase locking at different configuration achieved between microorganisms swimming at $Re = 0.13$, where contour shows the magnitude of pressure
Two different wavelengths are applied to the upper and lower microorganism

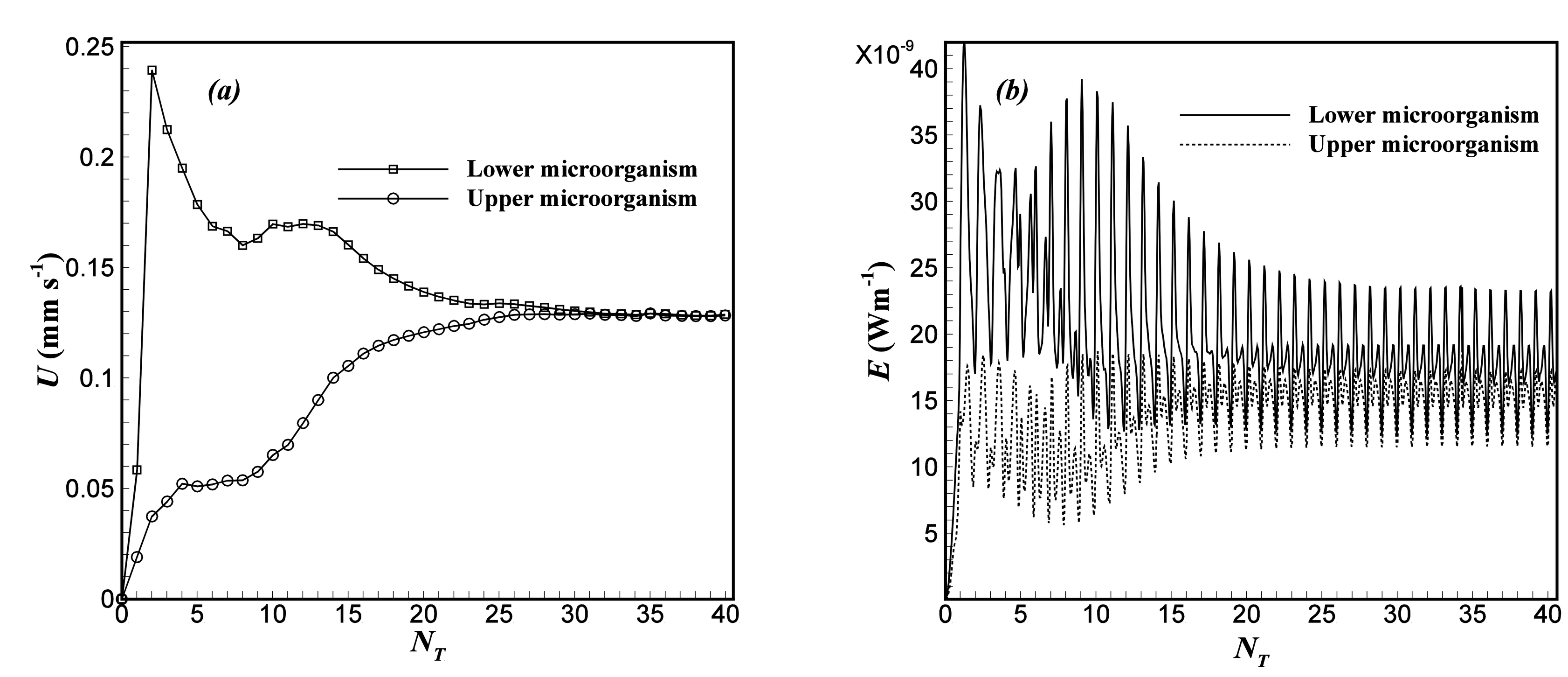


Figure 6: Evolution of (a) stabilized swimming speed (U) (b) Rate of dissipation of energy (E) with beating periods

CONCLUSIONS

- Successfully a computational model is developed in accordance to the Taylor's analytical propositions.
- An interesting flow physics is revealed in terms of synchronized swimming between two microorganisms inside a micro channel.
- At high ***Re*** (0.13), the two microorganisms attains anti-phase lock configuration in both parallel and approached swimming pattern. The synchronized swimming velocity obtained is more than un-synchronized pattern. Here in this case the rate of dissipation of energy is minimized.
- Similarly, at low ***Re*** (0.0003), the two microorganisms attains in-phase lock configuration in both swimming pattern. But the synchronized swimming velocity obtained in this case is less than un-synchronized pattern. While the rate of energy dissipation is maximized.
- We believe the results reported here will supplement significantly to enhance understanding about the auto-propulsion mechanism of flagellated microorganisms.

REFERENCES

1. Taylor G, 'Analysis of swimming microorganisms', *Royal Society of London Proceeding Series A*, vol 209, pp. 447-461. .(1951)
2. Fauci L.J and Peskin C.S. 'A computational model of aquatic animal locomotion', *Journal of Computational Physics,* vol.77 pp.85-108. (1988)
3. Qin F.H., Huang W.X and Sung H.J. ' Simulation of small swimmer motions driven by tail beating', *Computers and Fluids,* vol55, pp.109-117. (2012)