

Modeling 6-DOF Rigid-Body Motion Of A Thermocapillary Microswimmer

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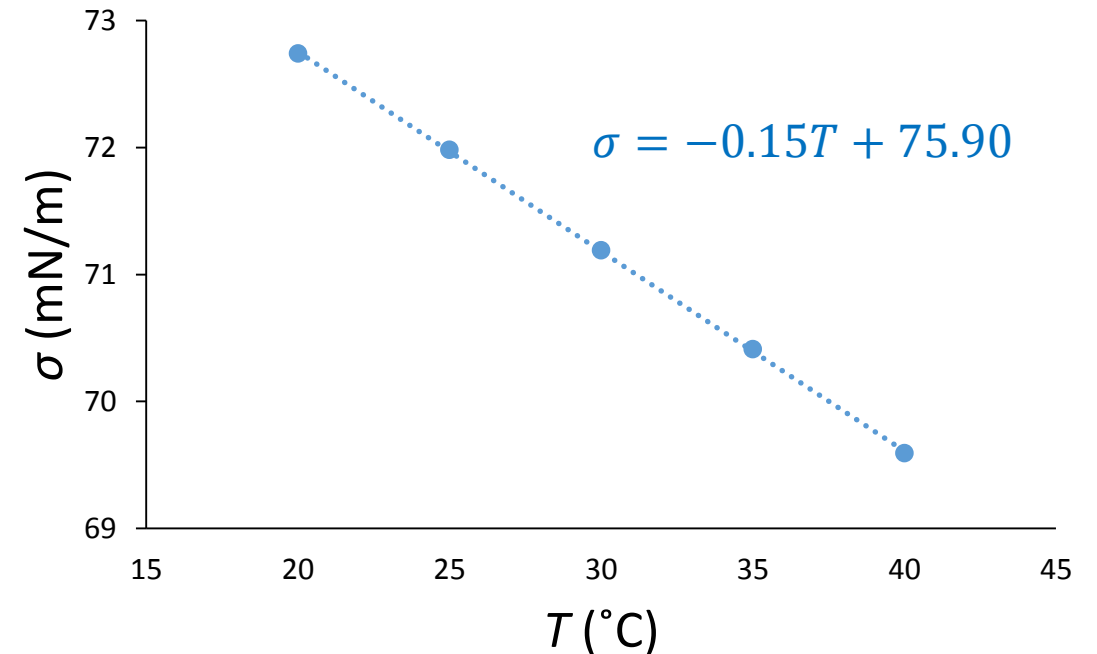
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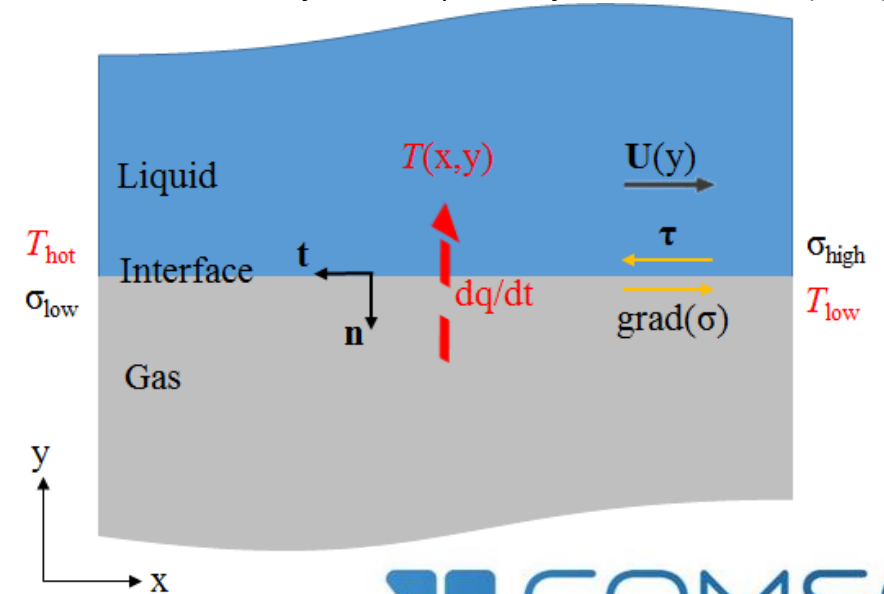
Physical Intelligence
Department

Thermocapillary Flow

- The surface tension of an air-water interface decreases with increasing temperature
- A gradient in surface tension leads to fluid flow at a fluid-gas or fluid-fluid interface
- At small scales, this phenomenon is very efficient, $F \propto L$

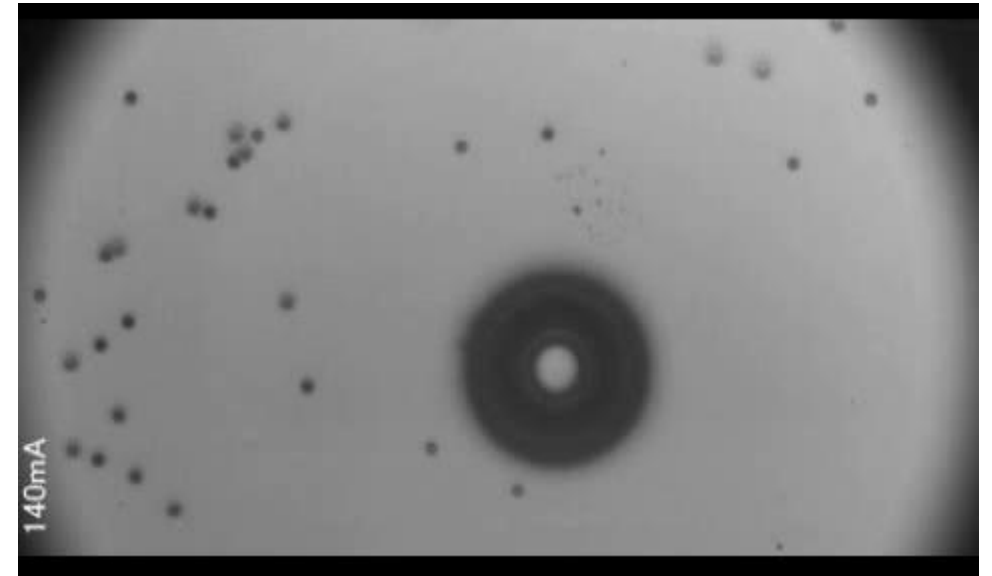


International Association for the Properties of Water and Steam (2014)



Thermocapillary Flow: Implementation

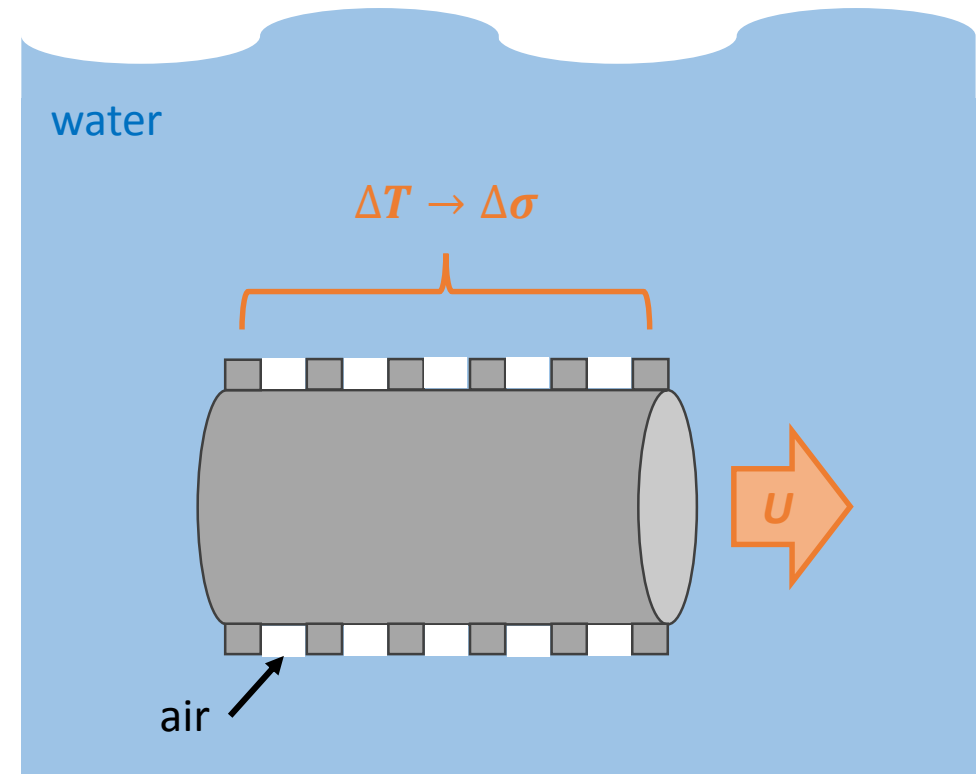
- Most work with thermocapillary flow is done on top of a water surface
- Recently researchers have shown thermocapillary flow with submerged air bubbles
- Flows on the order of cm s^{-1} have been observed for temperature gradients on the order of $^{\circ}\text{C cm}^{-1}$



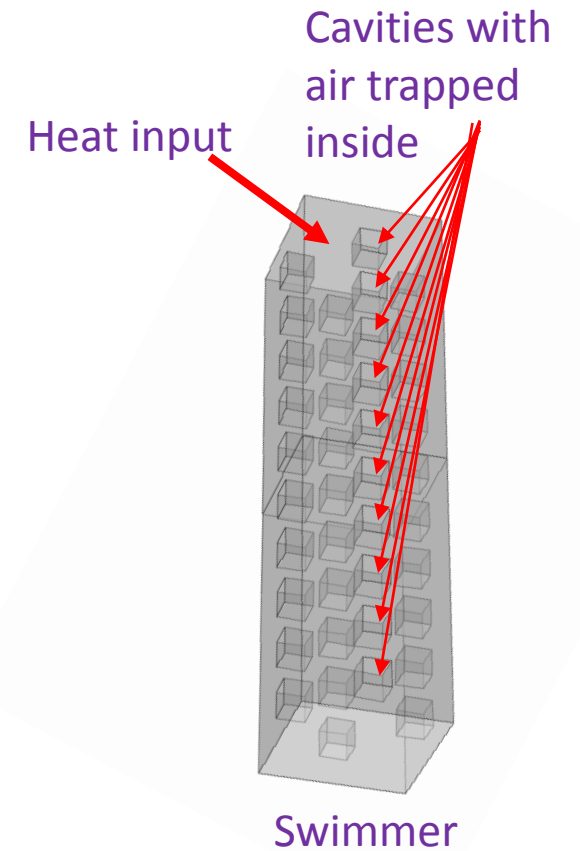
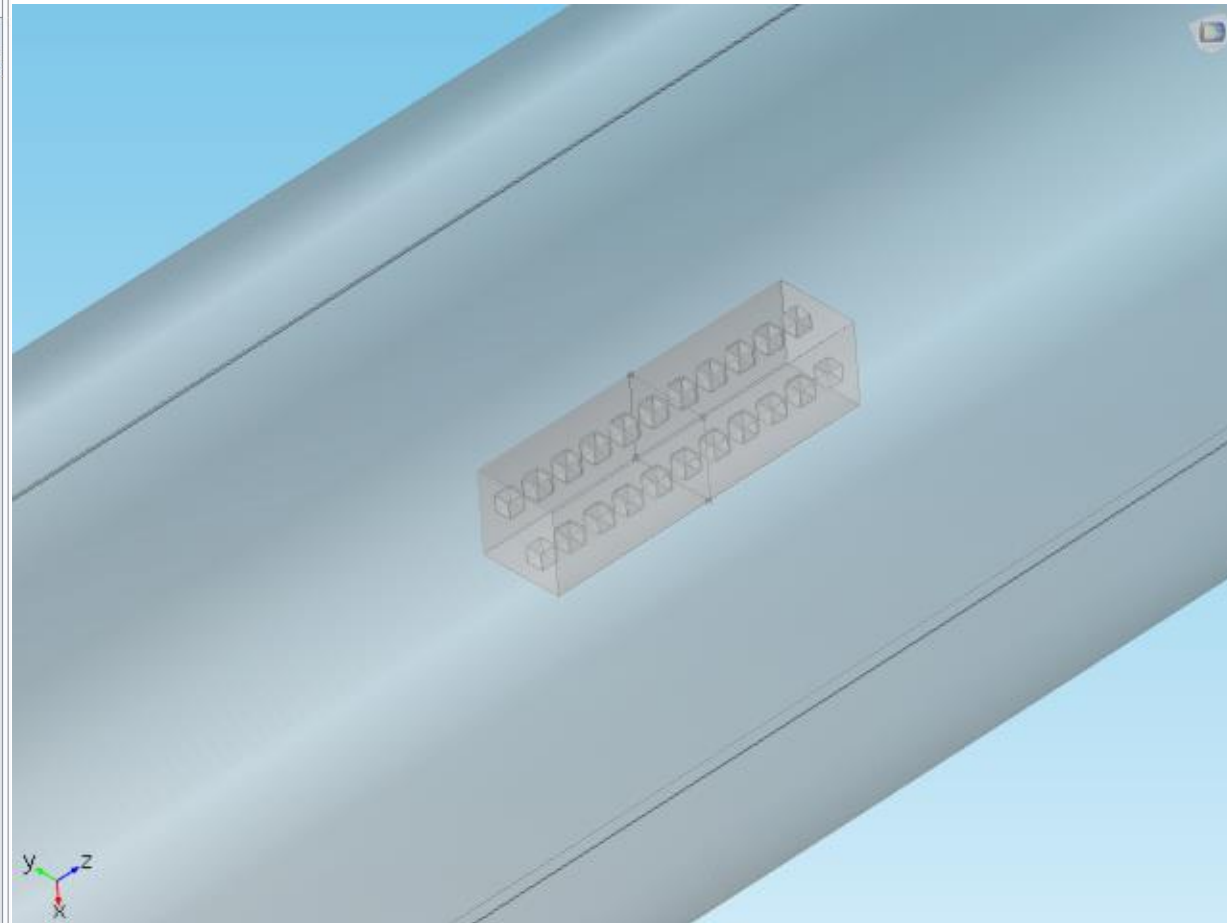
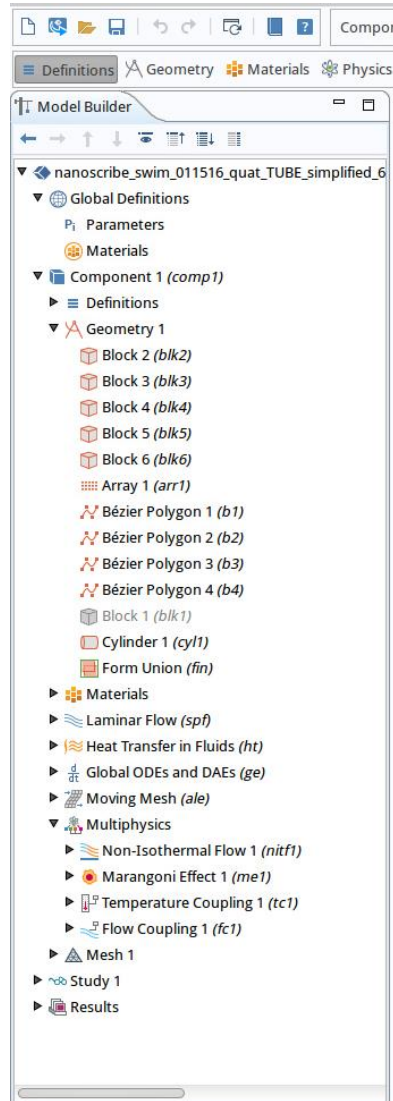
Namura *et al* (2015) *Appl Phys Lett*

Proposed Thermocapillary Microswimmer

- By trapping air on the surface of a submerged microswimmer, we may exploit interfacial phenomena
- Imposing a temperature gradient across the swimmer may generate a surface tension gradient
 - Remote heating by AC-magnetic field
- The net force from the surface tension gradient may drive flow around the swimmer, generating propulsion



Geometry: Channel and Swimmer



Main Modules

Component 1 (comp1) | Pi | a= | f(x) | [Icons]

Definitions | Geometry | Materials | **Physics** | Mesh | Study | Results

Model Builder

- nanoscribe_swim_011516_quat_TUBE_simplified_6
 - Global Definitions
 - Parameters
 - Materials
 - Component 1 (comp1)
 - Definitions
 - Geometry 1
 - Materials
 - Laminar Flow (spf)**
 - Fluid Properties 1
 - Initial Values 1
 - Wall 1
 - Fluid Properties 2
 - Wall 2
 - Pressure Point Constraint 1
 - Open Boundary 1
 - Equation View
 - Heat Transfer in Fluids (ht)
 - Global ODEs and DAEs (ge)
 - Moving Mesh (ale)
 - Multiphysics
 - Non-Isothermal Flow 1 (nitf1)
 - Marangoni Effect 1 (me1)
 - Temperature Coupling 1 (tc1)
 - Flow Coupling 1 (fc1)
 - Mesh 1
 - Study 1
 - Results

Settings

Laminar Flow
Equation form:

Study controlled

Show equation assuming:
Study 1, Time Dependent

$$\rho \frac{\partial \mathbf{u}}{\partial t} + \rho(\mathbf{u} \cdot \nabla)\mathbf{u} =$$

$$\nabla \cdot [-p\mathbf{I} + \mu(\nabla\mathbf{u} + (\nabla\mathbf{u})^T)] + \mathbf{F}$$

$$\rho \nabla \cdot (\mathbf{u}) = 0$$

Physical Model

Compressibility:
Incompressible flow

Turbulence model type:
None

Turbulence model:
k-ε

Neglect inertial term (Stokes flow)

Enable porous media domains

Reference pressure level:
Pref 1[atm] Pa

Consistent Stabilization

Inconsistent Stabilization

Advanced Settings

Discretization

Discretization of fluids:
P2+P1

Value types when using splitting of complex variables

Dependent variable	Value type
Velocity field	Real
Pressure	Real

Dependent Variables

Component 1 (comp1) | Pi | a= | f(x) | [Icons]

Definitions | Geometry | Materials | **Physics** | Mesh | Study | Results

Model Builder

- nanoscribe_swim_011516_quat_TUBE_simplified_6
 - Global Definitions
 - Parameters
 - Materials
 - Component 1 (comp1)
 - Definitions
 - Geometry 1
 - Materials
 - Laminar Flow (spf)
 - Heat Transfer in Fluids (ht)
 - Heat Transfer in Fluids 1
 - Initial Values 1
 - Thermal Insulation 1
 - Heat Transfer in Solids 1
 - Heat Transfer in Fluids 2
 - Boundary Heat Source 1
 - Open Boundary 1
 - Equation View
 - Global ODEs and DAEs (ge)
 - Moving Mesh (ale)
 - Multiphysics
 - Non-Isothermal Flow 1 (nitf1)
 - Marangoni Effect 1 (me1)
 - Temperature Coupling 1 (tc1)
 - Flow Coupling 1 (fc1)
 - Mesh 1
 - Study 1
 - Results

Settings

Heat Transfer in Fluids

ON

1

2

Active 3

4

5

Equation

Equation form:
Study controlled

Show equation assuming:
Study 1, Time Dependent

$$\rho c_p \frac{\partial T}{\partial t} + \rho c_p \mathbf{u} \cdot \nabla T + \nabla \cdot \mathbf{q} = Q + Q_p + Q_{vd}$$

$$\mathbf{q} = -k \nabla T$$

Physical Model

Surface-to-surface radiation

Radiation in participating media

Heat transfer in biological tissue

Isothermal domain

Heat transfer in porous media

Consistent Stabilization

Inconsistent Stabilization

Advanced Settings

Discretization

Temperature:
Quadratic

Compute boundary fluxes

Apply smoothing to boundary fluxes

Value type when using splitting of complex variables:
Real

Dependent Variables

Auxiliary Modules

The image displays three screenshots of the COMSOL Multiphysics software interface, illustrating the configuration of auxiliary modules for a simulation.

Left Screenshot: Global Equations

The **Global Equations** module is configured with the following equation:

$$f(u, u_t, u_{tt}, t) = 0, \quad u(t_0) = u_0, \quad u_t(t_0) = u_{t0}$$

Name	f(u, ut, utt, t) (1)	Initial valu	Initial v
velx	-Fx	0	0
vely	-Fy	0	0
velz	-Fz	0	0
omegax	-T_x	0	0
omegay	-T_y	0	0
omegaz	-T_z	0	0

Middle Screenshot: Prescribed Deformation

The **Prescribed Deformation** module is configured with the following domain selection and prescribed mesh displacement:

Domain Selection: All domains

Active: 1, 2, 3, 4, 5

Prescribed mesh displacement:

- d_x : $x_disp_ode * mesh_env$ m
- d_y : $y_disp_ode * mesh_env$ m
- d_z : $z_disp_ode * mesh_env$ m

Right Screenshot: Marangoni Effect

The **Marangoni Effect** module is configured with the following boundary selection and equation:

Label: Marangoni Effect

Name: me1

Boundary Selection: marangoni

Active: 11, 15, 19, 23, 27

Equation: Show equation assuming: Study 1, Time Dependent

$$\left[-p\mathbf{I} + \mu(\nabla\mathbf{u} + (\nabla\mathbf{u})^T) - \frac{2}{3}\mu(\nabla\cdot\mathbf{u})\mathbf{n} \right] \mathbf{n} = \gamma\nabla\sigma$$

Surface Tension: Surface tension coefficient type: Library coefficient, liquid/gas interface; Library surface tension coefficient: Water/Air

Coupled Interfaces: Fluid flow: Laminar Flow (spf); Heat transfer: Heat Transfer in Fluids (ht)

Rigid-body motion plus quaternion rotation -> integration

Inertia of the rigid-body can be included

Variables and Force-Integrations

The screenshot shows the COMSOL Multiphysics interface with three main windows: Model Builder, Settings, and Graphics.

Model Builder (Left): Shows the hierarchical structure of the model. Under 'Component 1 (comp1)', 'Definitions' includes 'Variables 1' and 'Integration 1 (thermal_fluids_forces)'. The 'Integration 1' node is expanded to show sub-nodes: 'cavity', 'swimmer', 'heat', 'marangoni', 'rigid_body', 'exterior', 'Boundary System 1 (sys1)', 'View 1', 'Geometry 1', 'Materials', 'Laminar Flow (spf)', 'Heat Transfer in Fluids (ht)', 'Global ODEs and DAEs (ge)', 'Moving Mesh (ale)', 'Multiphysics', 'Non-Isothermal Flow 1 (nitf1)', 'Marangoni Effect 1 (me1)', 'Temperature Coupling 1 (tc1)', and 'Flow Coupling 1 (fc1)'. Below these are 'Mesh 1', 'Study 1', 'Step 1: Time Dependent', 'Solver Configurations', and 'Solution 1 (sol1)'.

Settings (Middle): The 'Variables' tab is active for 'Integration 1 (thermal_fluids_forces)'. The 'Geometric Entity Selection' is set to 'Entire model'. A table lists the following variables:

Name	Expression	Unit
Fx	thermal_fluids_forces(-react(u))	m ²
Fy	thermal_fluids_forces(-react(v))	m ²
Fz	thermal_fluids_forces(-react(w))	m ²
T_z	thermal_fluids_forces(-x*react(v)+y*react(u))	m ³
T_x	thermal_fluids_forces(-y*react(w)+z*react(v))	m ³
T_y	thermal_fluids_forces(-z*react(u)+x*react(w))	m ³
u_rigid_ode	velx+omegay*Z-omegaz*Y	m
v_rigid_ode	vely+omegaz*X-omegax*Z	m
w_rigid_ode	velz+omegax*Y-omegay*X	m
dx_rot_ode	X*Rq11+Y*Rq12+Z*Rq13 -X	m
dy_rot_ode	X*Rq21+Y*Rq22+Z*Rq23 -Y	m
dz_rot_ode	X*Rq31+Y*Rq32+Z*Rq33 -Z	m
p2	v*v+u*u	m ²

Graphics (Right): Displays a 3D model of a rectangular block with a grid of small rectangular features on its top and side surfaces. A coordinate system (x, y, z) is visible in the bottom-left corner.

Coupling between modules are handled via boundary conditions and Multiphysics.

Marangoni Swimmer: Overview of the Numerical Setup

Component 1 (comp1) | Pi | a= | f(x) |

Definitions | Geometry | Materials | Physics | Mesh | Study | Results

Model Builder

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 - Marangoni Effect 1 (me1)**
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 - Flow Coupling 1 (fc1)
 - Mesh 1
 - Study 1
 - Results

Settings

Marangoni Effect

Label: Marangoni Effect 1

Name: me1

Boundary Selection

Selection: marangoni

ON	11
	15
	19
	23
	27

Equation

Show equation assuming: Study 1, Time Dependent

$$\left[-p\mathbf{I} + \mu \left(\nabla \mathbf{u} + (\nabla \mathbf{u})^T \right) - \frac{2}{3} \mu (\nabla \cdot \mathbf{u}) \mathbf{I} \right] \mathbf{n} = \gamma \nabla T$$

Surface Tension

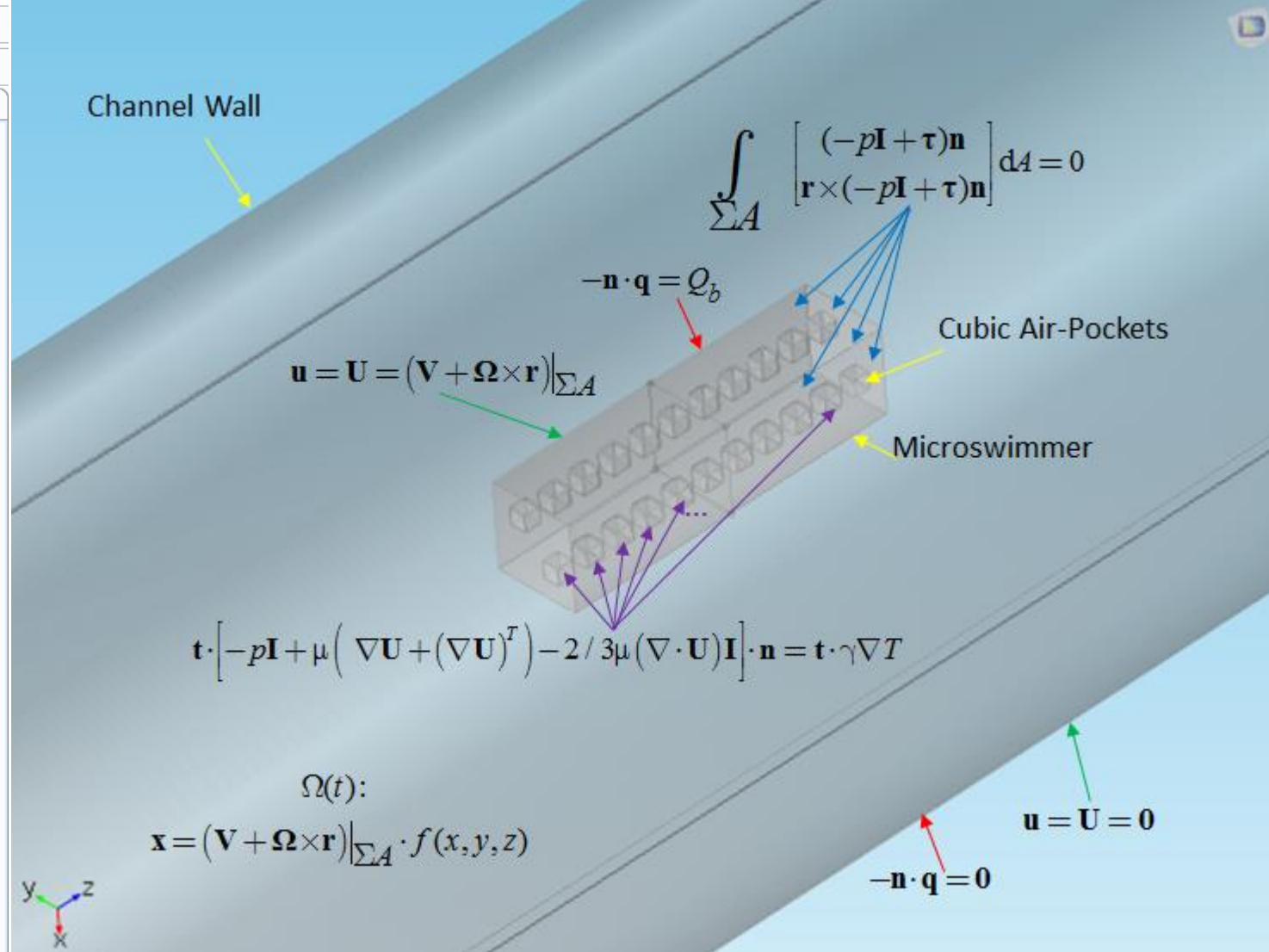
Surface tension coefficient type: Library coefficient, liquid/gas interface

Library surface tension coefficient: Water/Air

Coupled Interfaces

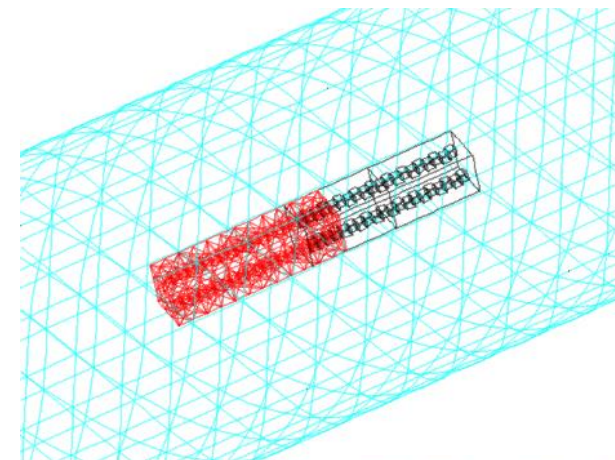
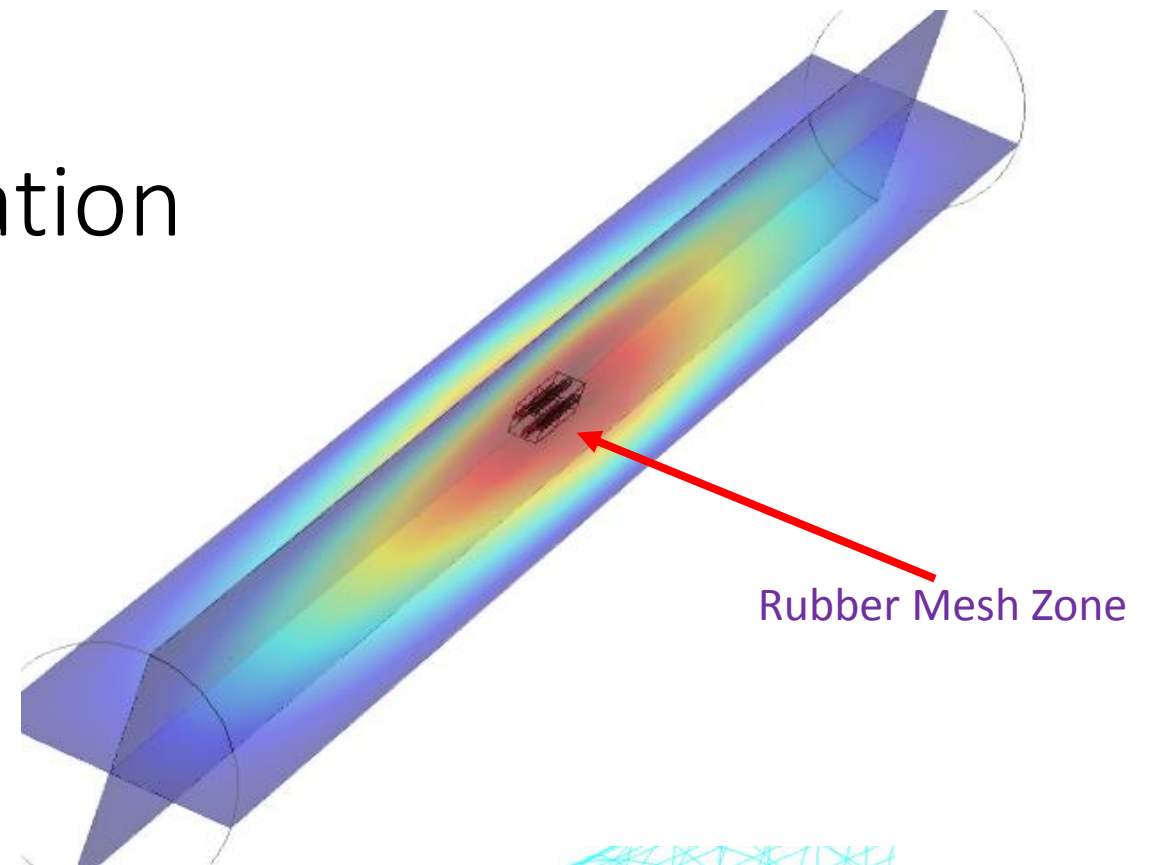
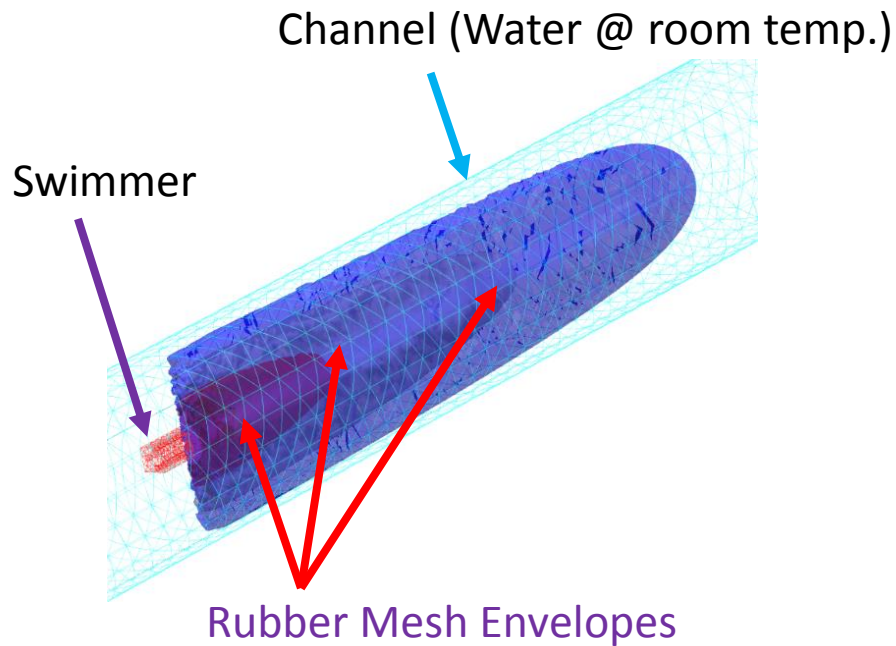
Fluid flow: Laminar Flow (spf)

Heat transfer: Heat Transfer in Fluids (ht)



Handling Mesh Deformation

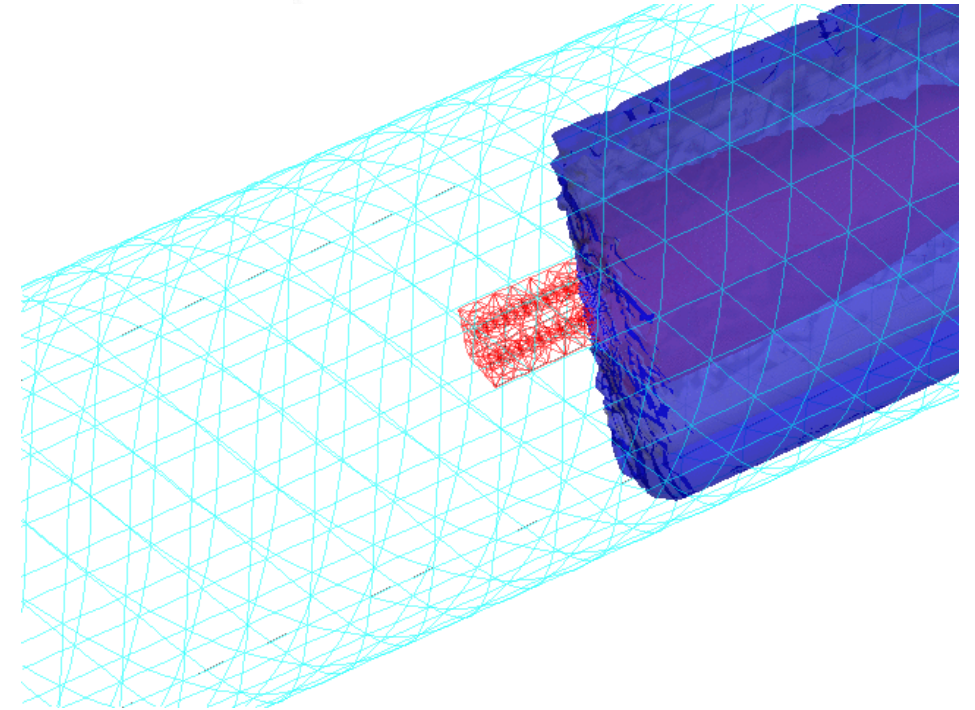
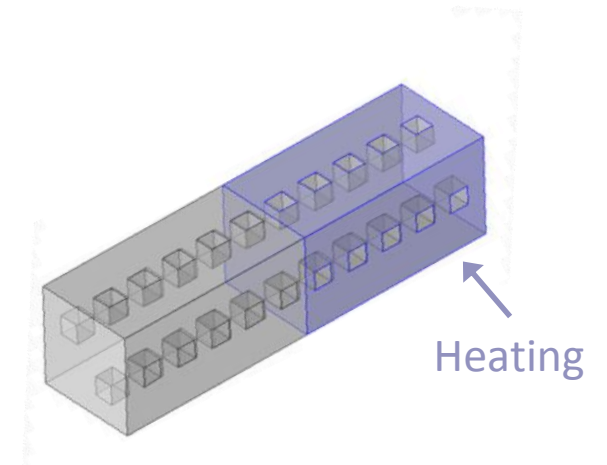
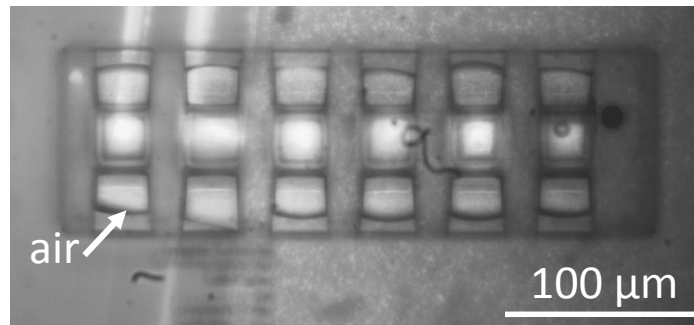
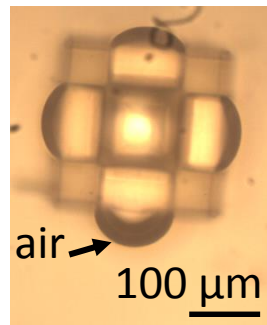
Mesh Deformation
(time-dependent ALE)



Rubber Mesh Ref: **Tabak, A.F.**, Simulation based experiments of travelling-plane-wave-actuator micropumps and microswimmers, MSc Thesis submitted to Faculty of Engineering and Natural Sciences, Sabanci University, Istanbul, 2007.

Microswimmer: Simulations

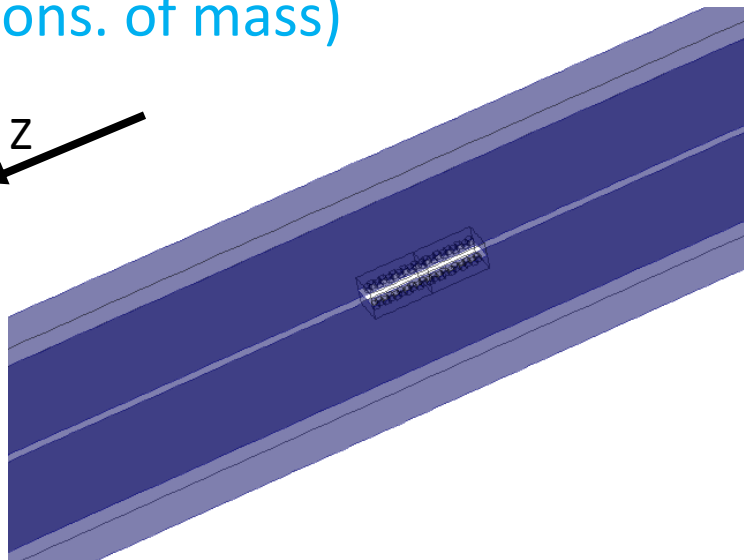
- Mimicked geometry that can be produced by two photon polymerization
 - 100 μm long, 25 μm wide, 10 μm cavities
- Use 30 μW of heating
 - Similar to measured hysteresis loss of 100nm-thick Ni film
- Swimmer propels at 1 body length s^{-1}



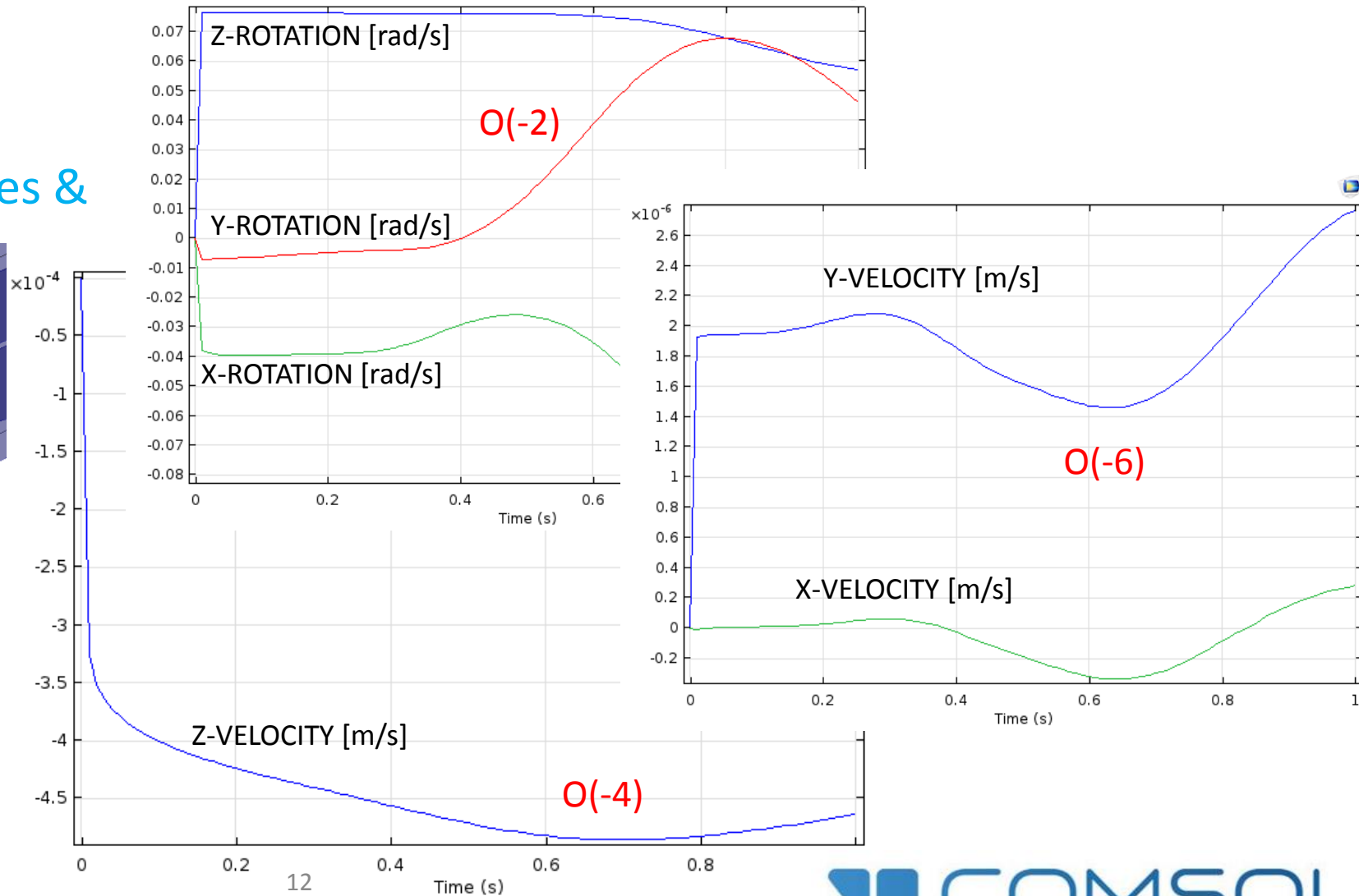
stationary: channel; moving: swimmer $\Delta t = 1 \text{ s}$

Marangoni Effect Swimming: Case Study

Flow Field
(time-dependent Navier-Stokes &
cons. of mass)

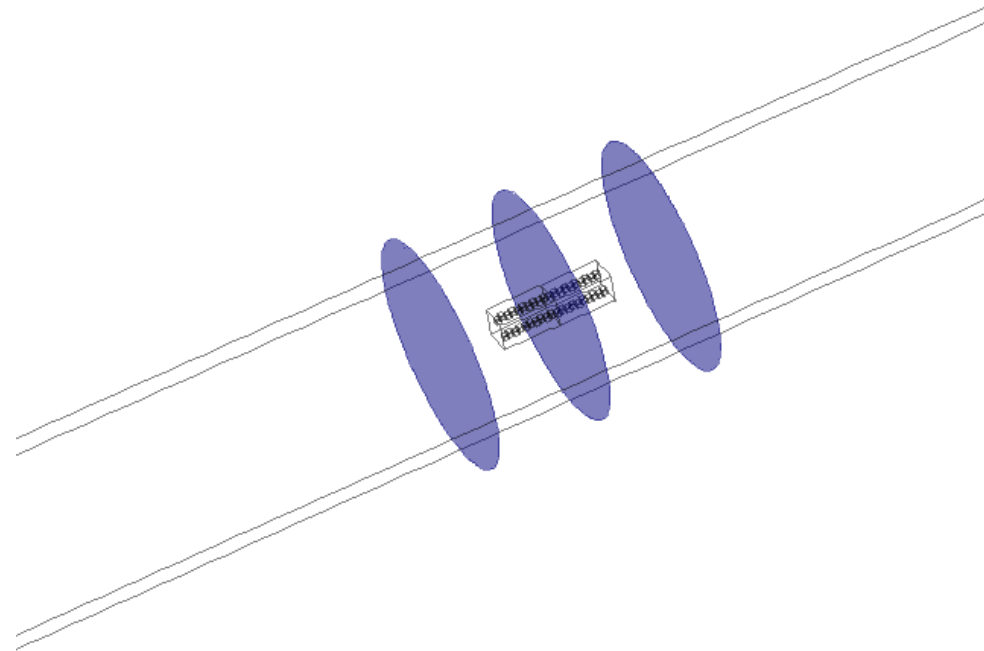
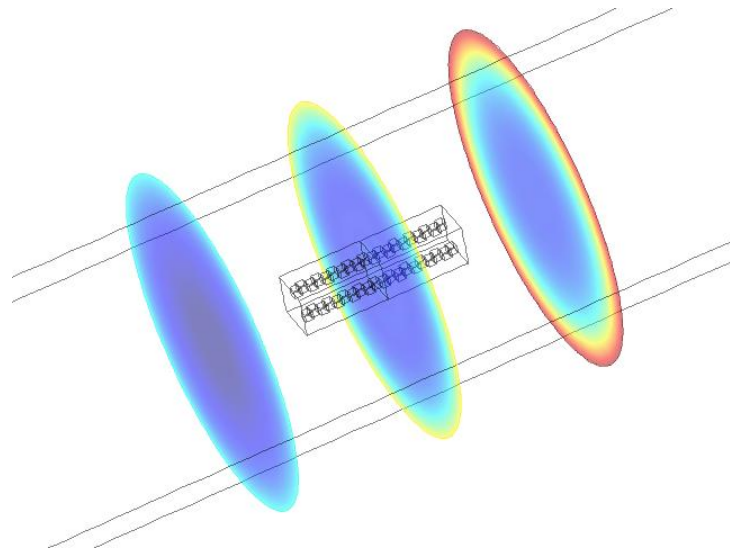


$Re_{max} \sim 0.5$!!!



Temperature Profile (at the trailing edge)

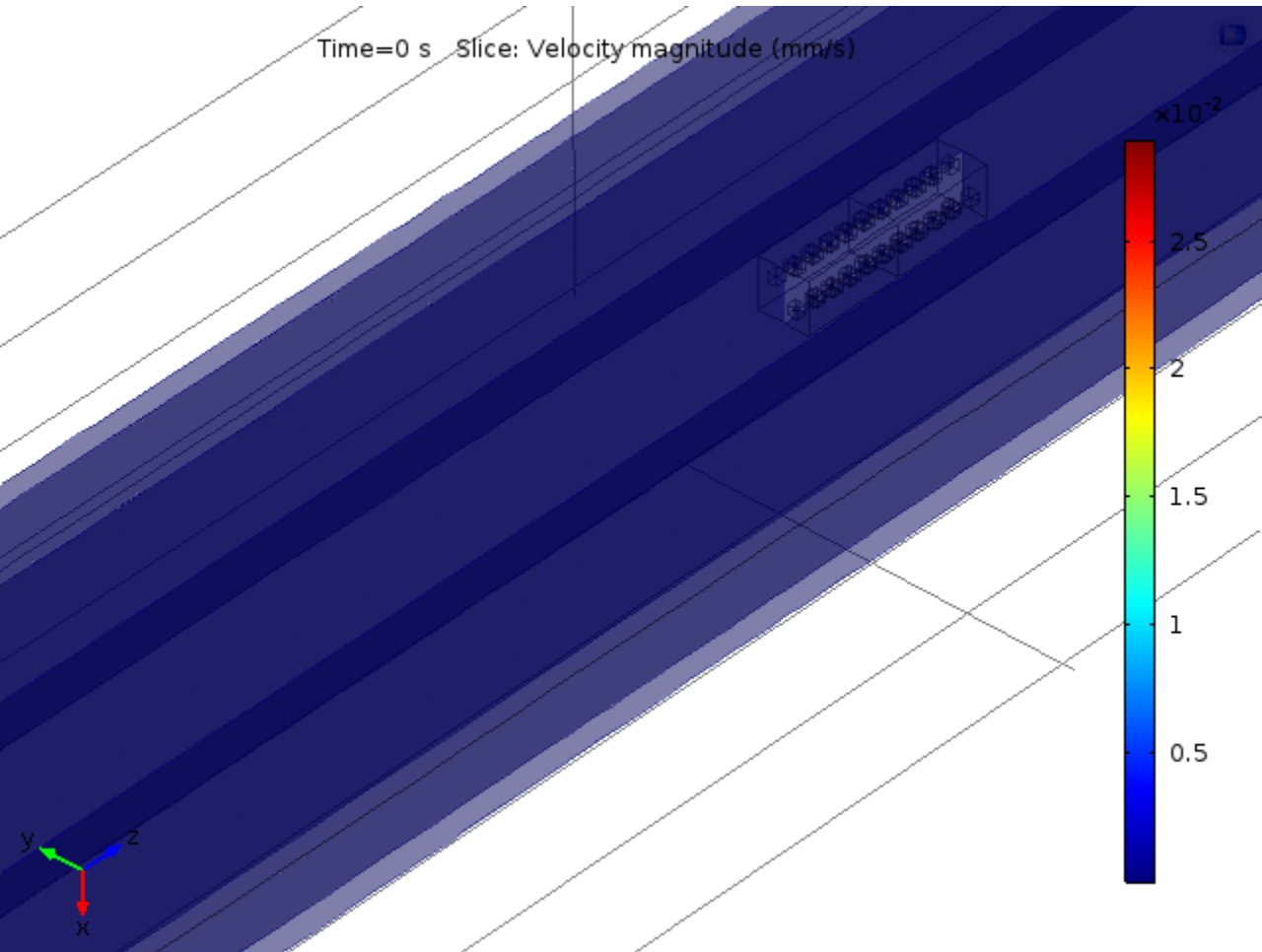
Temperature Profile
(time-dependent Cons. of Energy)



3 layers with moving mesh
 $0 [s] \leq t \leq 1 [s]$

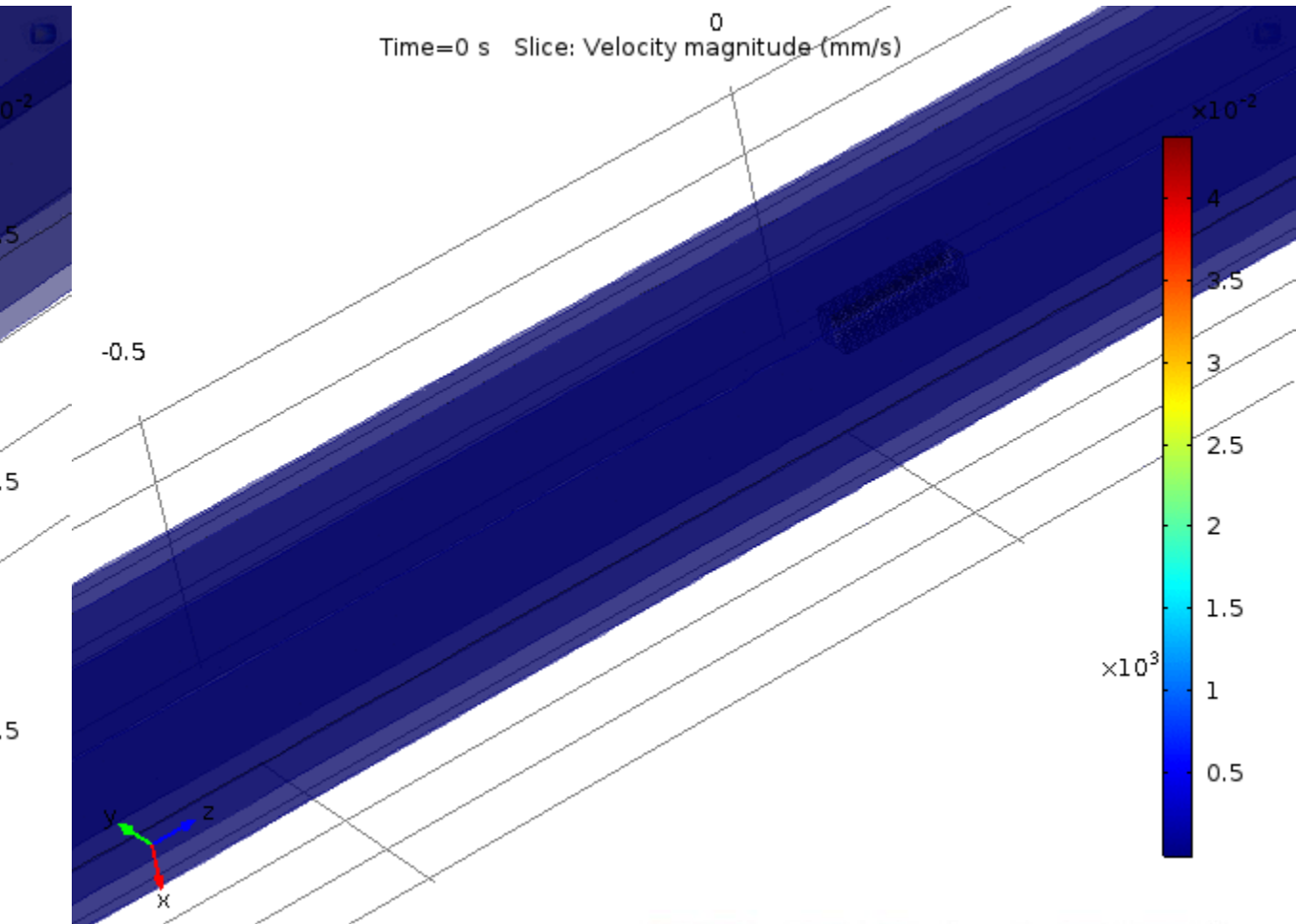
Simulation Results: Rectangle Swimmer

Rectangle, Janus ~ 4 body lengths per second



10/14/2016

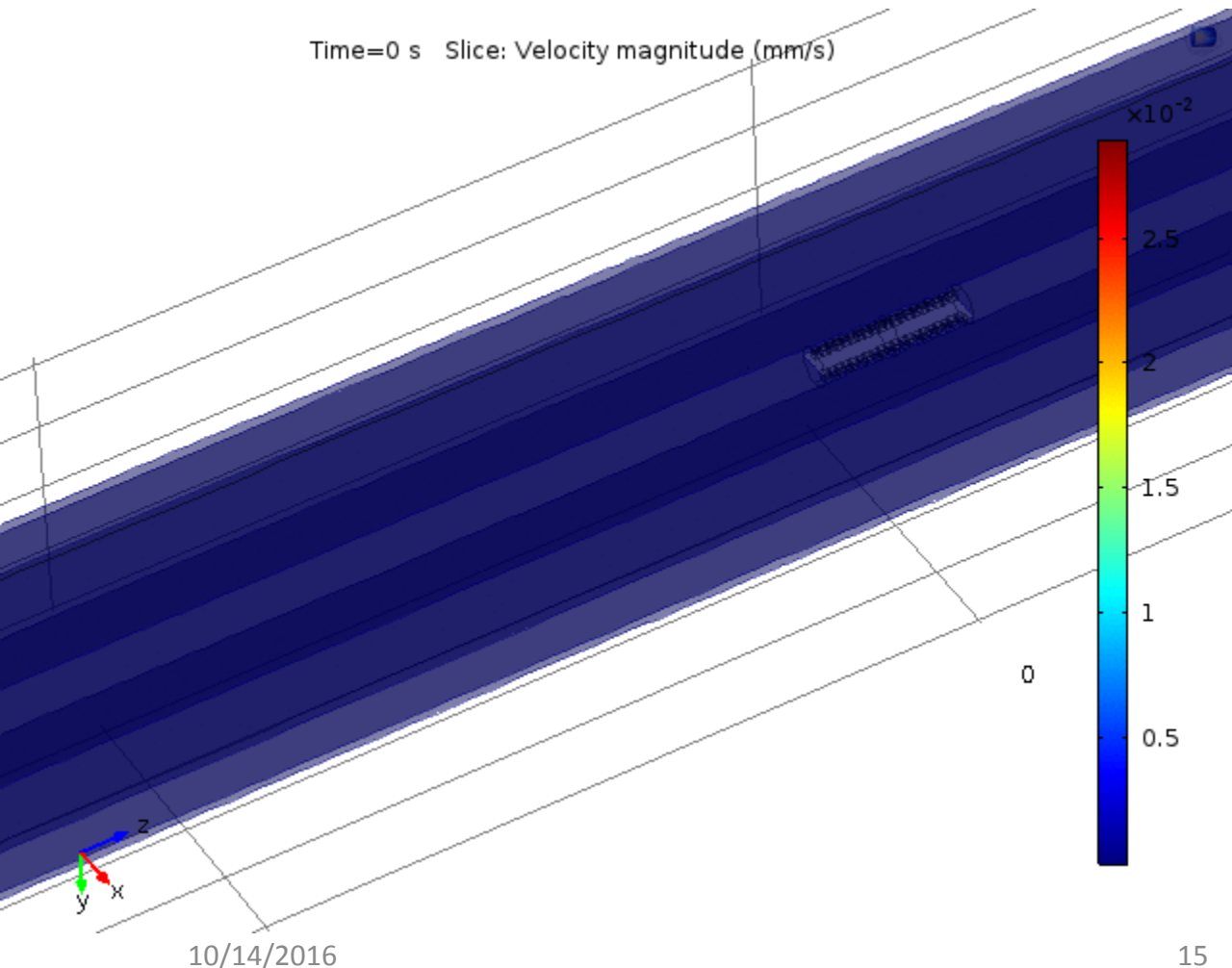
Rectangle, Striped ~ 4.5 body lengths per second



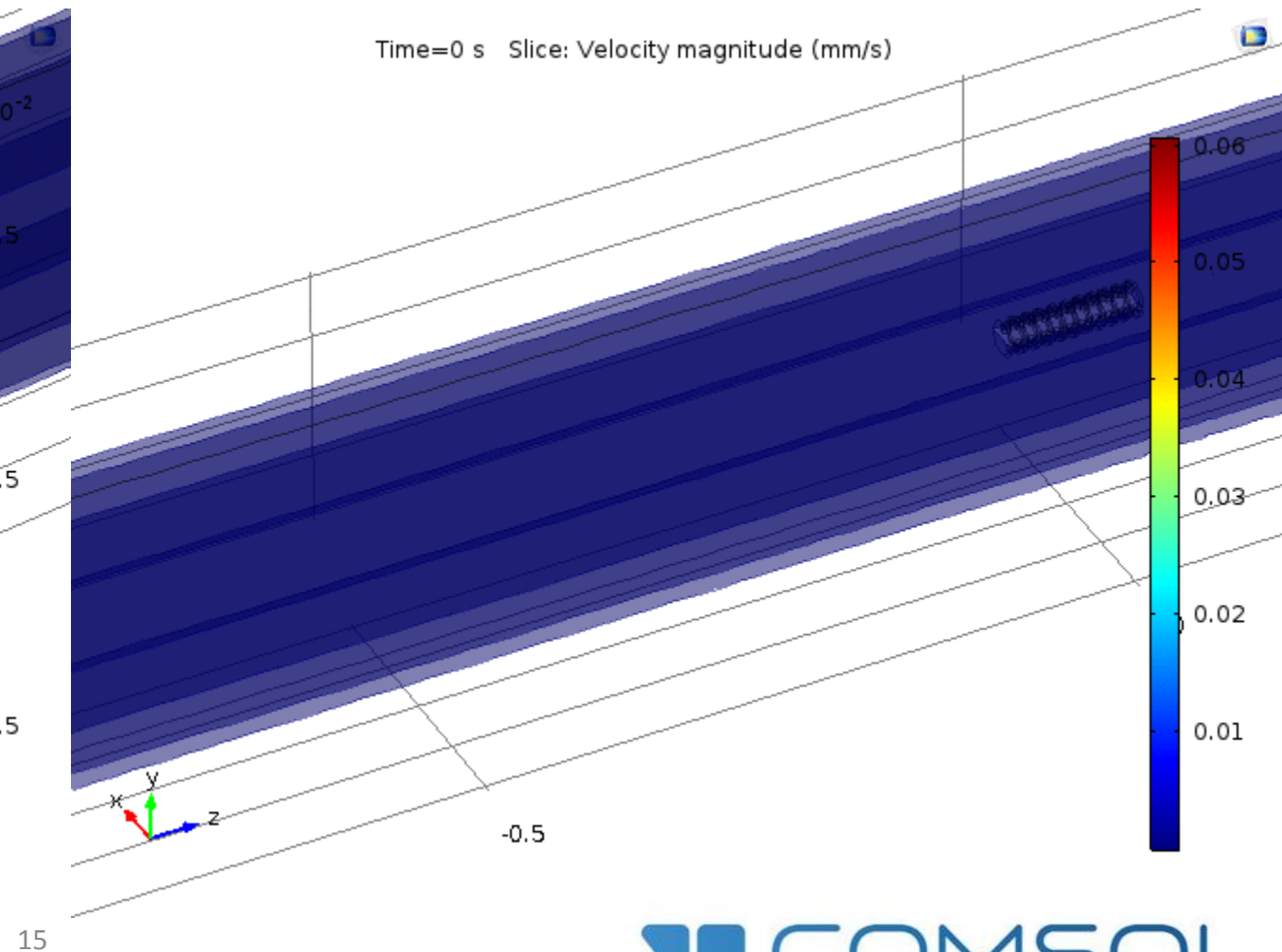
14

Simulation Results: Cylinder Swimmer

Cylinder, Janus ~ 4.5 body lengths per second

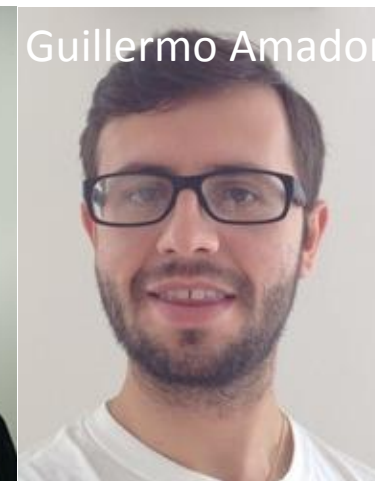
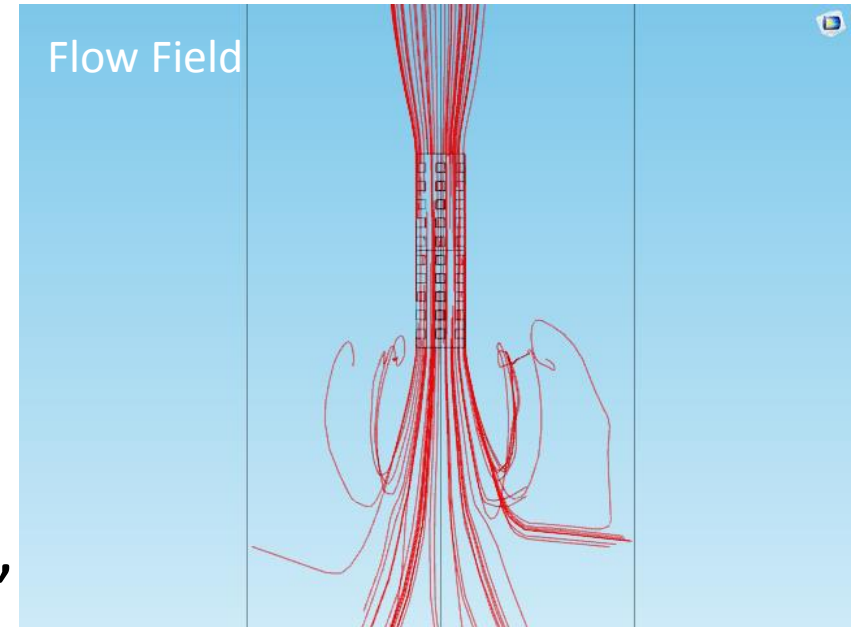


Cylinder, Striped ~ 6 body lengths per second



Conclusions and outlook

- Achieved the simulation of rigid-body motion with respect to given heat input,
- Local Marangoni-effect-based flow fields add up to a global flow field,
- Net-thrust is obtained by Marangoni-effect,
- N-S is more suitable to govern the flow field.



Q/A



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