

ME 651: Fluid Dynamics

Autumn 2014

Rajneesh Bhardwaj
Department of Mechanical Engineering
IIT Bombay

Timings and Venue

- *Timings*: SLOT 13, Mondays and Thursdays, 6:30 to 7:55 pm;
- *Venue*: CDEEP, A1A2 classroom, Mathematics building

Instructor and TAs

Instructor:

- Rajneesh Bhardwaj (rajneesh.bhardwaj0@gmail.com)
- Room 302, Pre Engg bldg (Near thermal hydraulics bldg)

Teaching Assistants:

- Atul Soti and Hemanshul Garg
- Room 103, Mechanical Engineering building
Emails: atulsoti@gmail.com, hemanshul.garg@gmail.com
- Mobile phones: [9167481612](tel:9167481612) and [9967308385](tel:9967308385)

Grading Policy

- Attendance: 5%
- Quizzes: 25%
- Mid Semester Exam: 25%
- End Semester Exam: 35%

Course outline

- Introduction: Review of vector calculus, Cartesian tensor notation.
- Kinematics of Fluid Flow: Description of fluid motion: Eulerian and Lagrangian approaches; Pathlines, Streaklines, Streamlines; Kinematic decomposition of velocity field.
- Fundamental Governing Equations: Conservation equations in differential and integral forms; Stresses in fluid; Rates of deformation and development of the constitutive equations of Fluid Dynamics (Stokes' relations); The Navier-Stokes (N-S) Equations; Special forms of the N-S equations; Initial and Boundary conditions; Differential form of Thermal and Mechanical energy equations; Introduction to non-dimensionalization and scaling; Non-dimensional numbers of interest in incompressible flow; Classification of incompressible flow on the basis of Reynolds number.

Course outline

- Laminar Flow: Creeping flow (Stokes' solution for flow past sphere, Hele-Shaw flow); Exact solutions to the incompressible N-S equations (e.g. Couette and Poiseuille flows, Flow between rotating cylinders, Stokes' First and Second problems, Stagnation point flow, Flow over a porous wall, etc.).
- Potential Flow: High Reynolds number approximation - inviscid flow; Circulation and Vorticity; Kelvin's theorem; Irrotationality; Simple Potential Flows; Superposition; Technique of Images; Introduction to the use of complex variables for plane Potential Flows; Introduction to lifting surfaces.
- Vortex Dynamics: Helmholtz theorems; Vorticity transport equation; Potential and Rankine vortex; Interaction of vortices.

Course outline

- Laminar Boundary Layers: Concept of a boundary layer in High Reynolds number flow; Scale analysis and development of Prandtl's boundary layer equations; Blasius' solution to flat plate; Boundary layer with pressure gradient (Falkner-Skan solutions); von-Karman-Pohlhausen integral analysis method; Boundary layer separation and control.
- (If time permits) Introduction to Turbulent Flow: Introduction to instability and transition; Origin of turbulence - role of vorticity and viscosity; Statistical description; Reynolds' averaging of N-S equations; Reynolds' stresses; Kinetic energy budget in turbulent flow; Wall turbulence: eddy diffusivity, Prandtl's mixing length hypothesis, von-Karman's stability hypothesis; Universal velocity profile.
- (If time permits) Introduction to Compressible Flow: A brief review of concepts from thermodynamics; Acoustic waves; Normal shock waves; Basic one-dimensional compressible flow in a duct with varying cross-sectional area; One-dimensional compressible flow with friction and heat transfer.

References

- Muralidhar K. and Biswas G., Advanced Engineering Fluid Dynamics, Narosa, 2004.
- Som S K, Biswas G and Chakraborty S, Introduction to Fluid Mechanics and Fluid Machines, Tata Mc-Graw Hill, 3rd ed, 2012
- Kundu P.K. and Cohen I.M., Fluid Mechanics, Elsevier, 2002.
- G. K. Batchelor, An Introduction to Fluid Dynamics, Cambridge (Indian Edition).
- R. W. Fox, P. J. Pritchard and A. T. McDonald, Introduction to Fluid Mechanics, Wiley India, 2010.
- Currie I.G., Fundamental Mechanics of Fluids, Marcel Dekker, 2002.
- F. M. White, Viscous Fluid Flow, Tata McGraw Hill, 2011.
- M. C. Potter, D. C. Wiggert, Mechanics of Fluids, Cengage Learning (Indian Edition), 2012.

Policy towards attendance

- According to institute rules, 80% attendance is mandatory to earn credit in this course:
- (<http://www.iitb.ac.in/academic/rules/summarymainpage.jsp>):
- "In case of poor attendance, kindly inform the faculty advisor and head of department, and warn the students about the attendance rules of the Institute (For attendance less than 80%, the student will be awarded "XX" grade)."
- No exceptions will be granted and any requests to consider reduced attendance for rare situations (medical emergency etc) will be forwarded to Dean (Acad) for consideration. Attendance rolls will be circulated in the class for signatures and proxy attendance cases will be dealt strictly.

Policy towards cheating

- Cheating is one of the most serious offence that you can commit at an academic institution. An act of cheating for this course includes:
 - Permitting any other student (s) to copy any part of your answer sheet
 - Copying off someone else's answer sheet, texting on a cellphone for answers and bringing in cheat sheets in examination hall.
- If found on one or all of theses counts, the student will be academically penalised according to institute rules. This could also result in 'F' (fail grade) in the course.

- **Information exchange**
- I will use email for broadcasting information and releasing solutions of exams. Students should add ME651 in the subject line while contacting me via email. This is for filtering of email messages.

- **Policy for latecomers**
- Latecomers will NOT be allowed after 6:45 pm. **Note that lecture will start promptly on 6:30 pm. Please make sure that you do not obstruct the view of the camera used for recording lectures while entering in class late.**

Tentative schedule of lectures and exams

- Four quizzes
- 1 Mid Semester exam
- 1 End Semester exam

Fluid dynamics: Applications in several disciplines

What is a fluid?

- Liquid or gas
- Can not resist even tiny shear force
- No static equilibrium with shear force loading
- Fluid statics vs Fluid dynamics

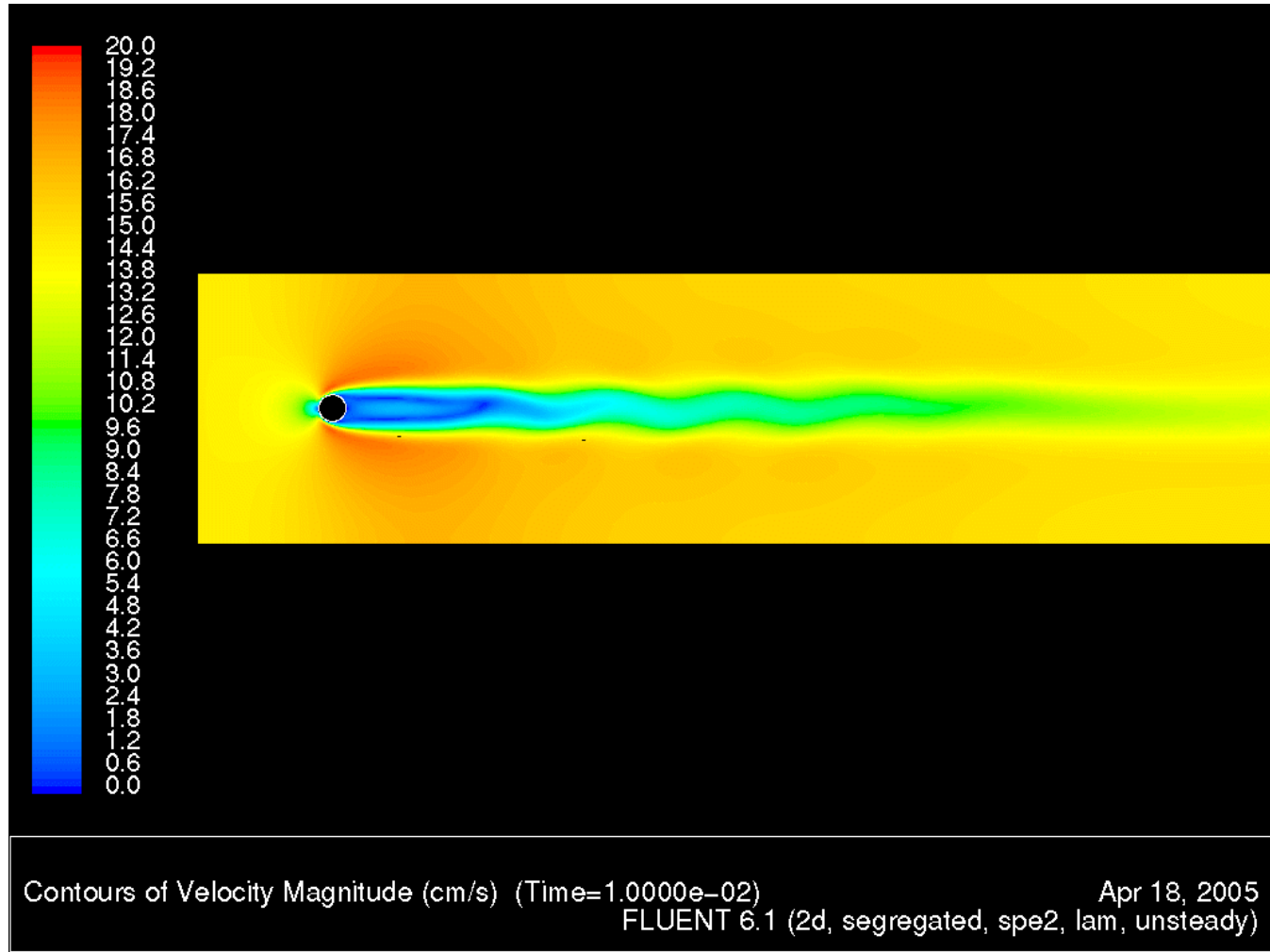
Flow past a circular cylinder

- *de facto* standard for benchmarking CFD codes
- Chimneys, designing poles/wires, pipes in ocean etc

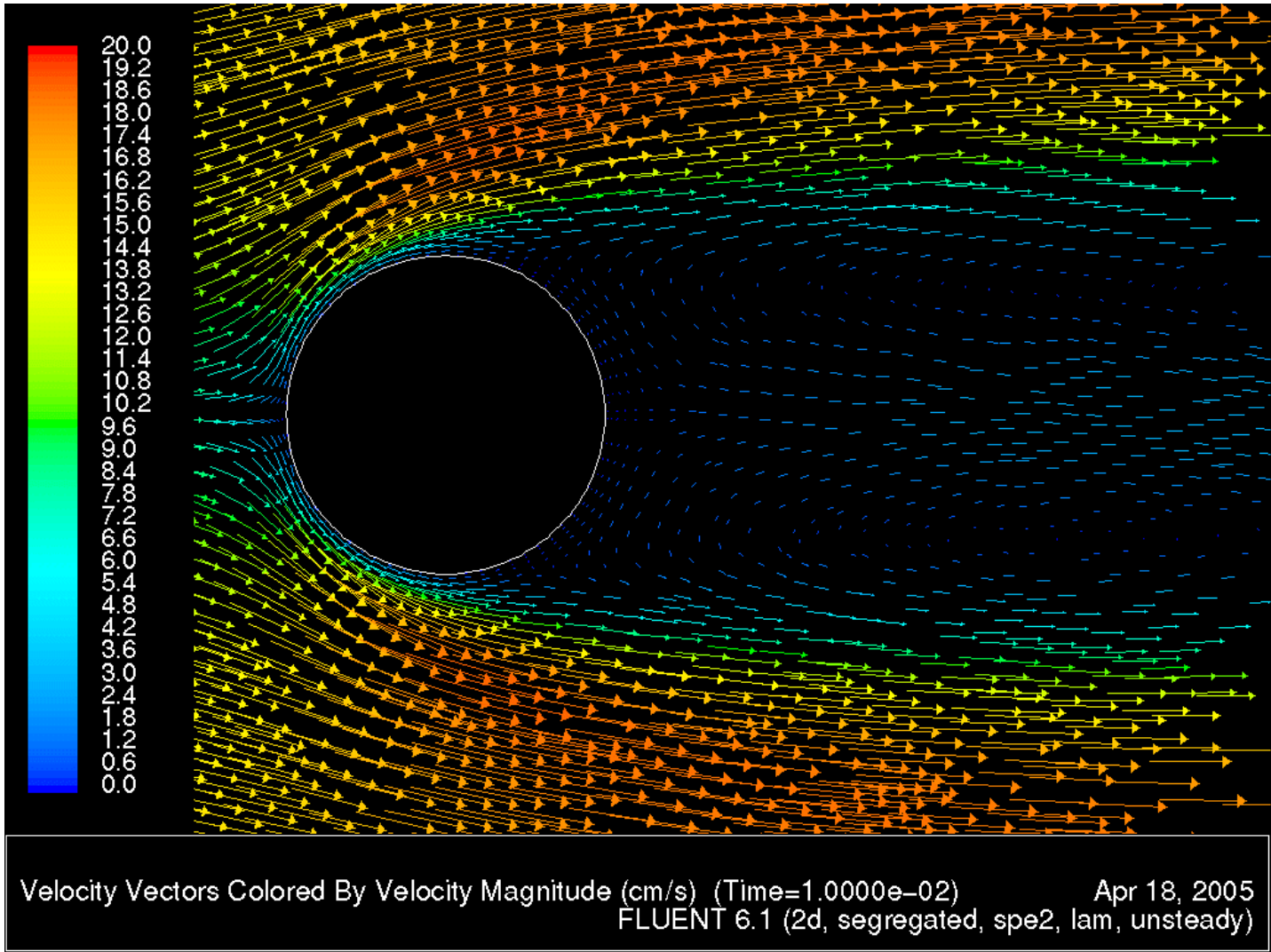
Wave energy converter in ocean
dcml.pratt.duke.edu/fsi.shtml



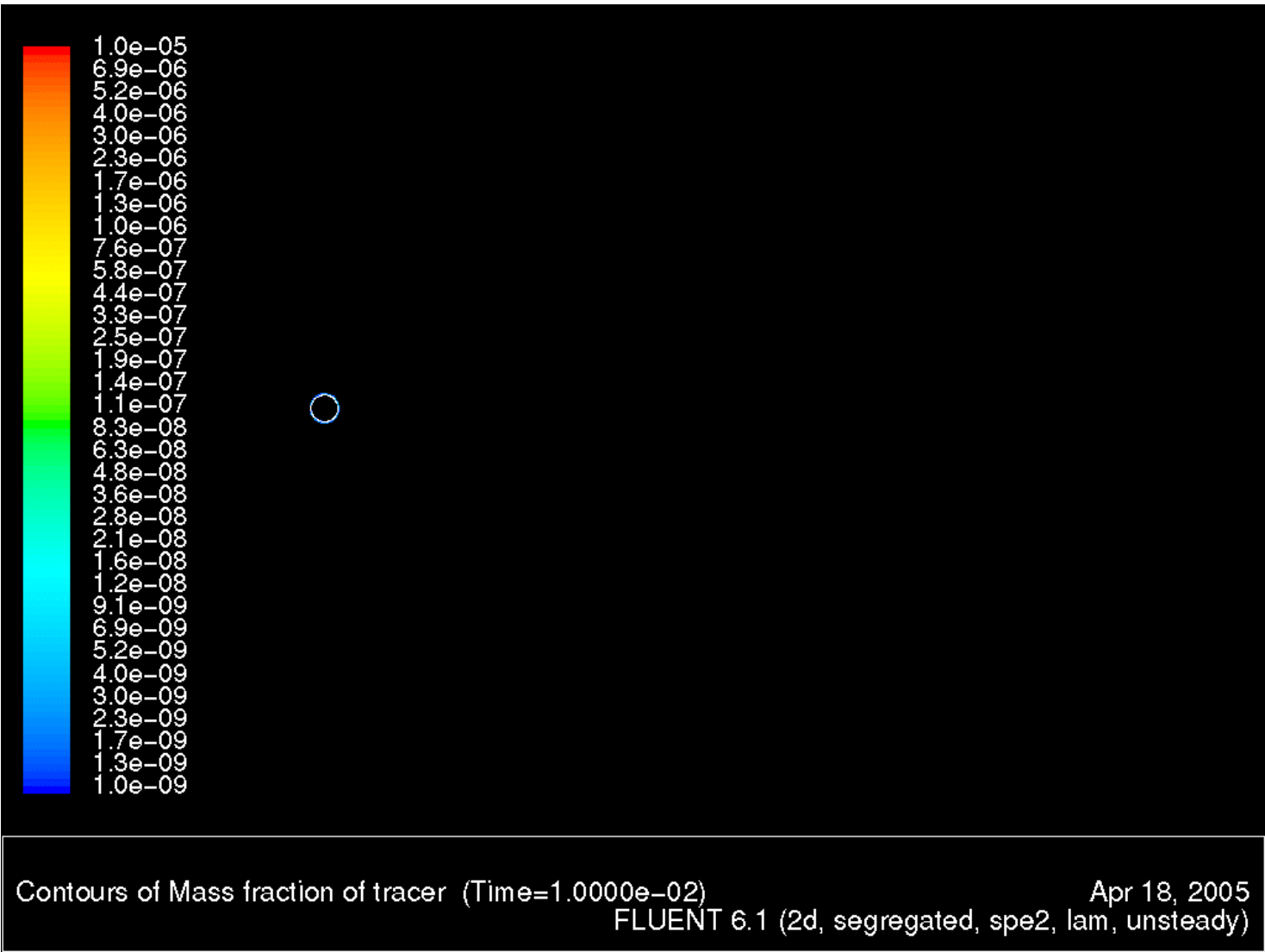
Re = 100



Courtesy: Prof E Panides, Columbia University

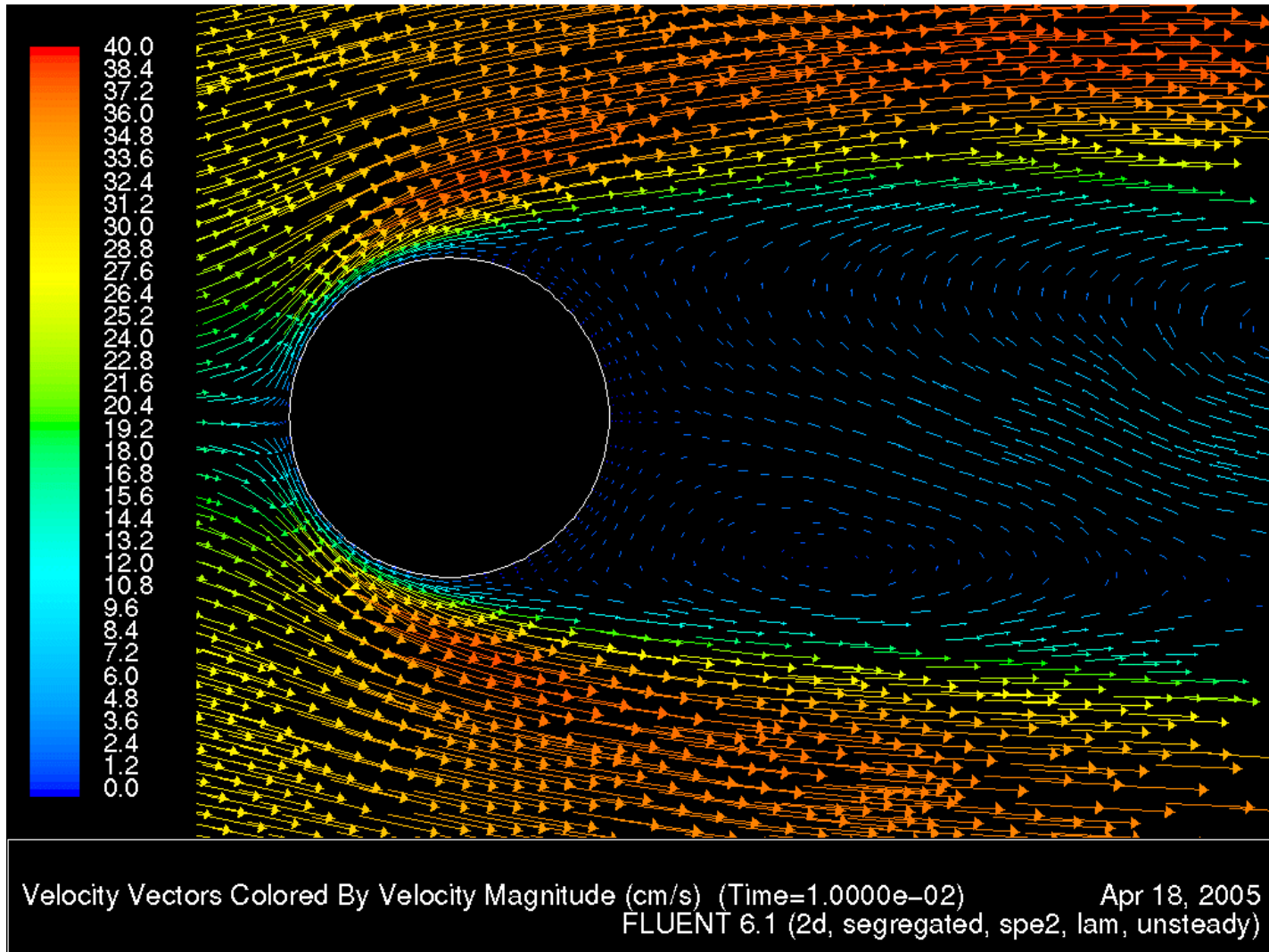


Courtesy: Prof E Panides, Columbia University



Courtesy: Prof E Panides, Columbia University

Re = 200



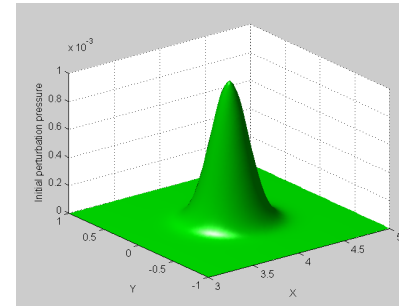
Courtesy: Prof E Panides, Columbia University

Compressible flows

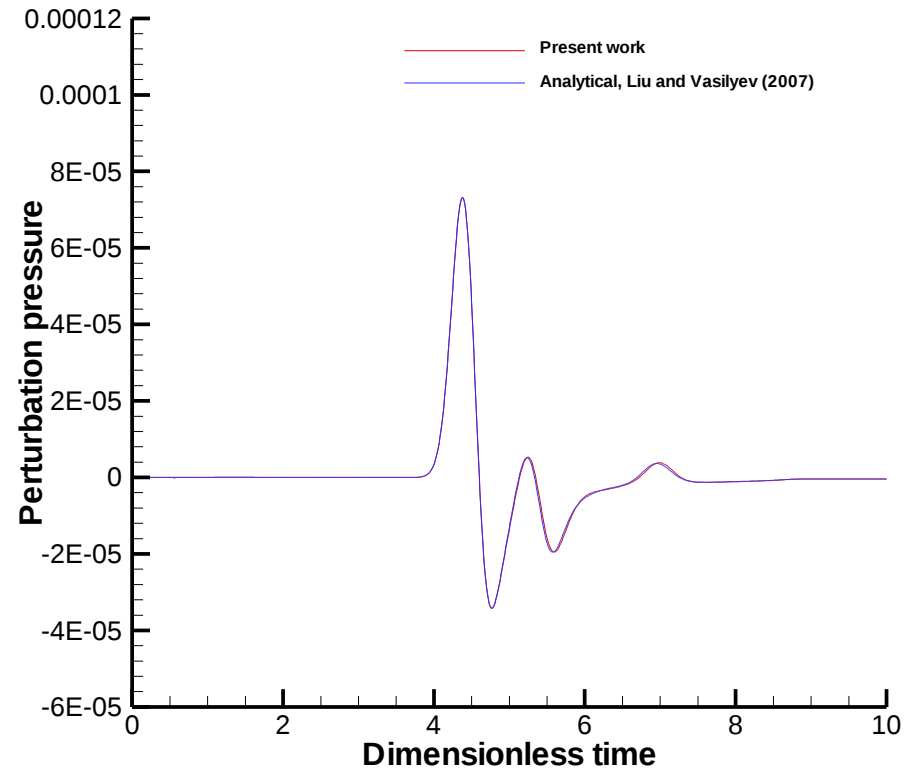
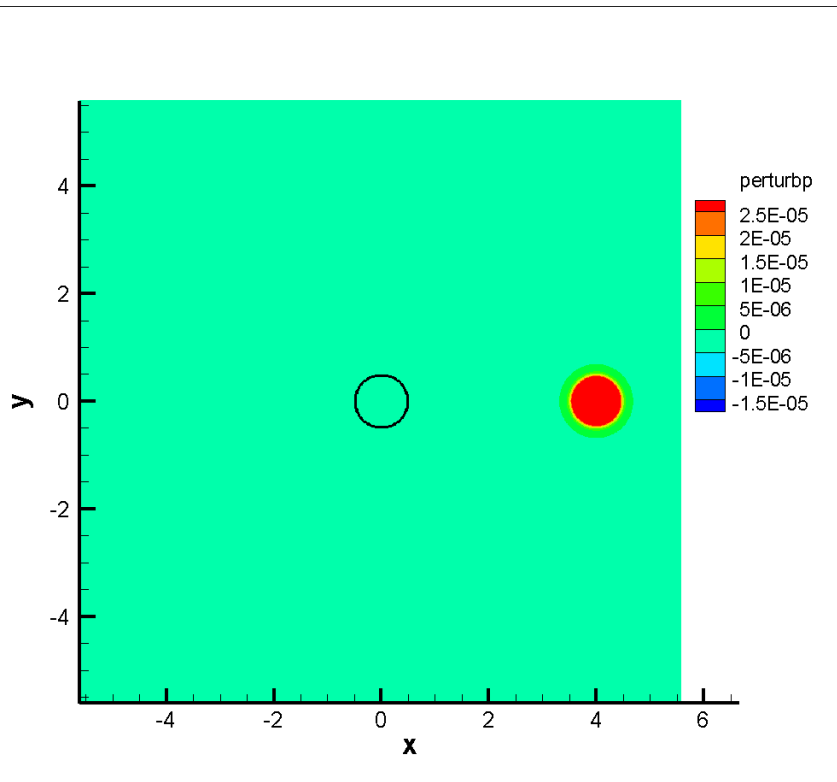
Compressible flows



Pressure perturbation at $t = 0$



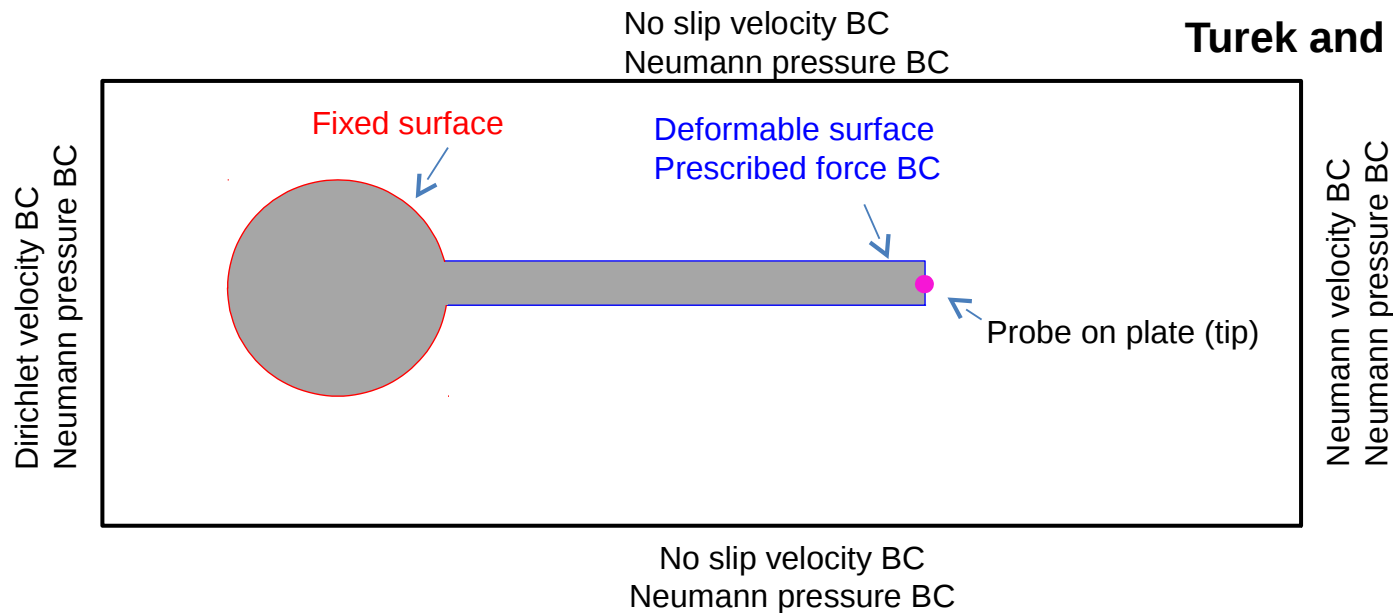
Perturbation pressure at Probe A



Fluid-structure interaction

FSI Benchmark: Flow past an elastic plate mounted on a stationary cylinder

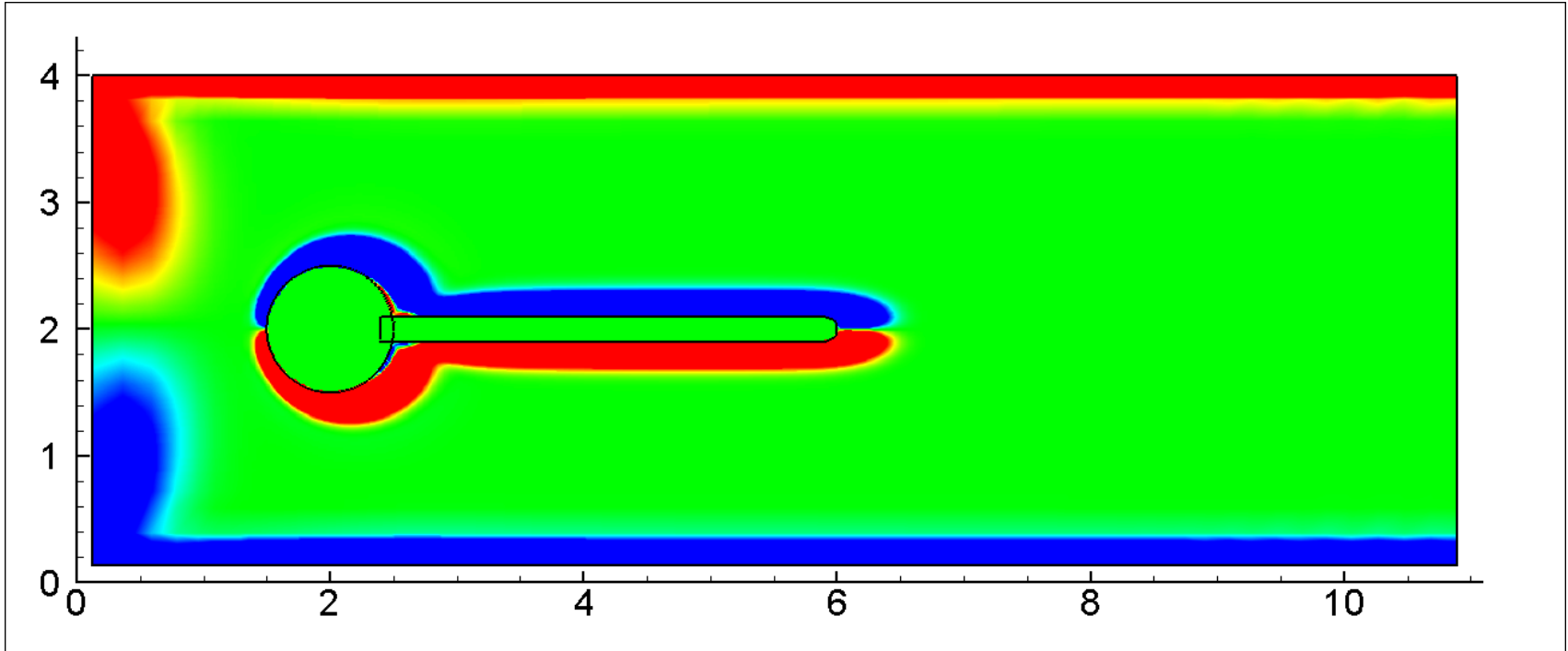
Turek and Hron, 2006



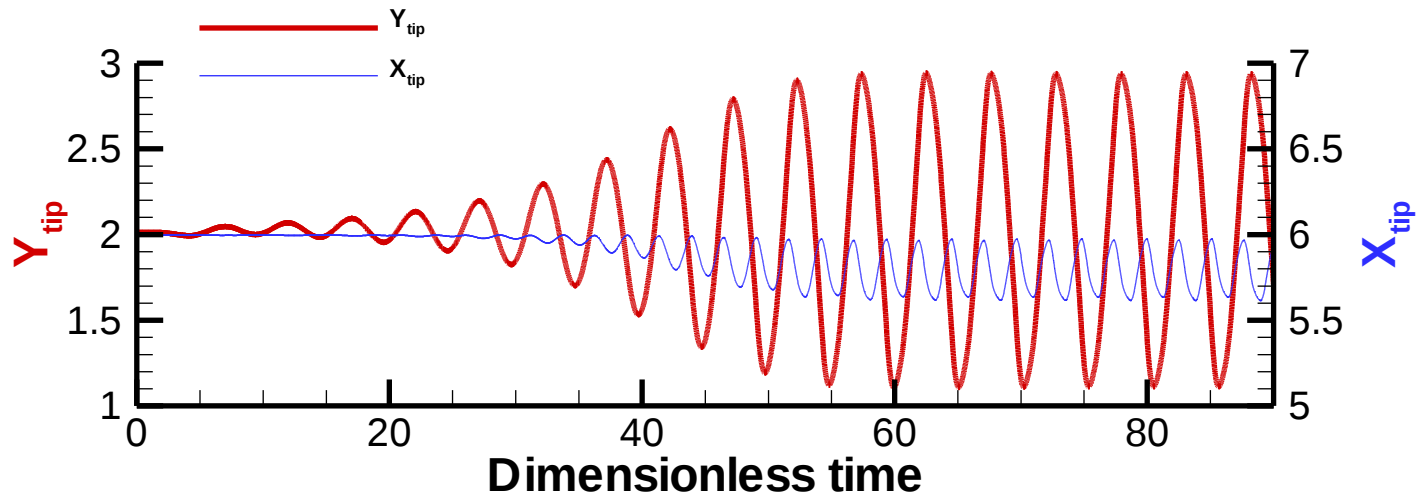
- Cylinder is rigid while plate deforms by fluid dynamic forces
- $Re = 100$ based on cylinder diameter $D = 1$ and mean velocity at left boundary
- $\rho_s/\rho_f = 10$
- Young Modulus = 1.4 MPa
- Linear elastic model
- Geometric non-linearity is taken into account

Vorticity field

Bhardwaj and Mittal, 2011



Dynamics of the elastic plate



Interfacial flows

Fluid dynamics in presence of the following interface(s):

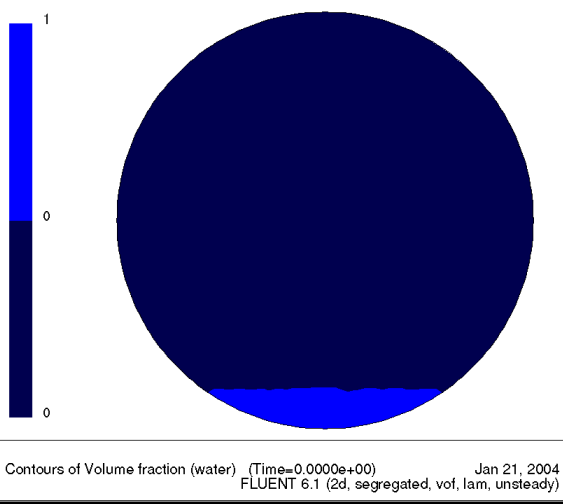
- Liquid-gas
- Liquid-liquid
- Liquid-solid
- Liquid-solid-gas



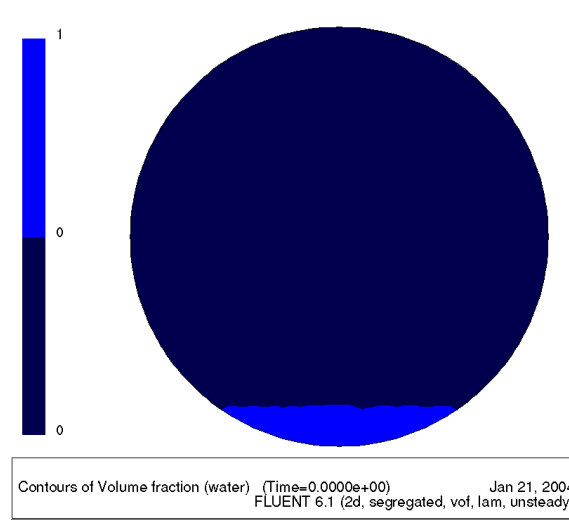
A bug on water surface

Flow in a rotating cylinder partially filled
with oil

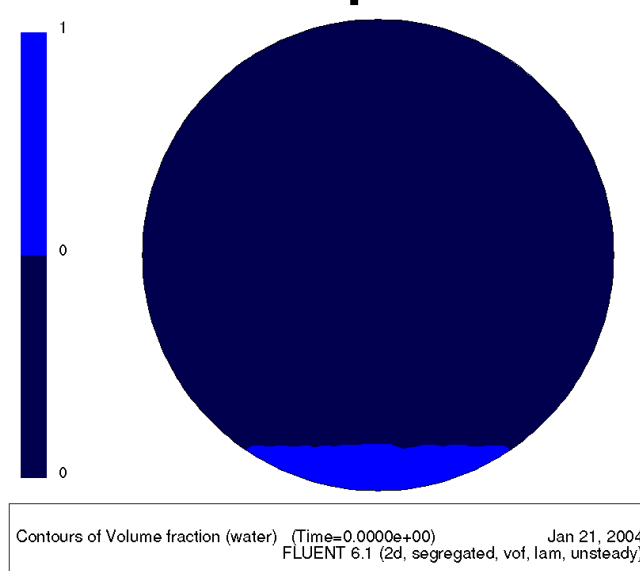
100 rpm



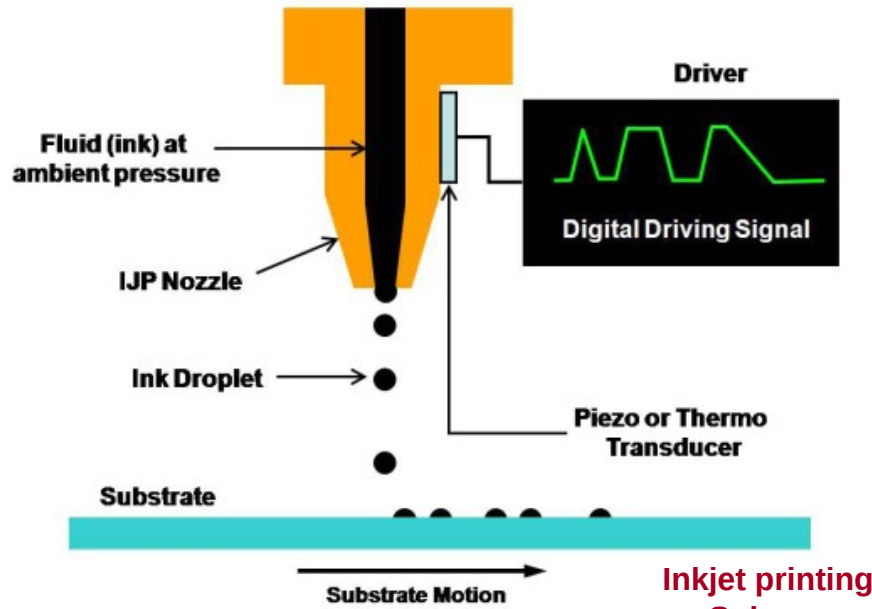
300 rpm



600 rpm



Inkjet printing

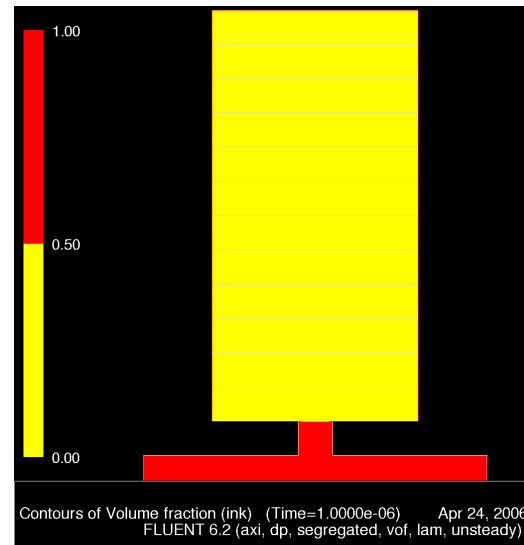
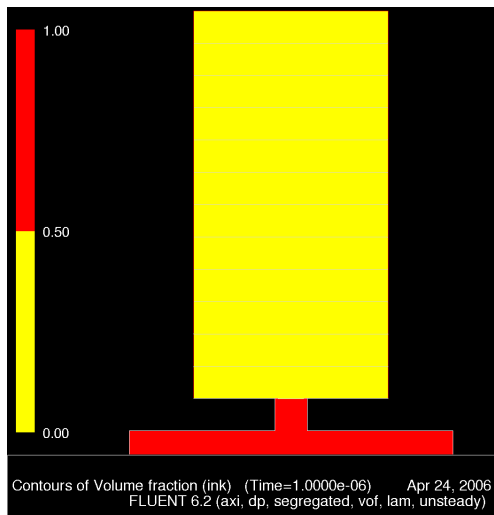


Inkjet printing
Spie.org



Droplet dispensing

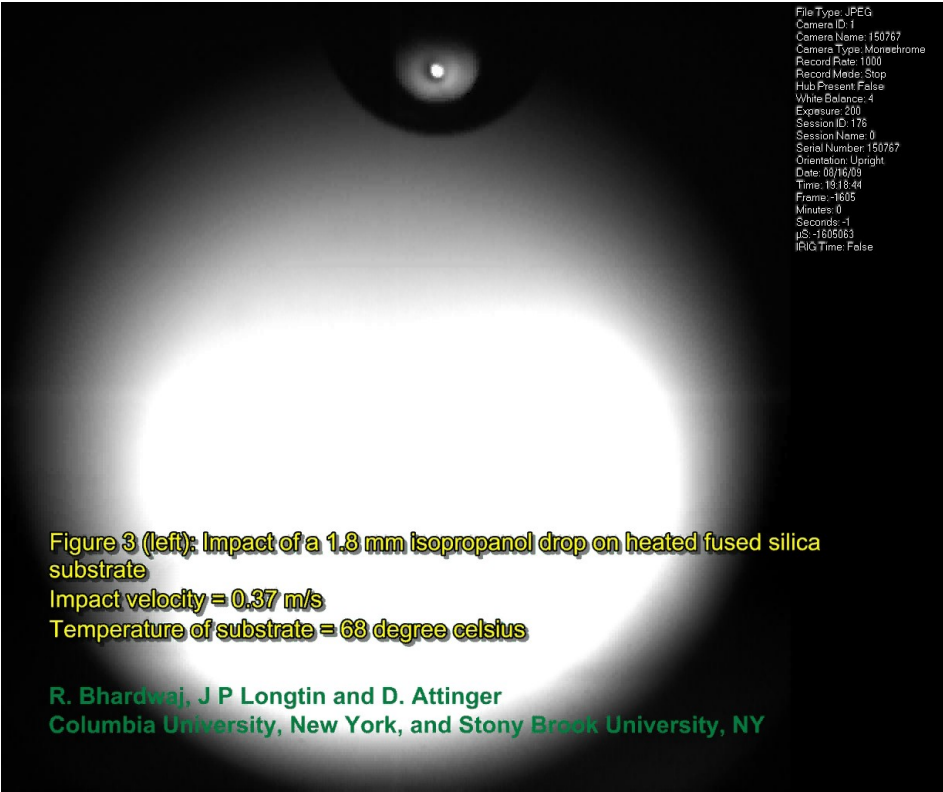
Xiong et al 1998



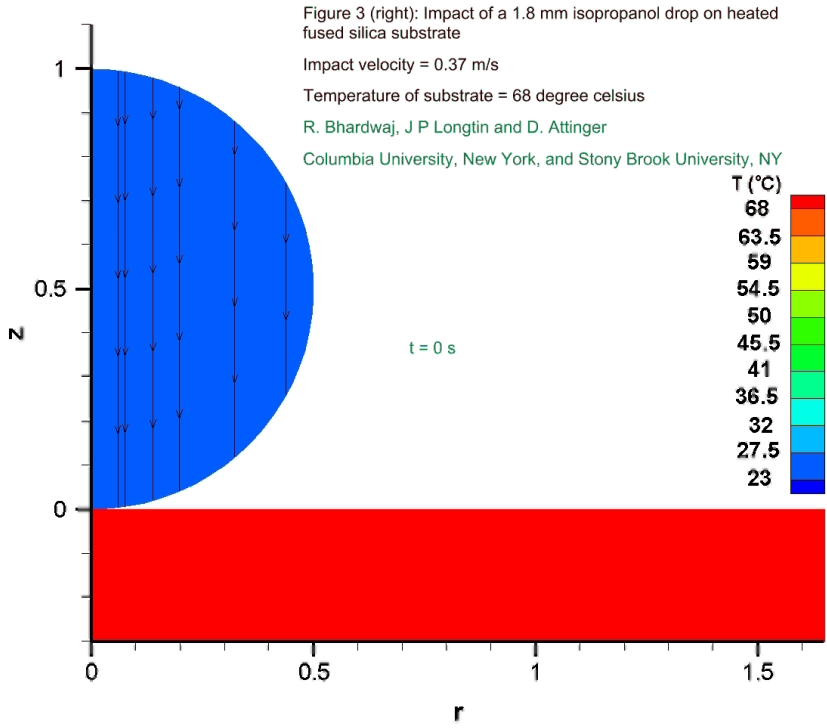
Courtesy:
Prof E
Panides,
Columbia
University

Droplet impact on a solid surface

High speed visualization

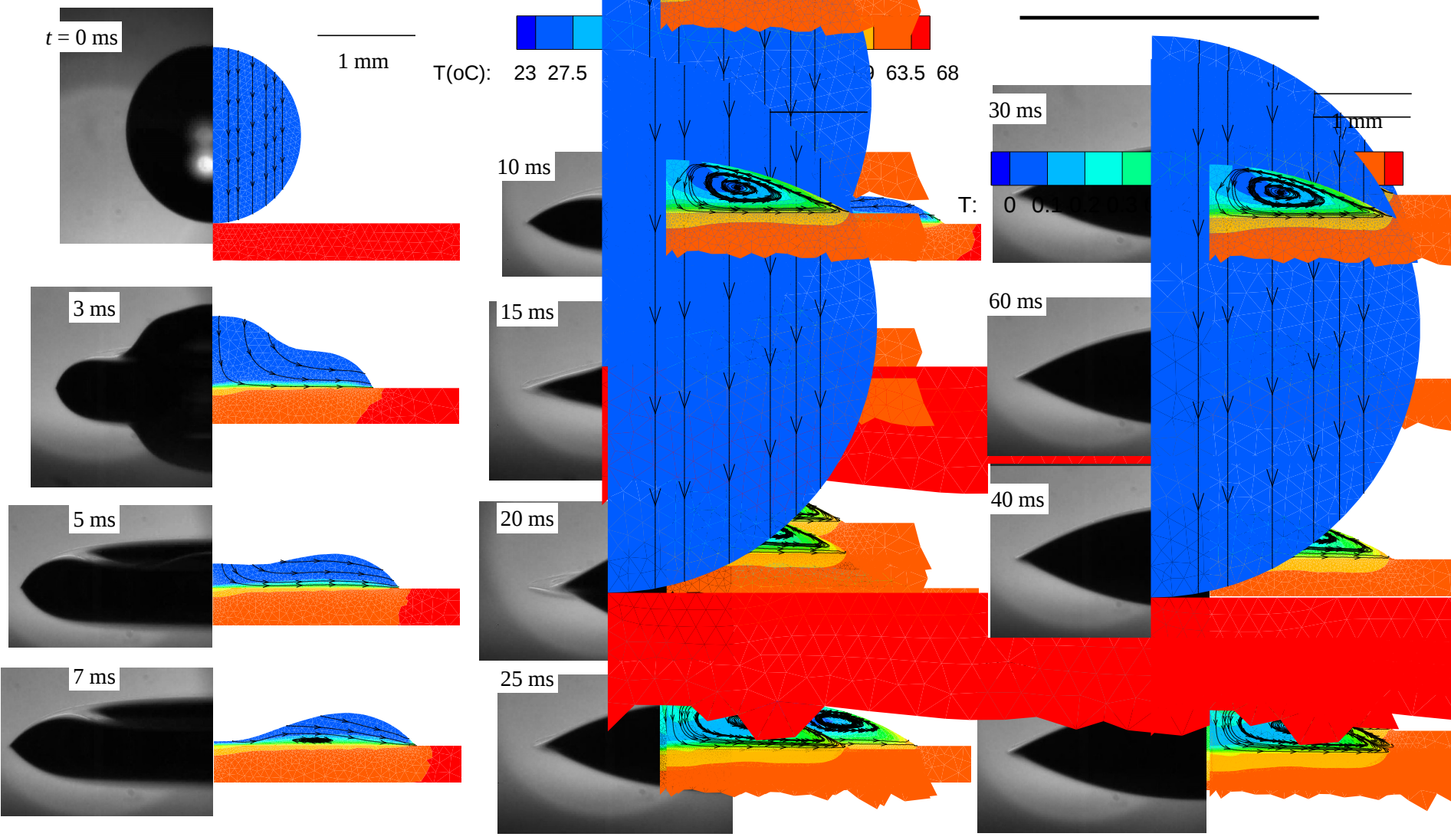
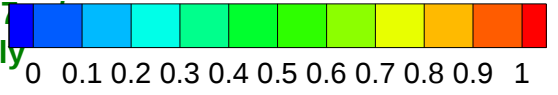


Numerical model



Fluid dynamics and heat transfer in a non-isothermal impact

Parameters: Isopropanol drop on fused silica, $d_0 = 1.5$ mm (volume = 0.141 mliter), $v_0 = 0.37$ m/s
 Initial drop and substrate temperatures: $T_d = 23$ °C, $T_s = 63.5$ °C, respectively

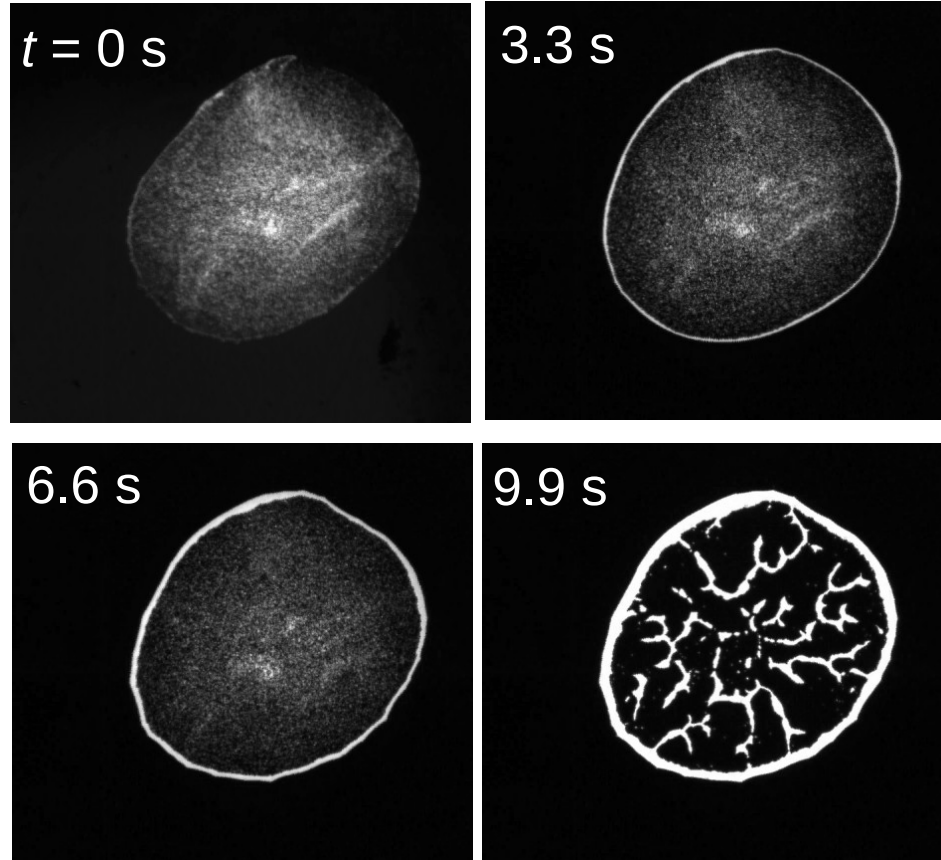


Particle visualization in evaporating nanoliter water droplet on glass

100 μm

Bhardwaj, Fang and Attinger, 2009

50 μm

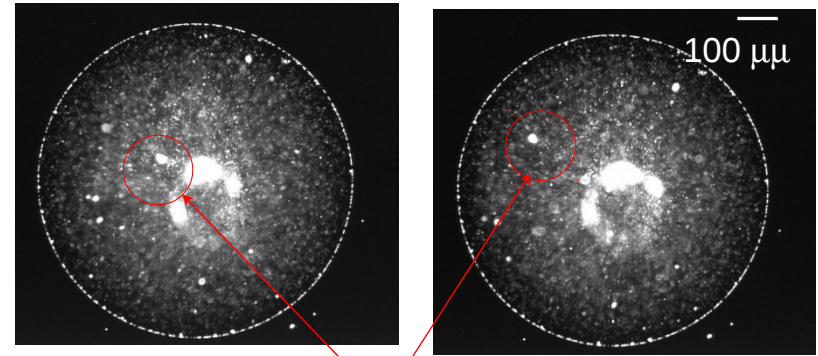


Water drop with fluorescent particles

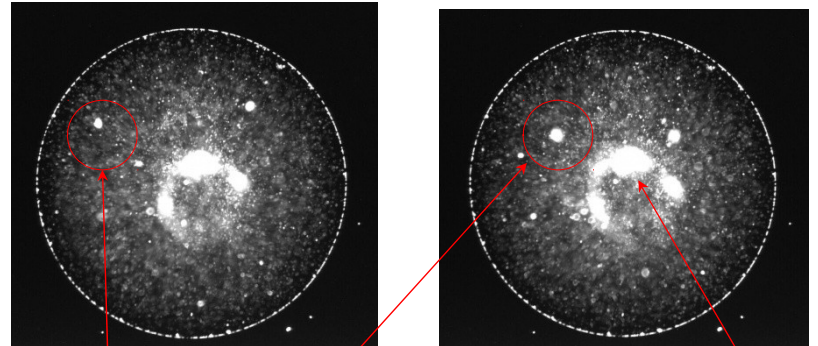
Glass slide

Microscope

Particle visualization in evaporating nanoliter isopropanol droplet on PDMS



3 s 3.3 s
1 2
Particle moves radially outward



3.5 s 3.8 s
3 4
Particle returns to stagnation point
Increase in particles concentration at stagnation point

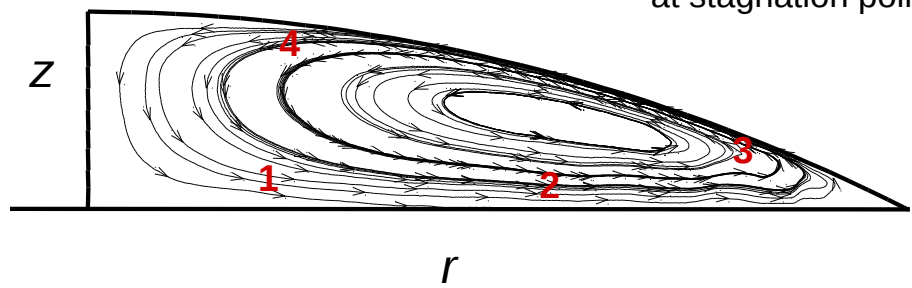
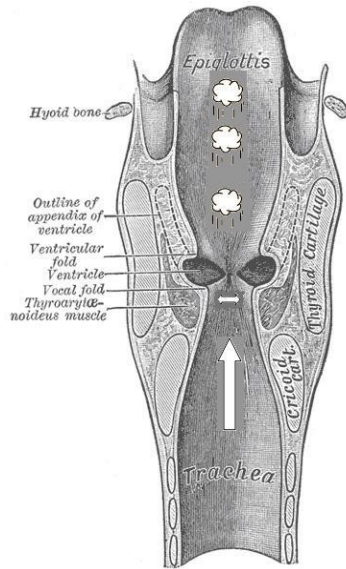


Figure 16: Particle visualization during the evaporation of a 38 nL colloidal isopropanol drop on PDMS at ambient temperature
Initial wetted diameter = 874 microns
Initial wetting angle = 32 degrees
Initial concentration of 1 micron polystyrene particles = 0.1%

Laboratory for Microscale Transport Phenomena
R. Bhardwaj and D. Attinger
Columbia University, New York, NY

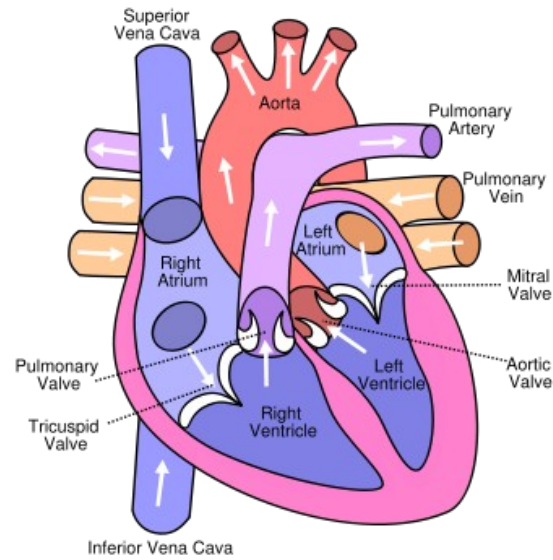
Biological/biomedical flows

Phonation

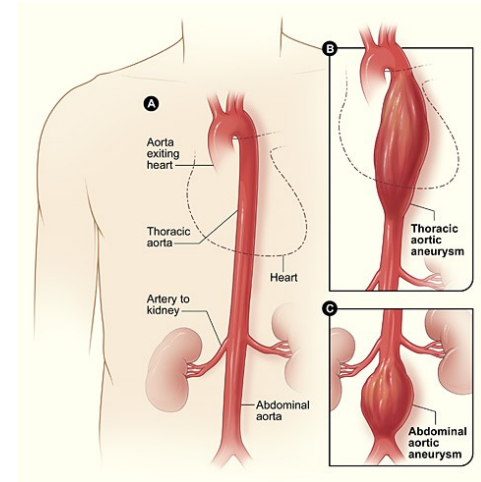


Wikipedia.org

Cardiac flows

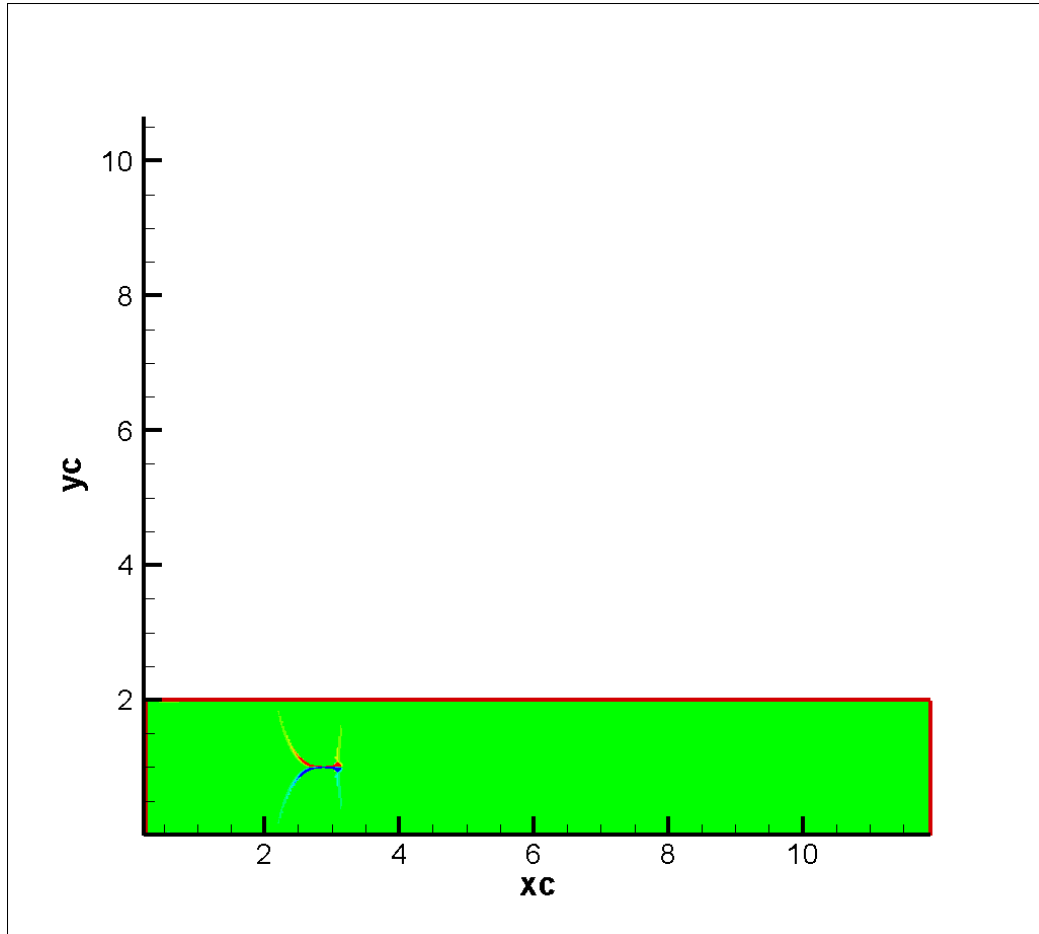


Hemodynamics of aneurysms in coronary arteries or aorta



Nih.gov

Flow around vocal folds

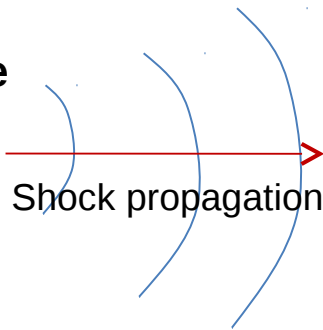


Courtesy:
X Zheng
And R. Mittal
JHU

Impingement of Blast Wave on Human Eye

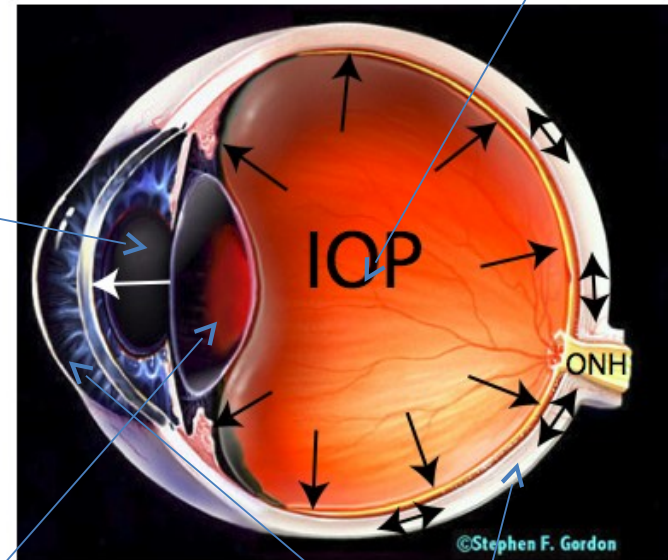
- Applications in understanding combat ocular injuries
- Compressible flow field outside eye
- Non uniform and highly transient pressure loading on cornea
- Shock propagation inside Newtonian and viscoelastic fluid
- Fluid-Structure interaction of Newtonian/viscoelastic fluid with Isotropic/Anisotropic and Elastic/hyperelastic Material

Blast source



Shock propagation

**Aqueous humor
(Newtonian fluid)**



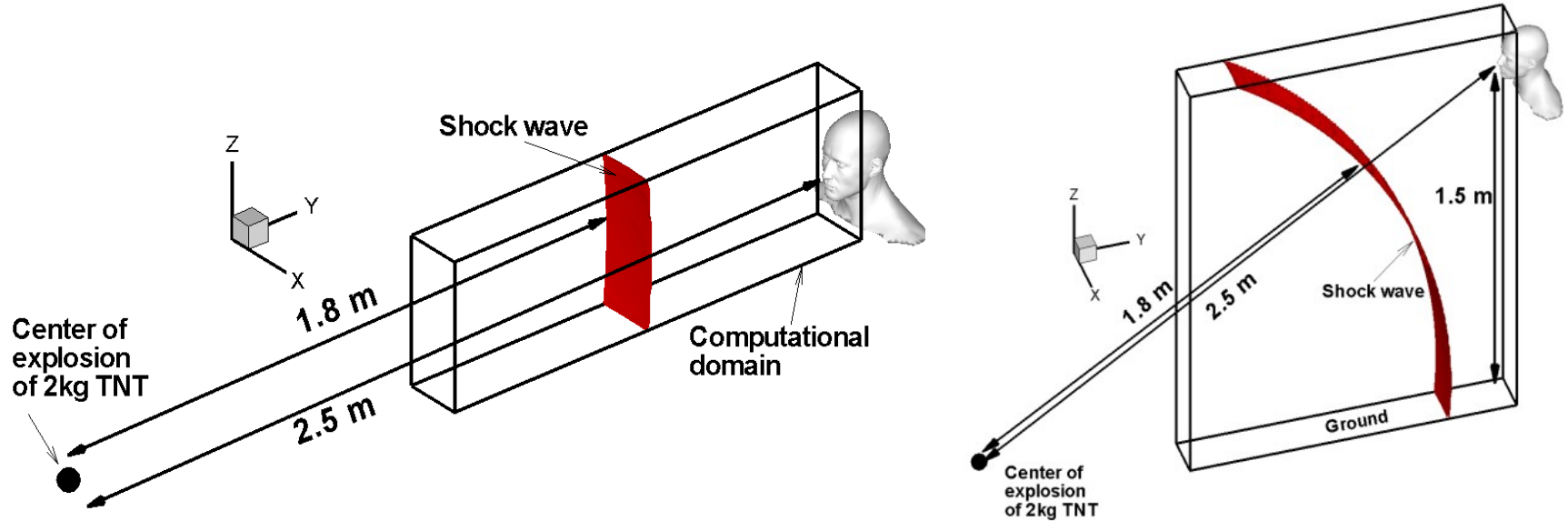
**Vitreous humor
(Viscoelastic fluid)**

**Lens
(Isotropic material)**

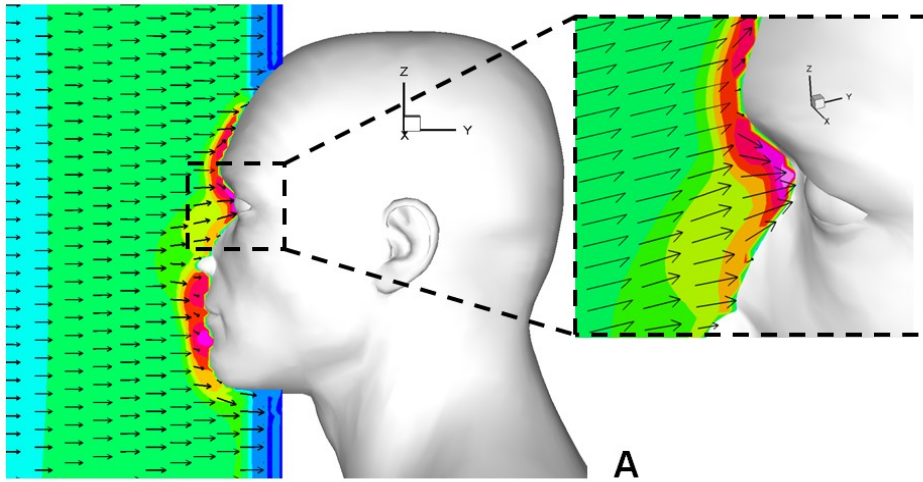
**Cornea and Sclera
(Anisotropic and hyperelastic Material)**

©Stephen F. Gordon

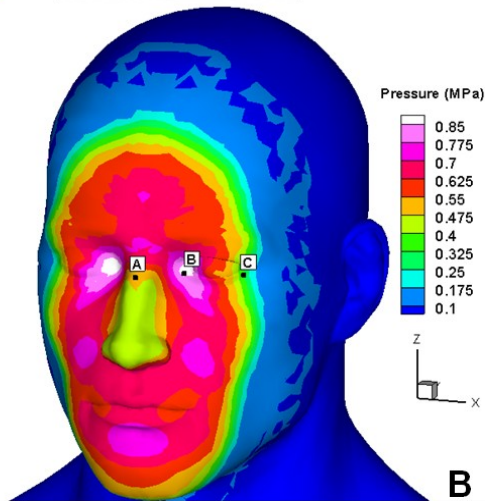
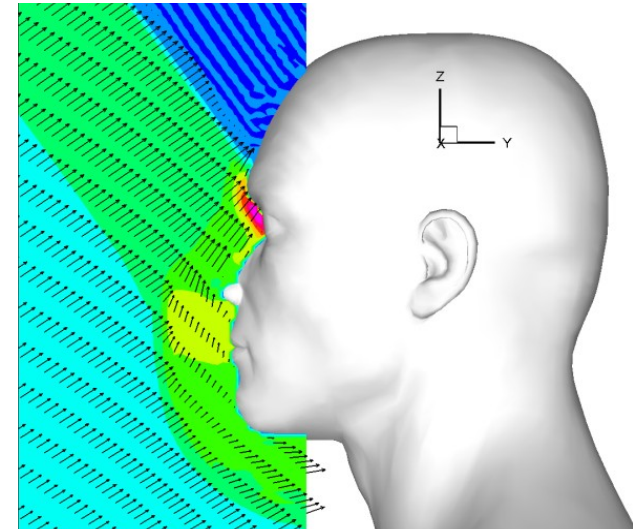
Blast loading on human eye



Air flow around the eye



A

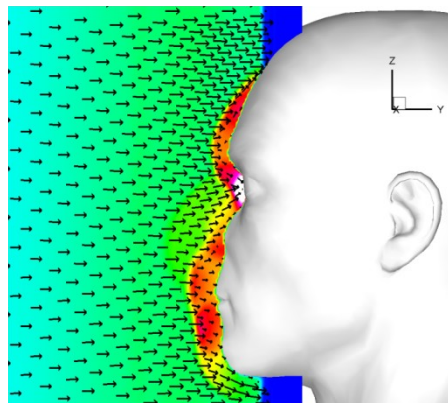


B

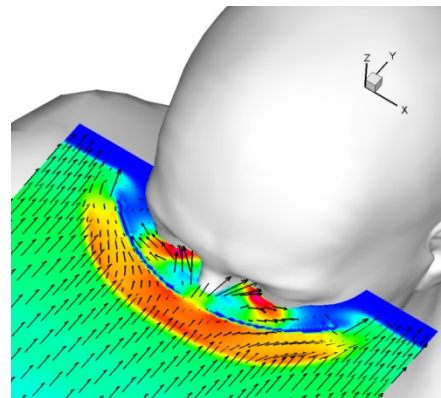
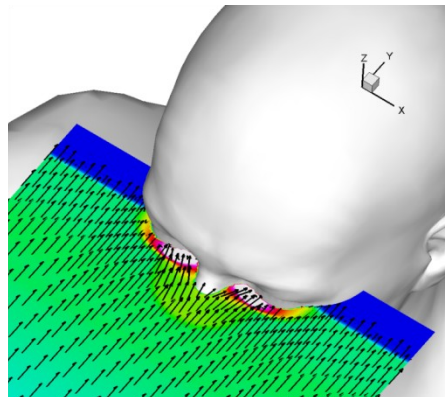
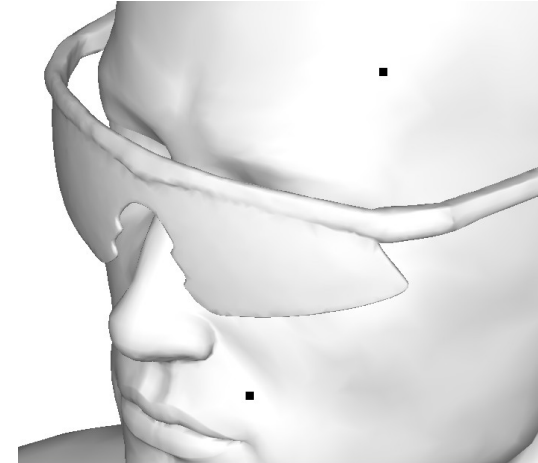
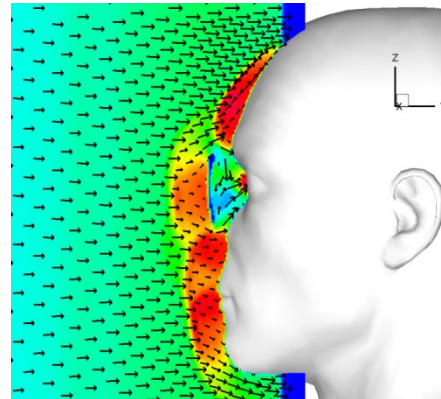
Bhardwaj et al., 2013

Air flow around the eye

Without armor



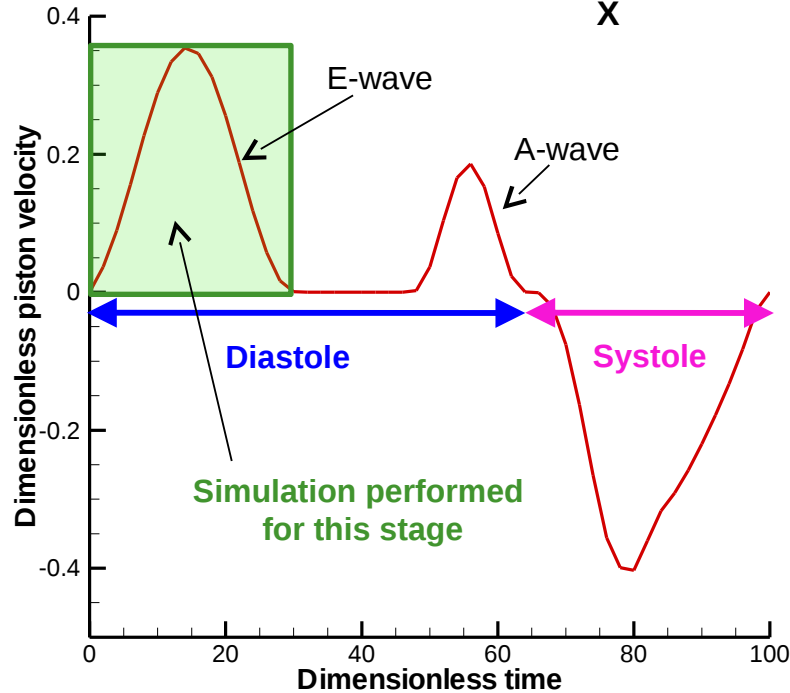
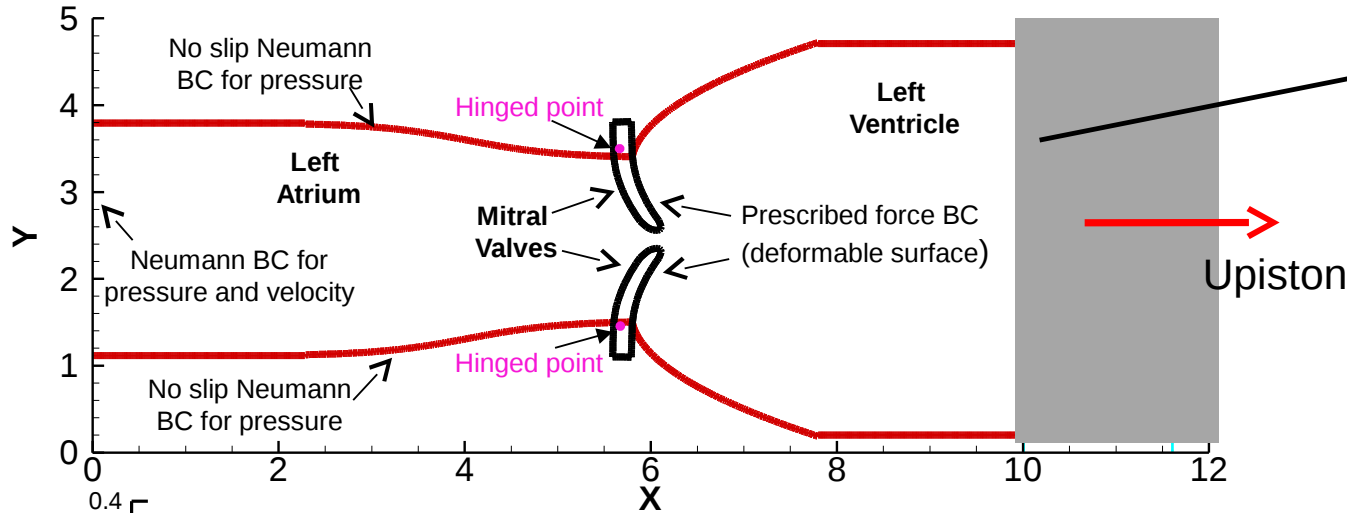
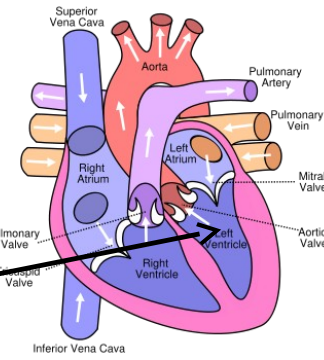
With armor



Bhardwaj et al., 2013

Flow induced deformation of mitral leaflets in left ventricle

Pathologies of mitral leaflets are implicated in many heart conditions including mitral-valve stenosis and prolapse induced regurgitation



Parameters

- Reynolds number = 3800 (based on annulus diameter and peak mitral jet velocity)
- Strouhal number = 0.07 (based on annulus diameter, peak mitral jet velocity and duration of E-wave)
- Non-linear elastic solver
- Young Modulus = 0.8 Mpa
- Poisson ratio = 0.45
- Structure-fluid density ratio = 1.04

Bhardwaj and Mittal, 2011

Left ventricular hemodynamics

- Opening and closing of mitral leaflets is influenced by piston acceleration
- Vortex ring is formed by the rolling of the mitral jet by viscous forces of the quiescent fluid in the left ventricle
- Formation time of vortex ring has been correlated to heart conditions by Gharib et al., 2007

