Department of Mechanical Engineering
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Activity Report during May 2014 to April 2019

by

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ACKNOWLEDGEMENTS

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ACKNOWLEDGEMENTS

UG/PG students
Colleagues/collaborators
Technical staff at IITK
Engineering community
Friends and family

Phase-change Thermal Systems Laboratory

Joint Output

HRD

4 books
8 patents
6 book chapters
90 Scopus publications
90 peer reviewed conferences
20 invited talks and key note lectures

2004 – 2019: 15 Years Journey at IIT, Kanpur

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In this presentation

- Introduction: Liquid-vapour/gas interfacial systems
- Engineering systems involving interfacial thermo-hydrodynamics
  - Pulsating Heat Pipe
  - Loop Heat Pipe
  - Spray Cooling of LEDs

  → **Space and terrestrial sector** (thermal management application)

  - Enrichment of Heavy Metals
  - Nuclear Containment Safety

  → **Nuclear engineering sector** (Safety and strategic application)

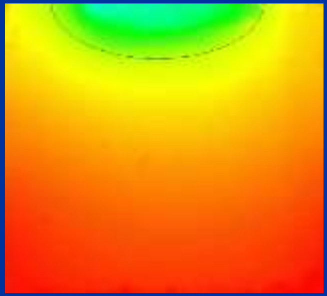
- Experimental techniques and representative results (HSV/ IRT/ PIV/ CFM/ XRT)
- Summary and Outlook

Introduction

Aims and Objectives

Interface shape
Interfacial heat and mass transfer
Three-phase contact line dynamics
Force interactions: surface, viscous, inertia, gravity
Wall Transport: shear and thermal energy
Interaction of interfaces
Multi-Scale Effects
Instrumentation
Scaling laws
Instabilities

Taylor slug flows

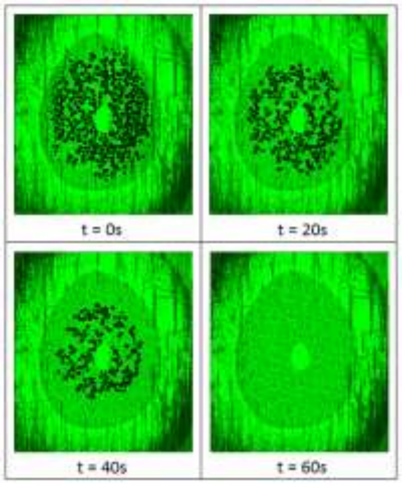


IRT: Porous media

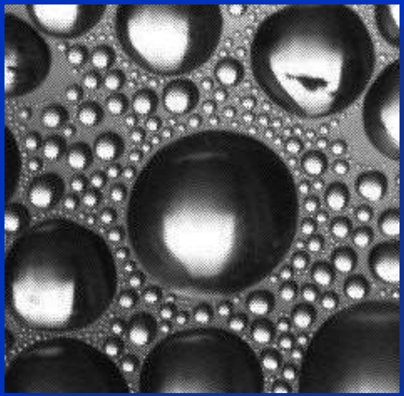

Sprays/Jets/Mist


High speed videography: deforming and merging interfaces

Pool Boiling



Confocal interface microscopy



Dropwise Condensation

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Experimental research: Challenges

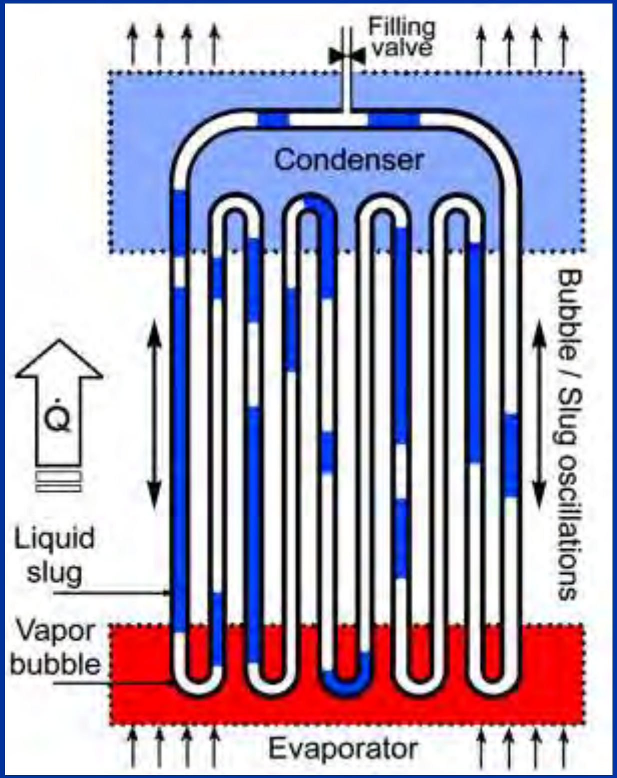
- Control on the boundary conditions: Heat flux/ Temperature/ Wall
- Visualization, coupled with application of boundary conditions
- Strong surface effects: repeatability of experimental data
- Instrumentation at microscale: Intrusive vs non-intrusive
- Viability and applicability of assumptions
- Purity of materials/ dissolution of gases
- Optical alignment/ Signal to noise ratio
- Thermal-hydrodynamic coupling
- Thermal conjugate effects
- Vacuum and leakage

GOAL

Local level understanding to global system development

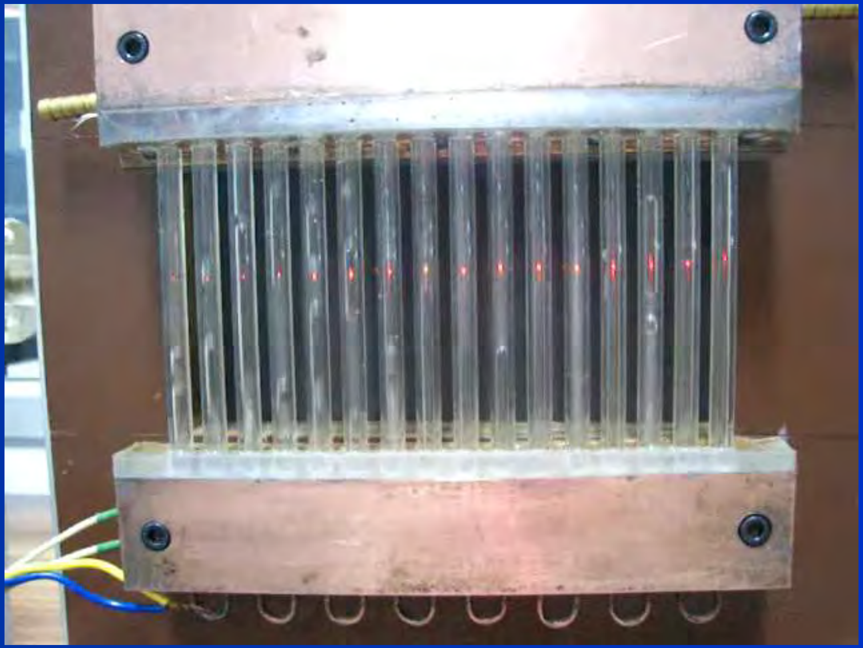
Work undertaken on Engineering Systems with Strong Involvement of Interfacial Physics

Pulsating Heat Pipe

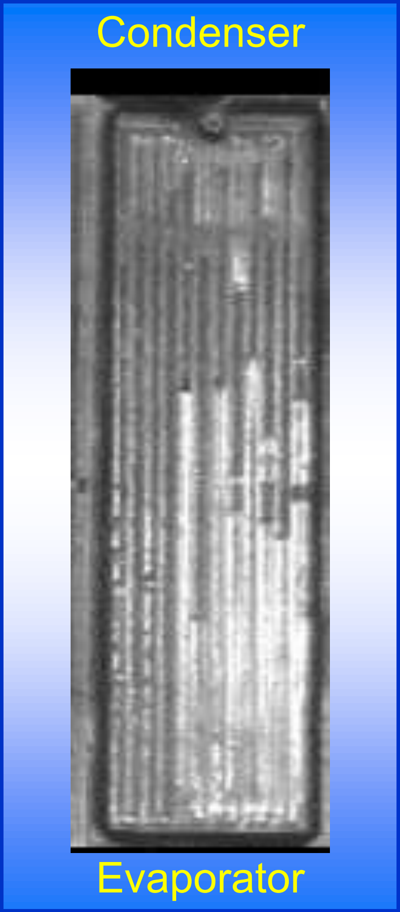


- Simple meandering capillary tube
- No wick or porous structure inside it
- Evacuated, filled partially with a fluid

Thermally induced self excited oscillations commence



Glass tube PHP Video



Aluminum plate PHP

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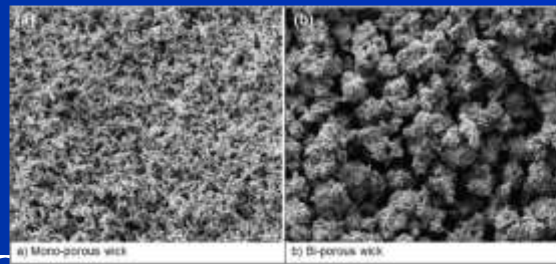
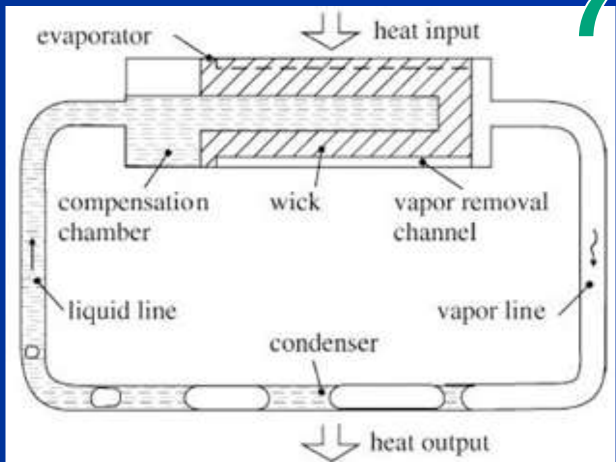
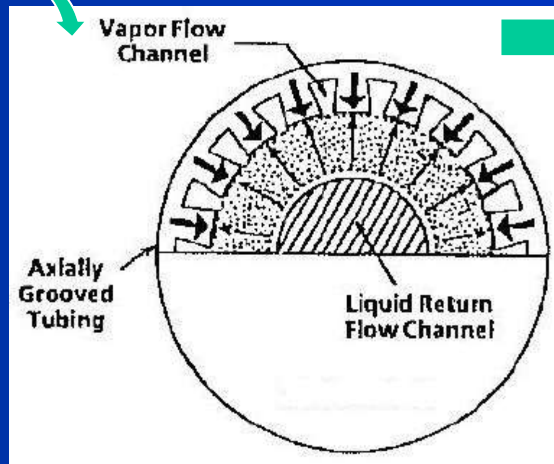
Loop Heat Pipe

- Highly efficient mono-porous/ bi-porous wick structure
- Excellent passive design for high heat removal
- Invented by Dr. Yuri Maydanik in Russia





Schematic of LHP: Main Components



Wick details

Evaporator Wick

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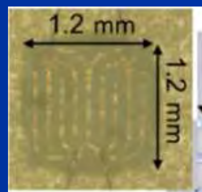
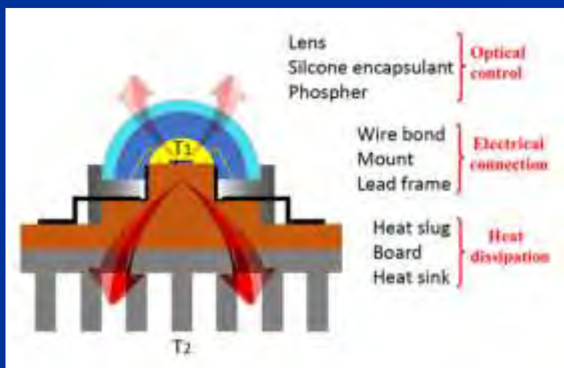
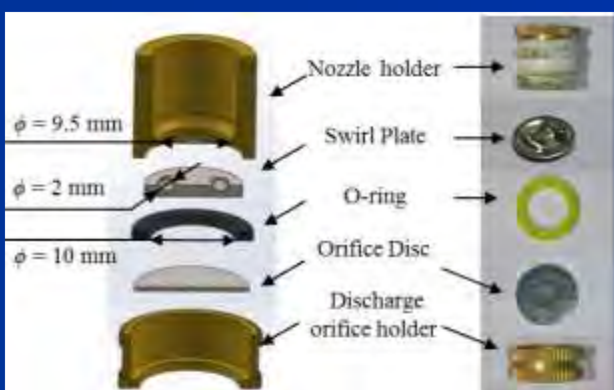
Spray Impingement Cooling

Single LED Chip

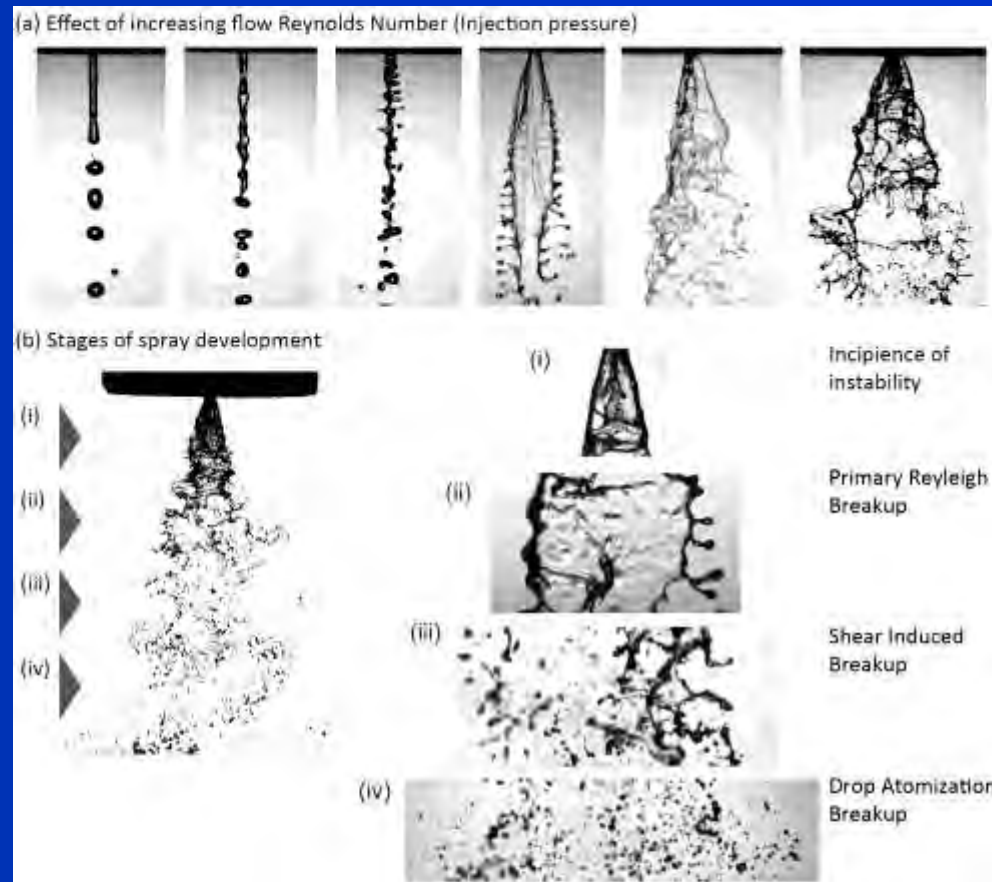


300 W LED Module





Spray Cooling



Details of a liquid spray hydrodynamic flow regimes

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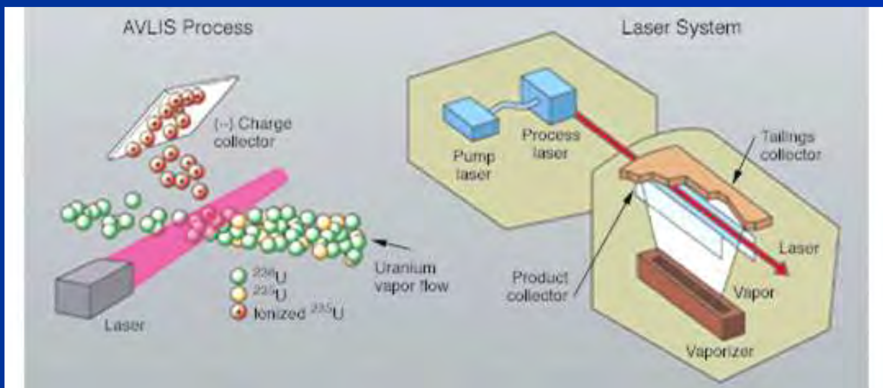
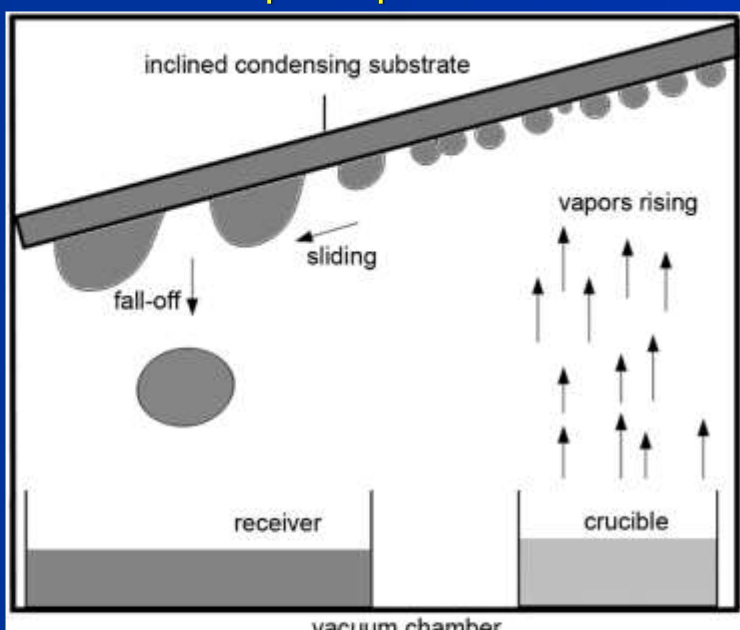
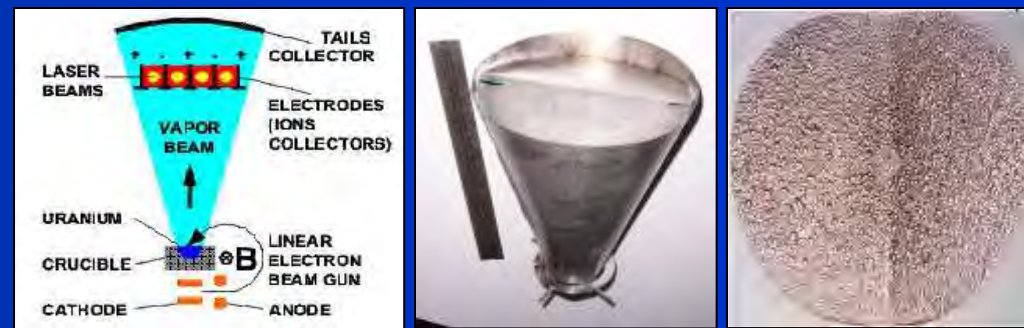
Enrichment of Heavy Metals



Laser Isotope Separation Process





(a) (b) (c)

(a) Schematic of the reflux condensation experiment

(b) A conical shaped reflux condensation chamber used for condensation of Bismuth

(c) Typical condensation patterns of Bismuth on the substrate at 400ºC and 20º inclination angle (Experiments: BARC, Mumbai, India)

<u>Another motivation</u>

Cooling of containment walls of nuclear reactor

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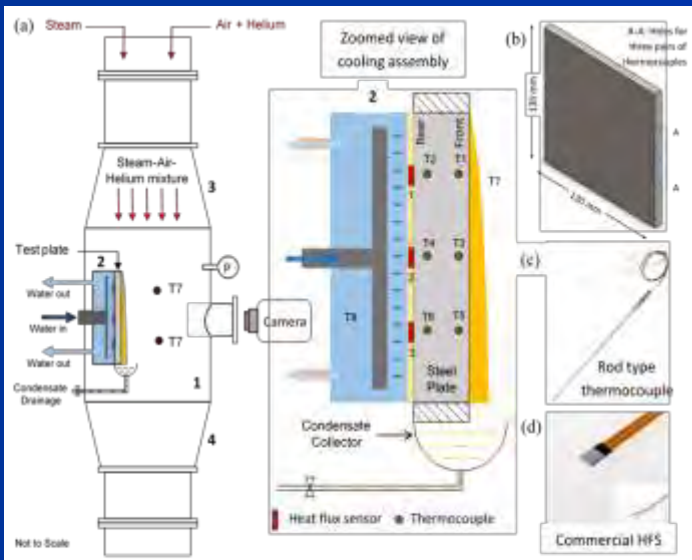
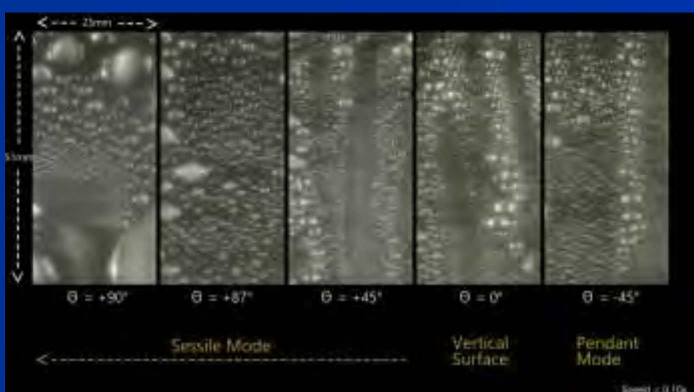
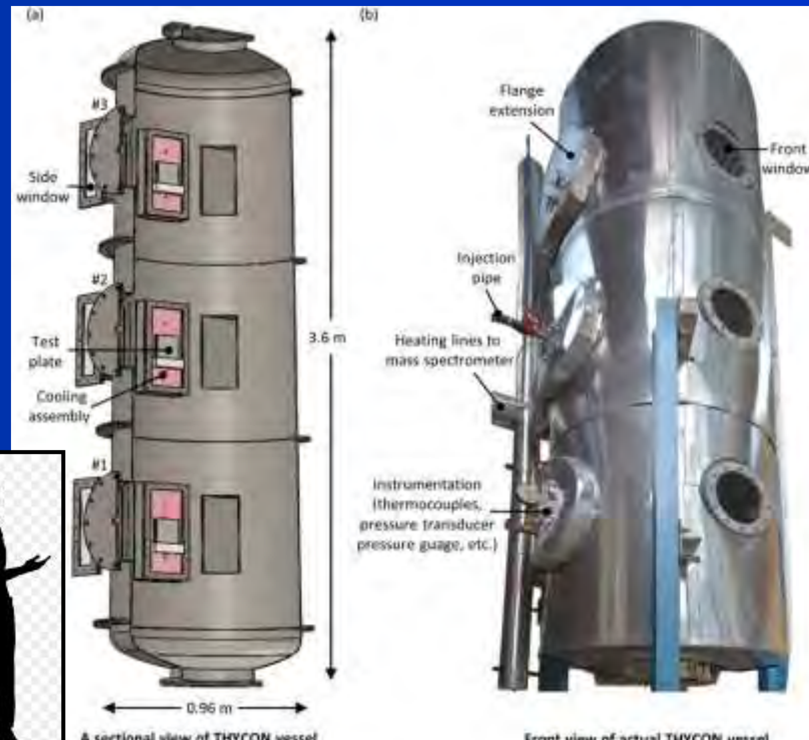
Reactor Containment Safety



Condensation test section





THYCON Facility – IIT Kanpur

- Experimentally simulating post-severe accident scenario
- Steam condensation in the presence NCGs
- Steam + Air + Hydrogen

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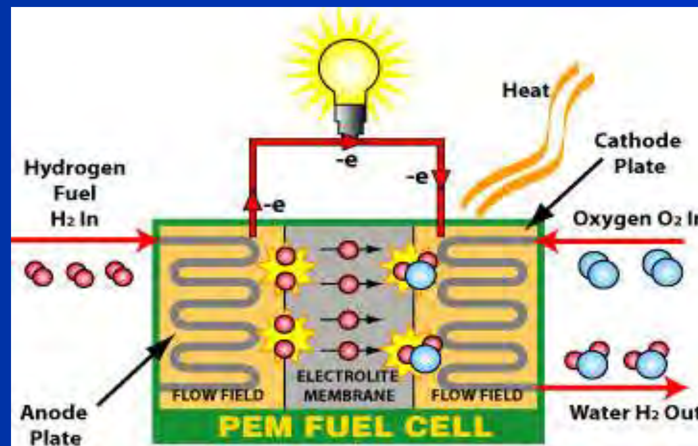
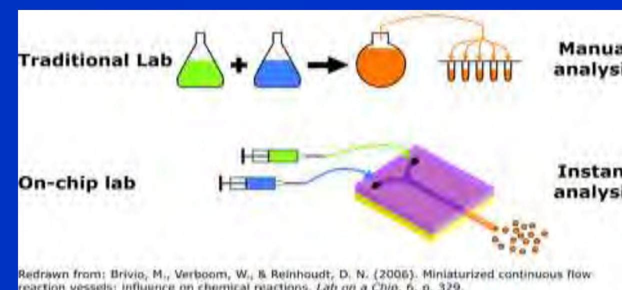
Several Other Applications

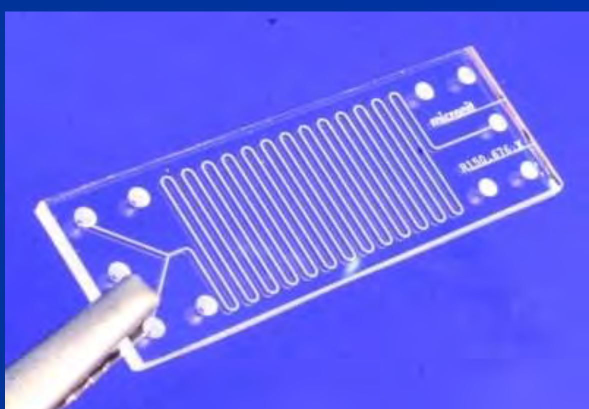
- Compact
- High area/volume
- Better transport

Integrated electronics cooling

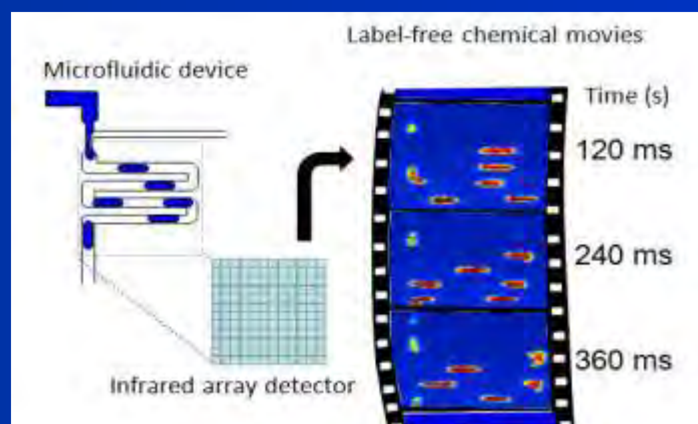


Transport in fuel cells

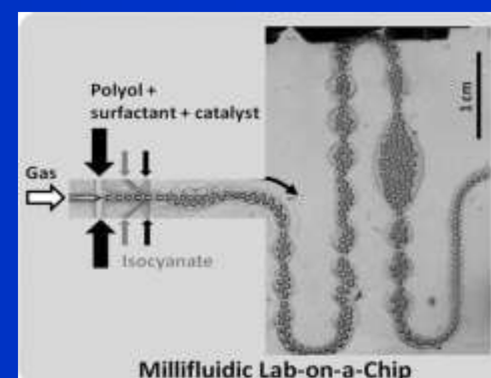




Gas-liquid micro-reactors



Microfluidic devices



Lab-on-chip

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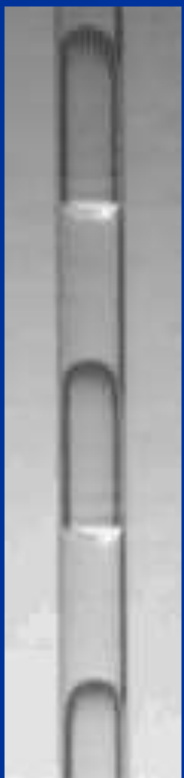
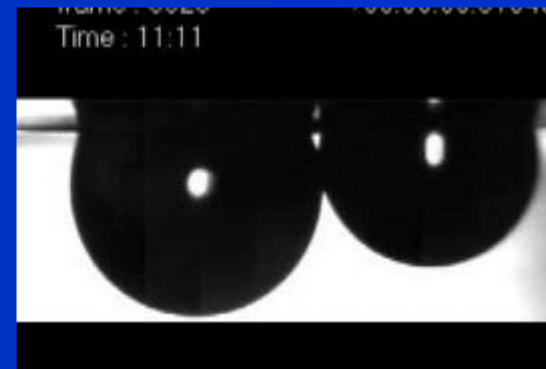
Scaling of Forces



- **Dominance of interfacial force**
  - Bond number (Bo) – Gravity/surface tension

$$Bo = \frac{\Delta \rho d D^2}{\sigma} < 2$$

Surface tension >> gravity



Droplet motion/ coalescence

- **Meniscus shape**
  - Young-Laplace at equilibrium
  - Capillary number (Ca) – Viscous/surface tension

$$Ca = \frac{\mu V}{\sigma} < 10^{-3}$$

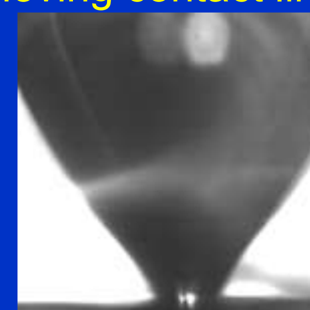
Surface tension >> Viscous


Moving contact lines

- **Inertia**
  - Weber number (We) – Inertia/surface tension

$$We = \frac{\rho U^2 D}{\sigma}$$

Surface tension >> Inertia


Bubble growth

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Interfacial Transport: Multi-scale Hierarchical System

Stage 1 (Atomic to Nanoscale)

→ Molecular potentials, Adatom dynamics, Cluster dynamics, surface diffusion, Stable cluster size and population density, Accommodation coefficient

Stage 2 (Nanoscale to Microscale)

→ Film stability, topography interaction, stable interfaces, pinning dynamics, wetting-dewetting dynamics, Young-Laplace condition

Stage 3 (Microscale to Macroscale)

→ Interfacial growth, coalescence, merger, interaction of surface force, body force, viscous force and inertia force, momentum flux transfer

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Experimental Tools: Fluid-Thermal Laboratory


Laser confocal microscope


Thermal diffusivity system


X-Ray tomography


Infra-red camera


High-speed camera


Micro PIV


Goniometer

High Speed Videography

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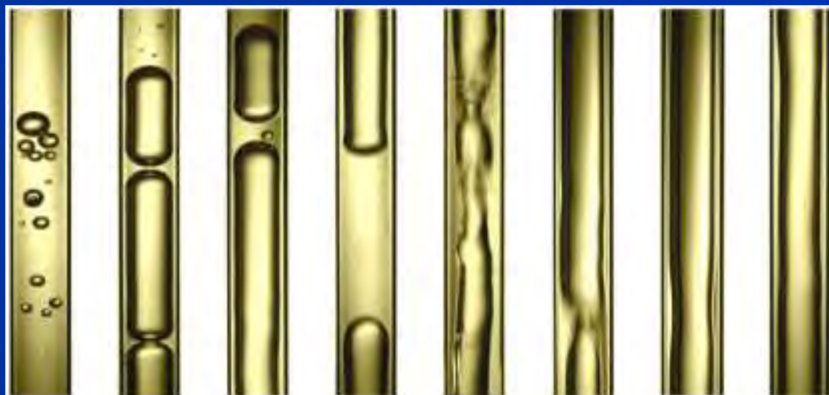
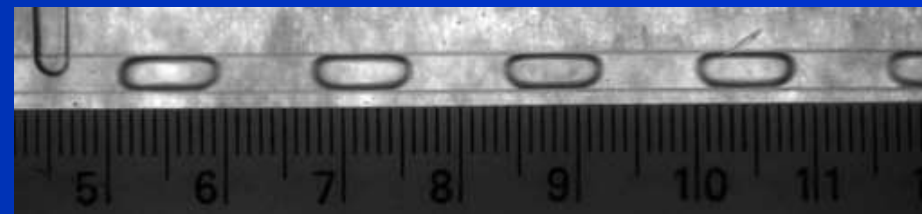
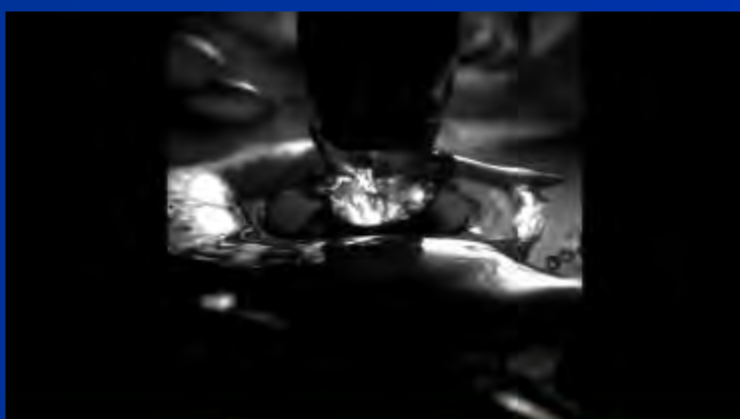
Two-phase Flow and Heat Transfer



Upward flow boiling patterns in a 2.0 mm tube under different input heat flux conditions



J_{tot} = 0.15 m/s



Critical Heat Flux with water jet at low pressure

Effect of surface morphology on spray impingement

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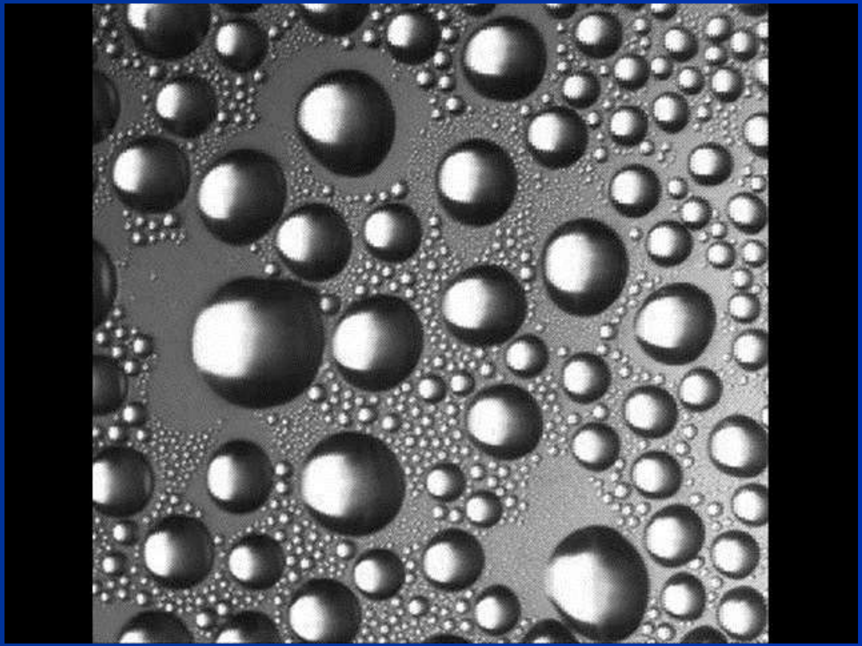
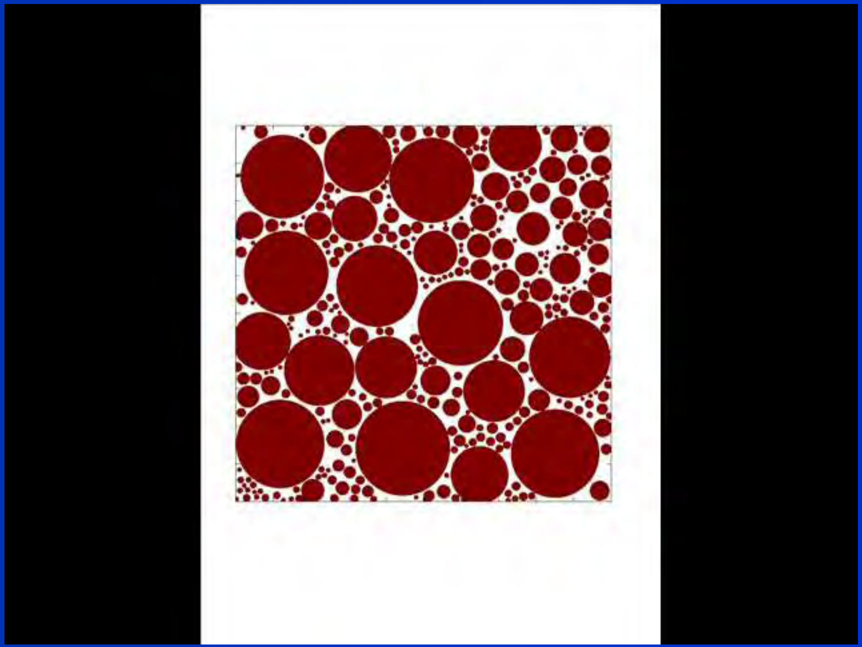
Sliding path of moving droplet in experiment and simulation



from experiment



from simulation

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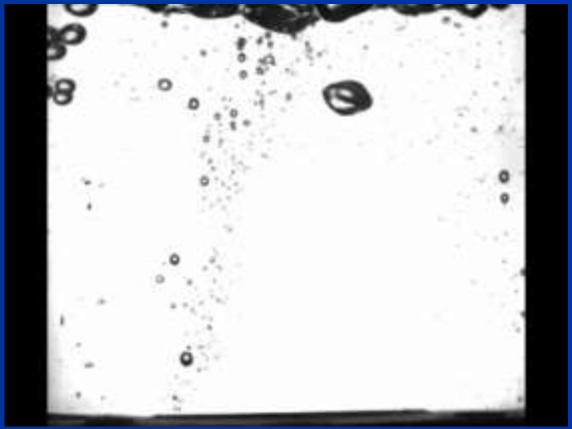
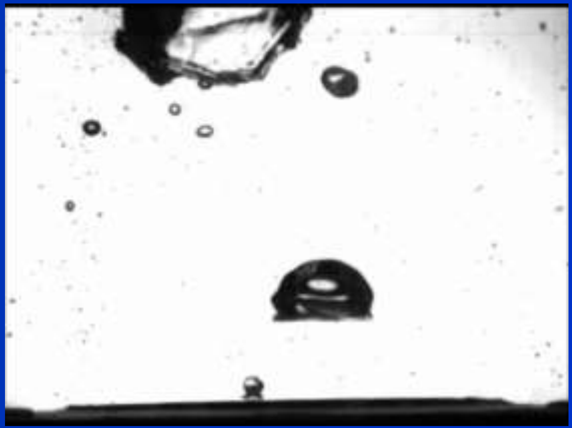
Bubble Growth in Binary Mixtures of Aqueous Ethanol

Effect of ethanol concentration

2.0% ethanol
T_{sat} = 50°C,
q" = 0.046 MW/m^2

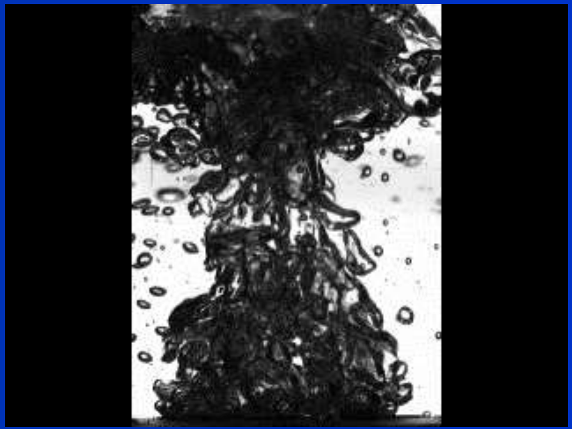




25.0% ethanol
T_{sat} = 50°C,
q" = 0.046 MW/m^2

Effect of surface roughness

R_a = 0.8 μm



R_a = 20 μm

Infra Red Thermography

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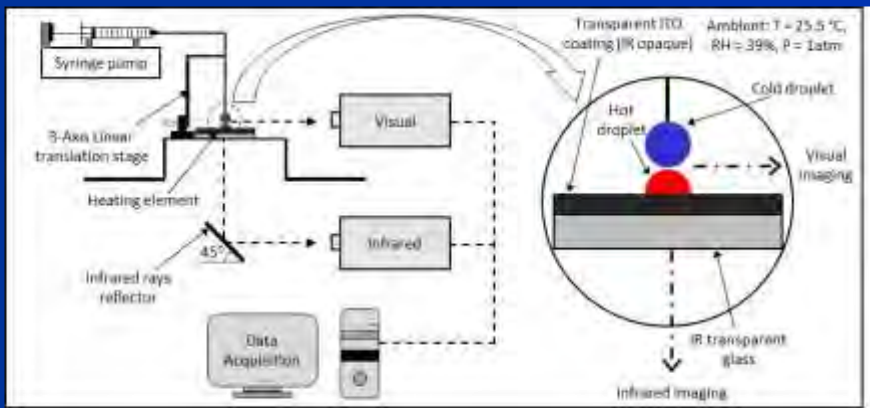
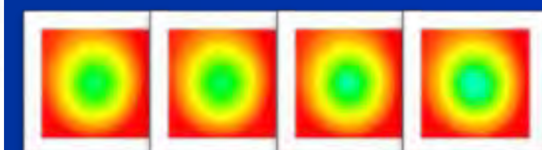
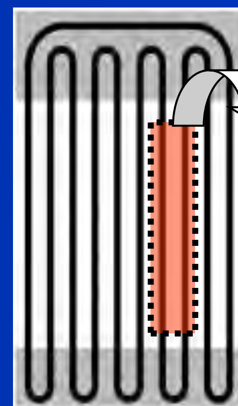
IRT of Micro-channel Flows and Droplets

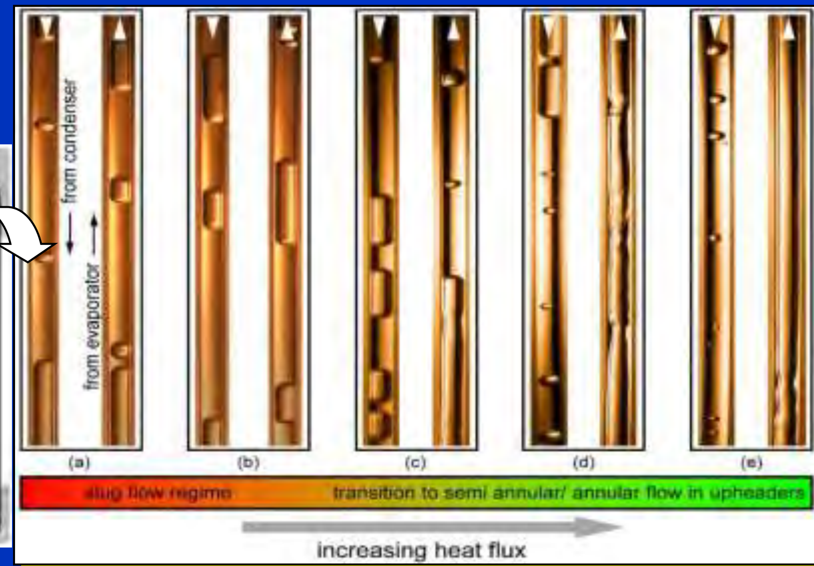


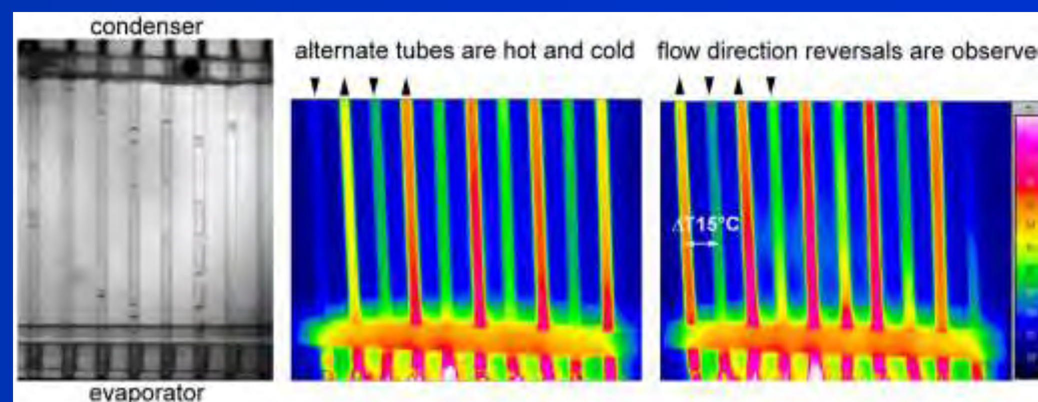


We = 13
Heat Flux = 0.92 W
$T_{equilibrium}$ (plate) = 47 °C

Interface shapes and thermal footprints during droplet dynamics







Flow patterns in a PHP

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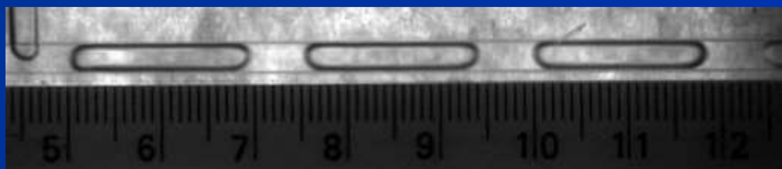
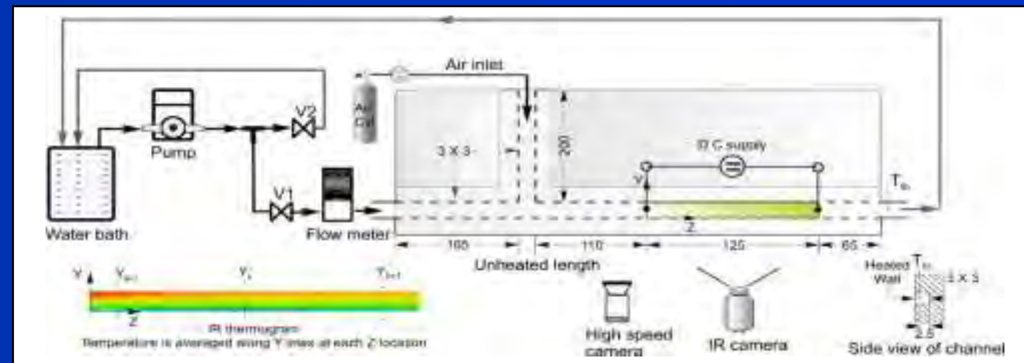
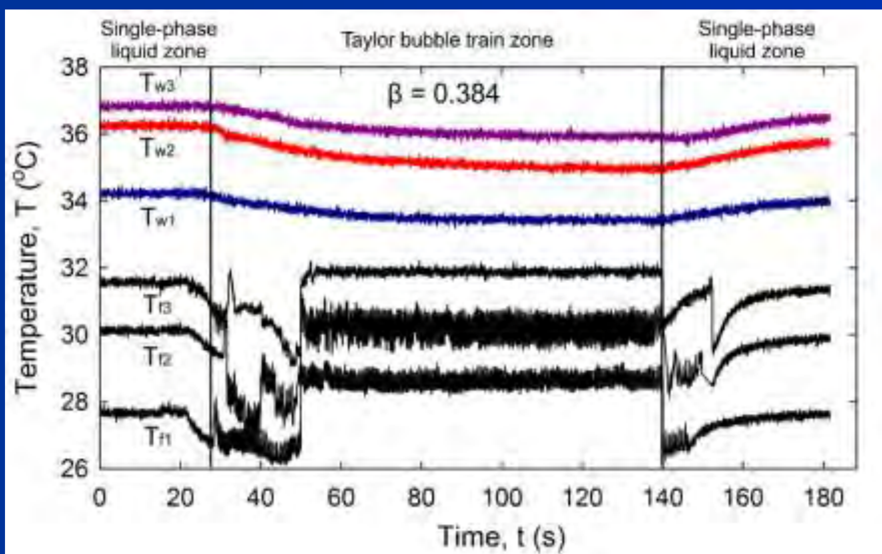
Transient Temperature Profiles and Nusselt number

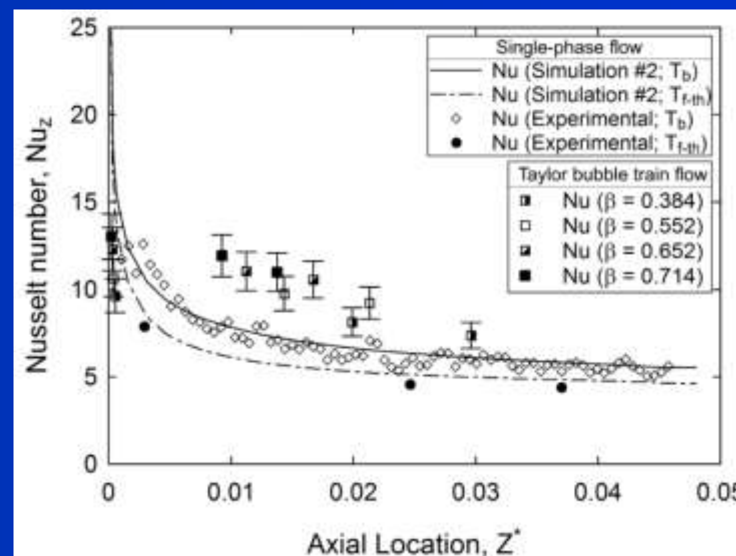


J_{tot} = 0.11 m/s





Variation of wall and fluid temperature with time for Taylor bubble train flow for β = 0.384 and 0.652, respectively.



Axial variation of Nusselt number for different volume flow ratio of Taylor bubble-train flow

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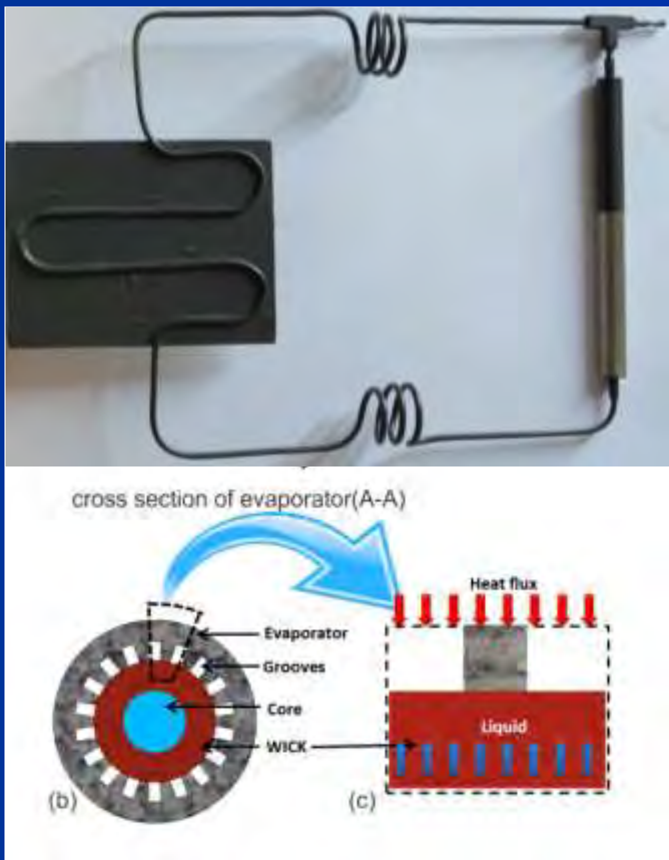
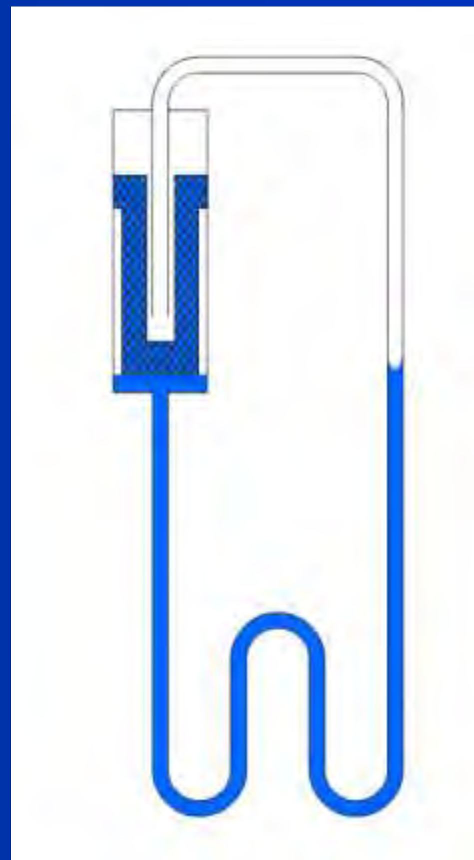
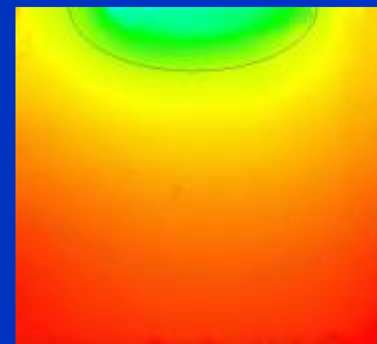
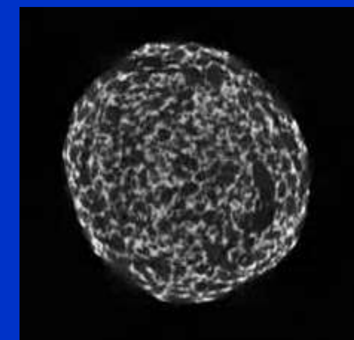
Loop Heat Pipe: IRT for Wick Design



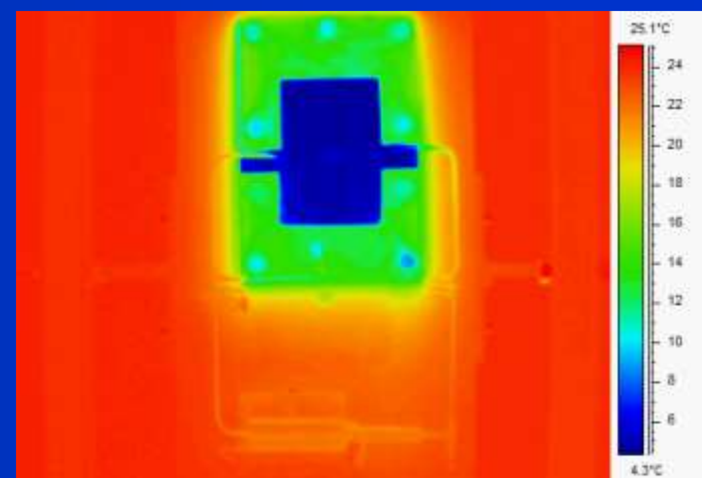


(a) Schematic of loop heat pipe (b) Cross-section of evaporator and unit cell (c) Infrared imaging setup (d) Location of the evaporation front from thermography





Evaporation front in the porous sample



System level thermography

Particle Image Velocimetry

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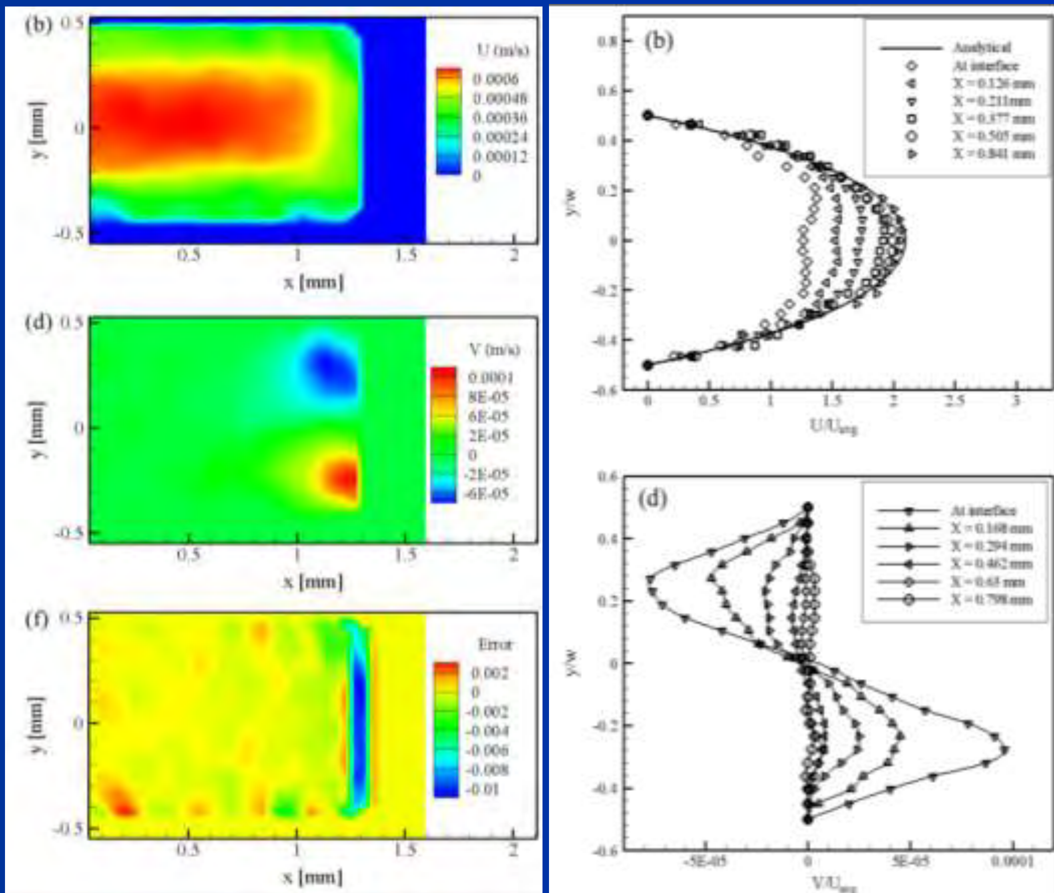
PIV of single meniscus

U

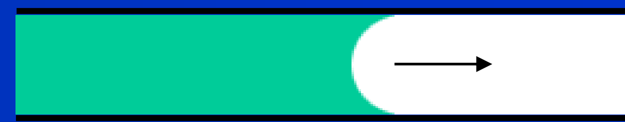
V

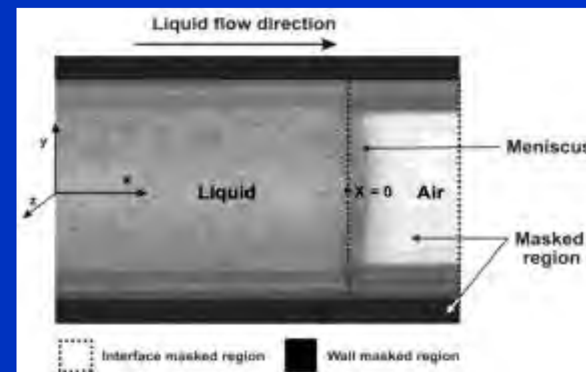
Error in 2D continuity



Velocity distribution at the moving liquid-air interface for U_{avg} = 0.166 mm/s, (Ca = 2.27e-6):

Moving Liquid-gas interface





- Enhancement in transport due to V comp.
- Away from interface, U is parabolic
- Close to the interface U-velocity reduces, with U_{max} away from center
- Flow becomes 3D very near to interface
- Circulating vortices are observed behind the interface

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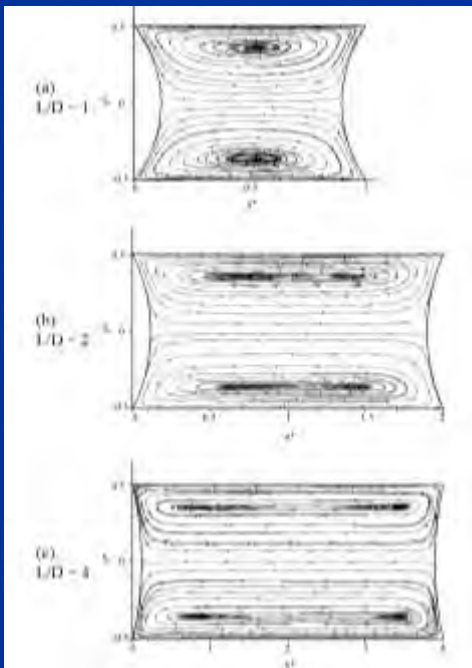
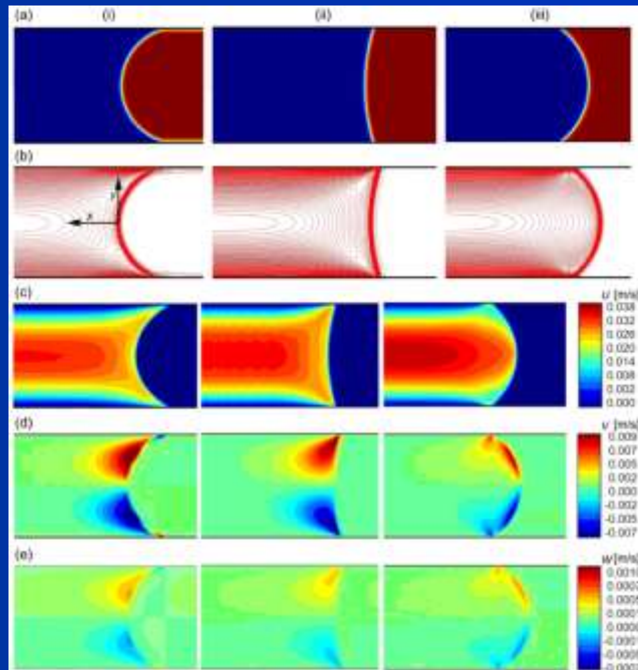
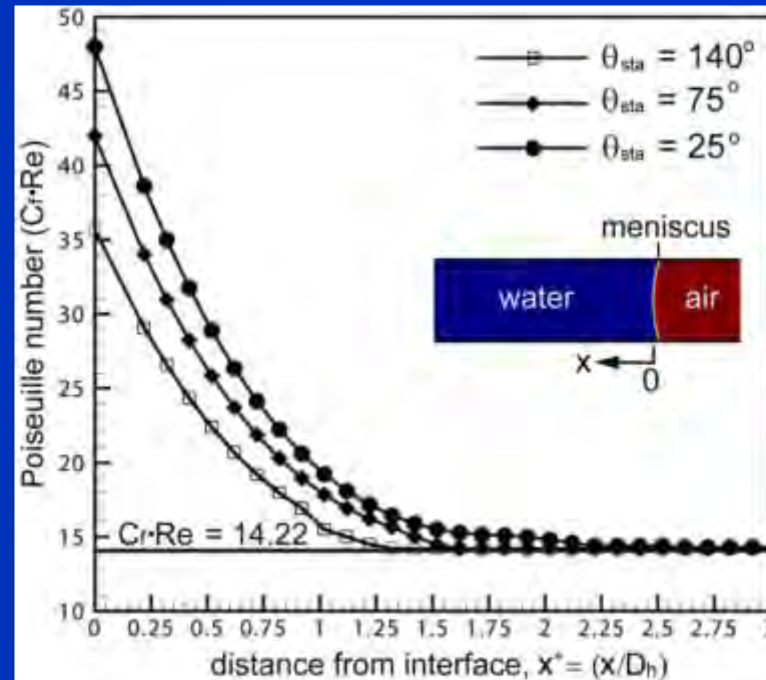
Flow field and its modeling





(a) Streamlines of water plug at Ca = 1e-3 (b) Meniscus shape for various capillary tube wettability at commencement of motion (contact angle 140° for avg. velocity (U_{avg}) is = 0.038 mm/s (Ca = 5e-4))



Variation of Poiseuille number (C_f·Re) experienced along the wall due to the steady meniscus motion, for the three cases of wettability respectively.

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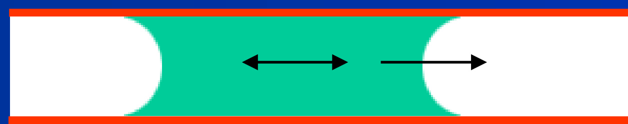
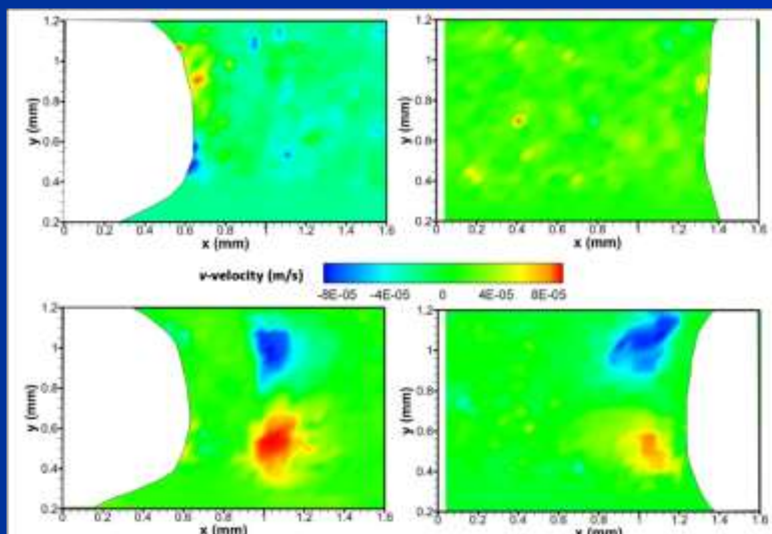
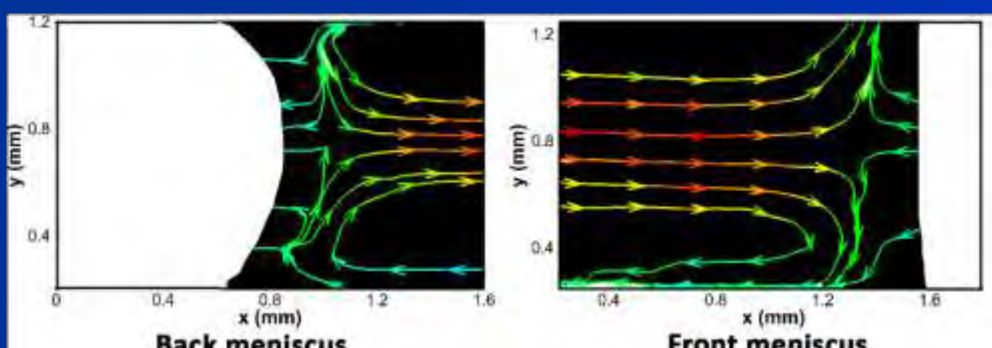
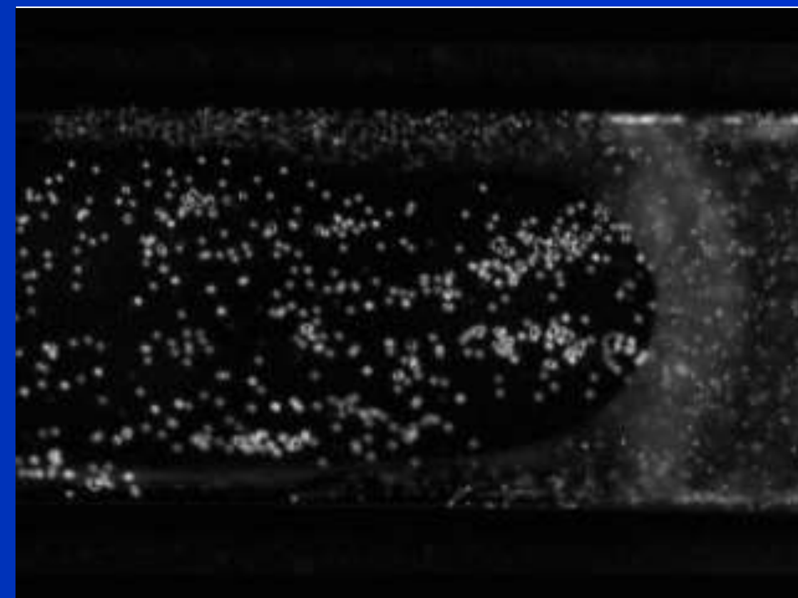
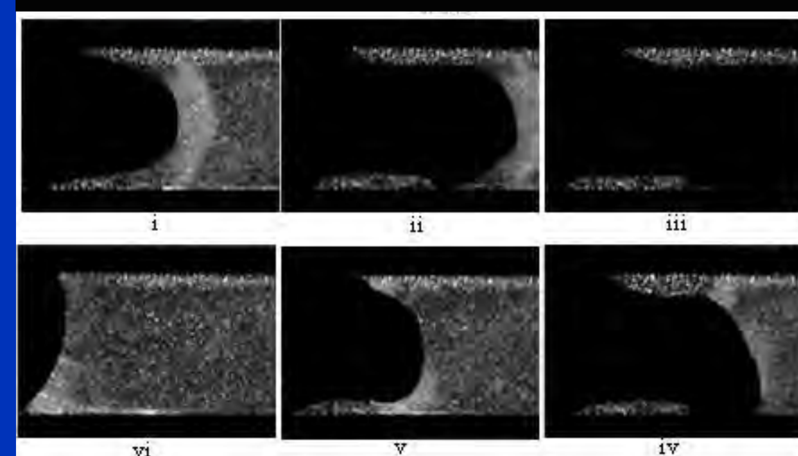
PIV of Oscillating Taylor Plug











Confocal Microscopy

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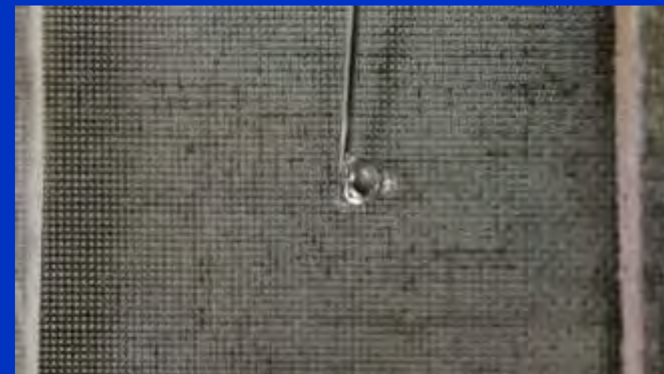
Change of Mesh Wettability through Heat Treatment

SS#100

untreated
SS#100 mesh

8μl drop on untreated
SS#100 mesh
CA ~ 120°

Heat treated
SS#100 mesh



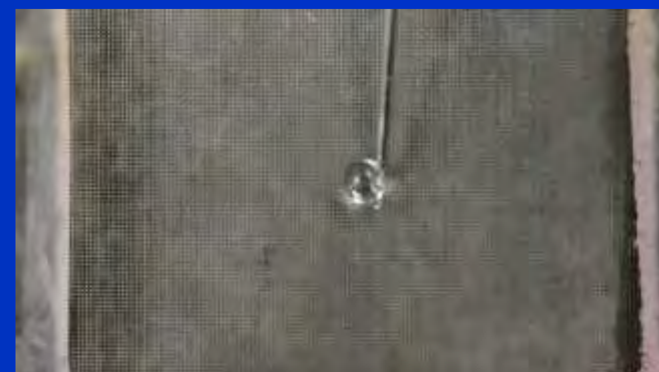
SS#200

untreated
SS#200 mesh

8μl drop on untreated
SS#200 mesh
CA ~ 120°

The SS Mesh is inherently hydrophobic by nature.

Heat treated
SS#200 mesh



Through thermal oxidation, the SS Mesh is made hydrophilic.

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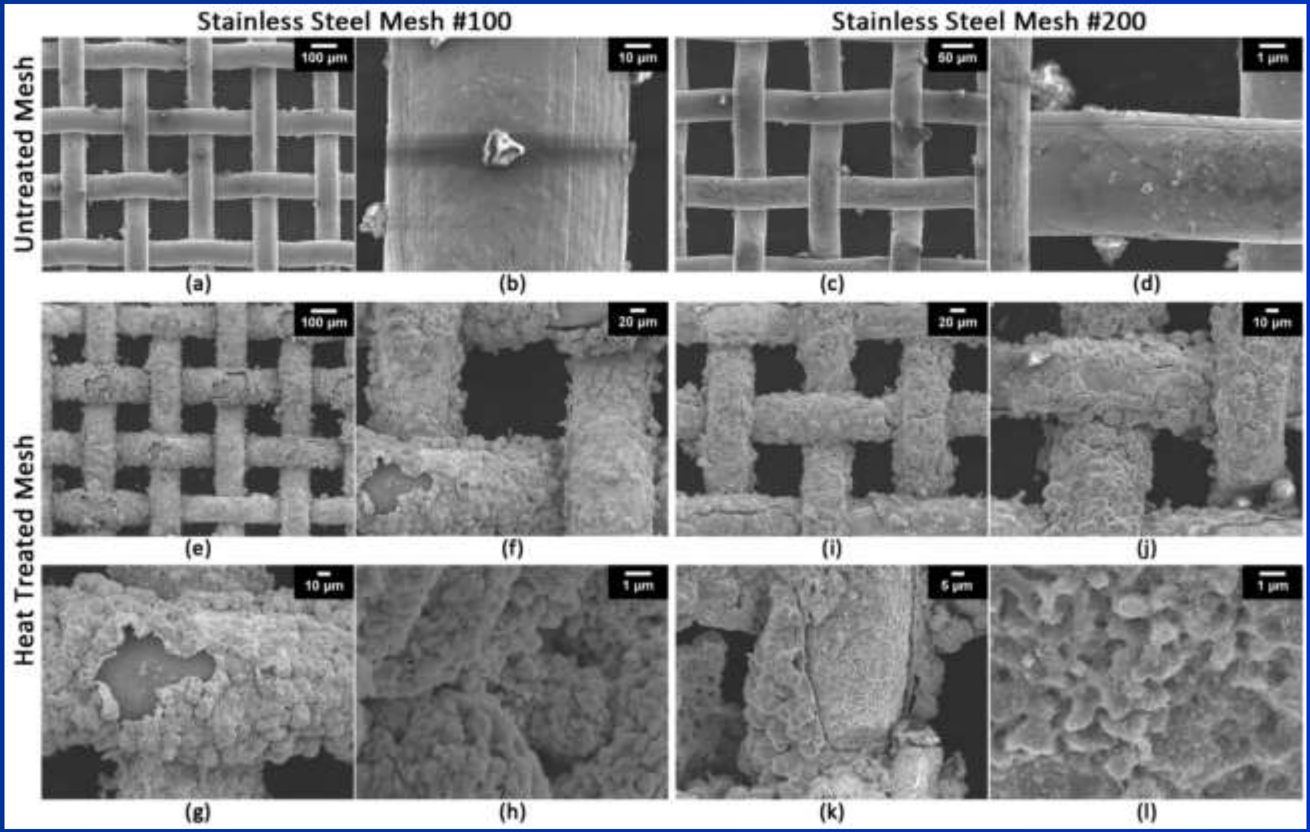
Microstructure Growth on Heat Treatment



In untreated mesh: only primary pores are present

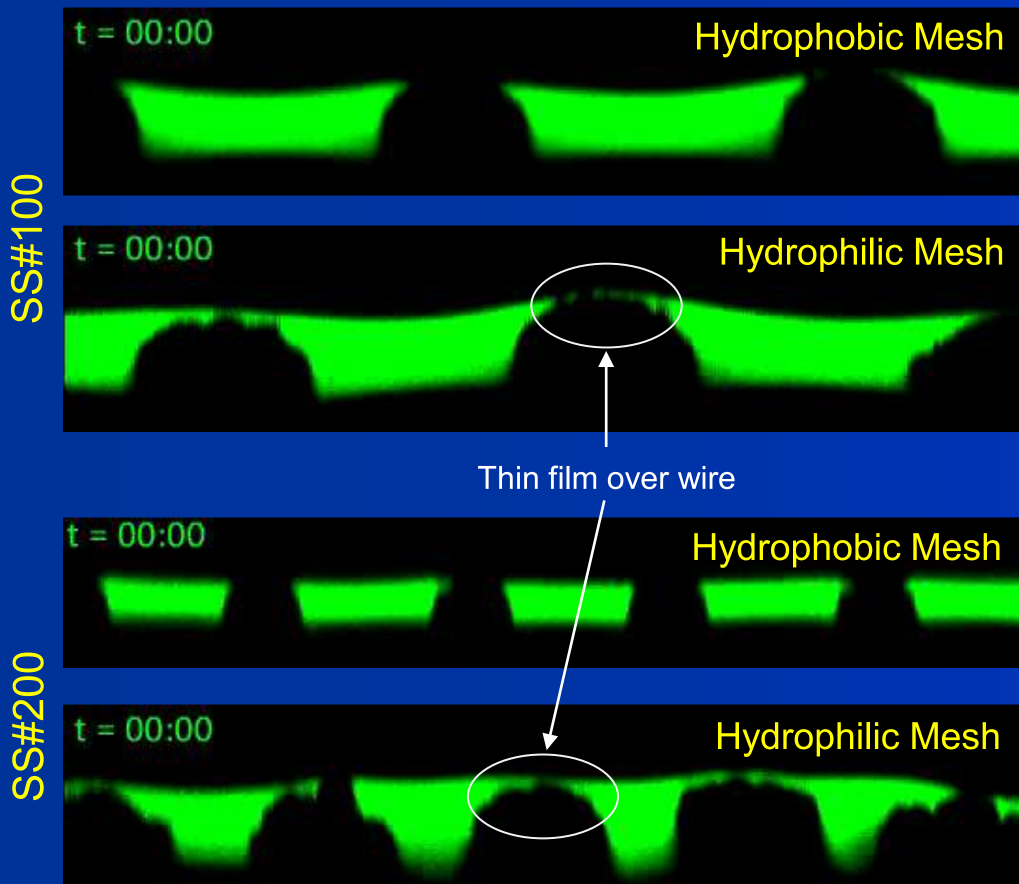
Mesh #100:
Average pore size 148 µm
Wire diameter = 94 µm

Mesh #200:
Average pore size 76 µm
Wire diameter = 47 µm

Metal oxide layers are usually hydrophilic and moreover, oxide structures provide secondary micro-pores
Chemical+Physical

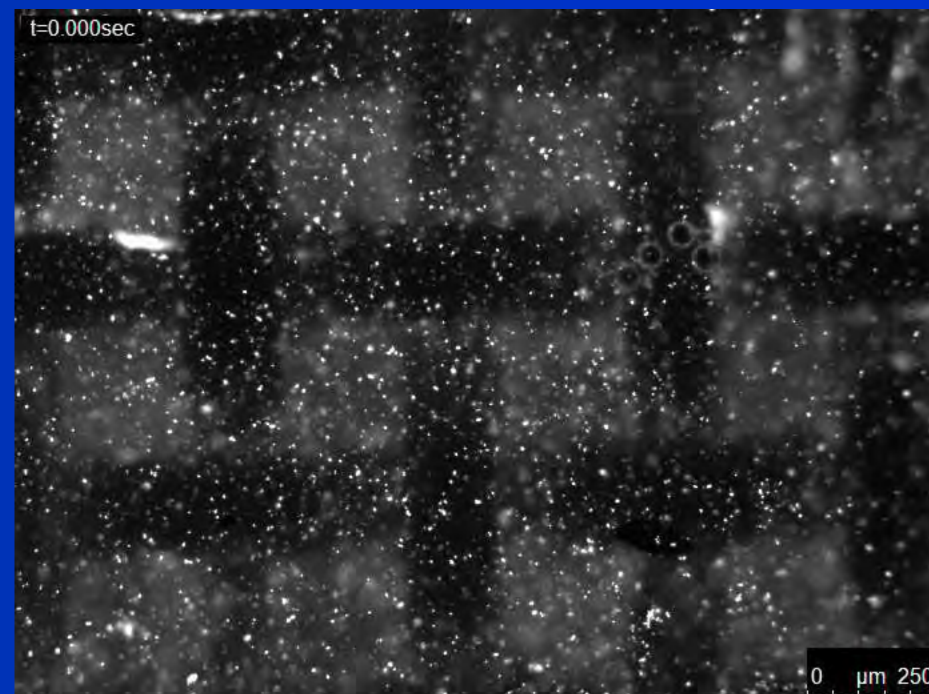
In heat treated mesh: primary as well as secondary pores due to oxide growth
Wire diameter tends to increase/swelling (8-12 µm)
Consequently, two length scales appear

Visualization of Thin-film Evaporation through Confocal Microscopy



Time evolution of menisci during evaporation in saturated screen mesh

Evaporation dynamics ?
Microscale fluid flow during evaporation ?



Fluid motion during thin film evaporation in saturated screen mesh

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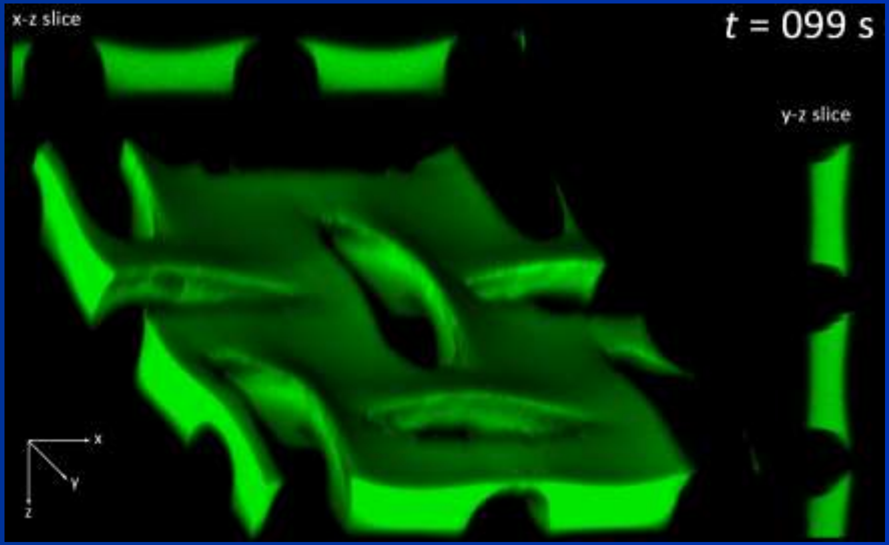
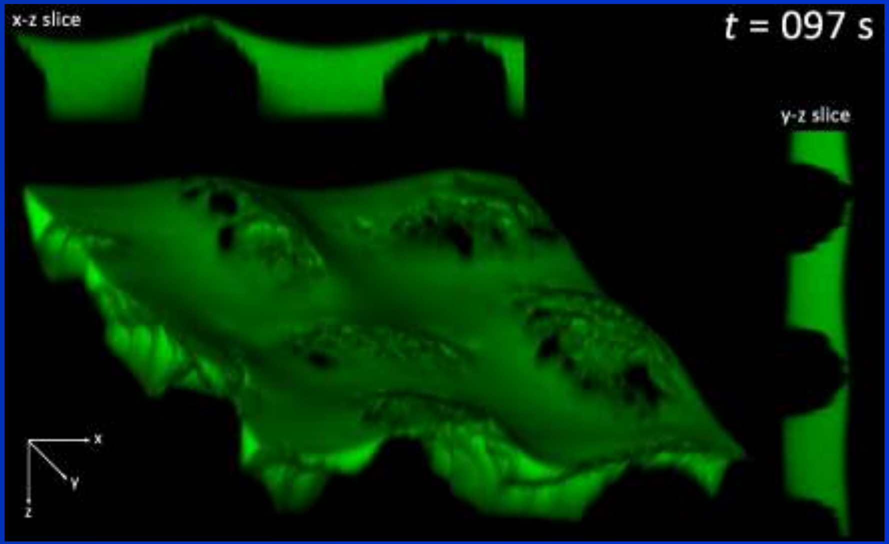
Visualization of Thin-film Evaporation through Confocal Microscopy



Untreated SS#100 mesh

No liquid film over the wires of mesh
Contact line motion on the wires
Higher meniscus RoC at rupture
Lesser time for complete evaporation



HT SS#100 mesh

Liquid film over the wires – secondary pore
No CL motion – secondary pore –film hold up
Lower meniscus RoC at rupture
Longer time for complete evaporation

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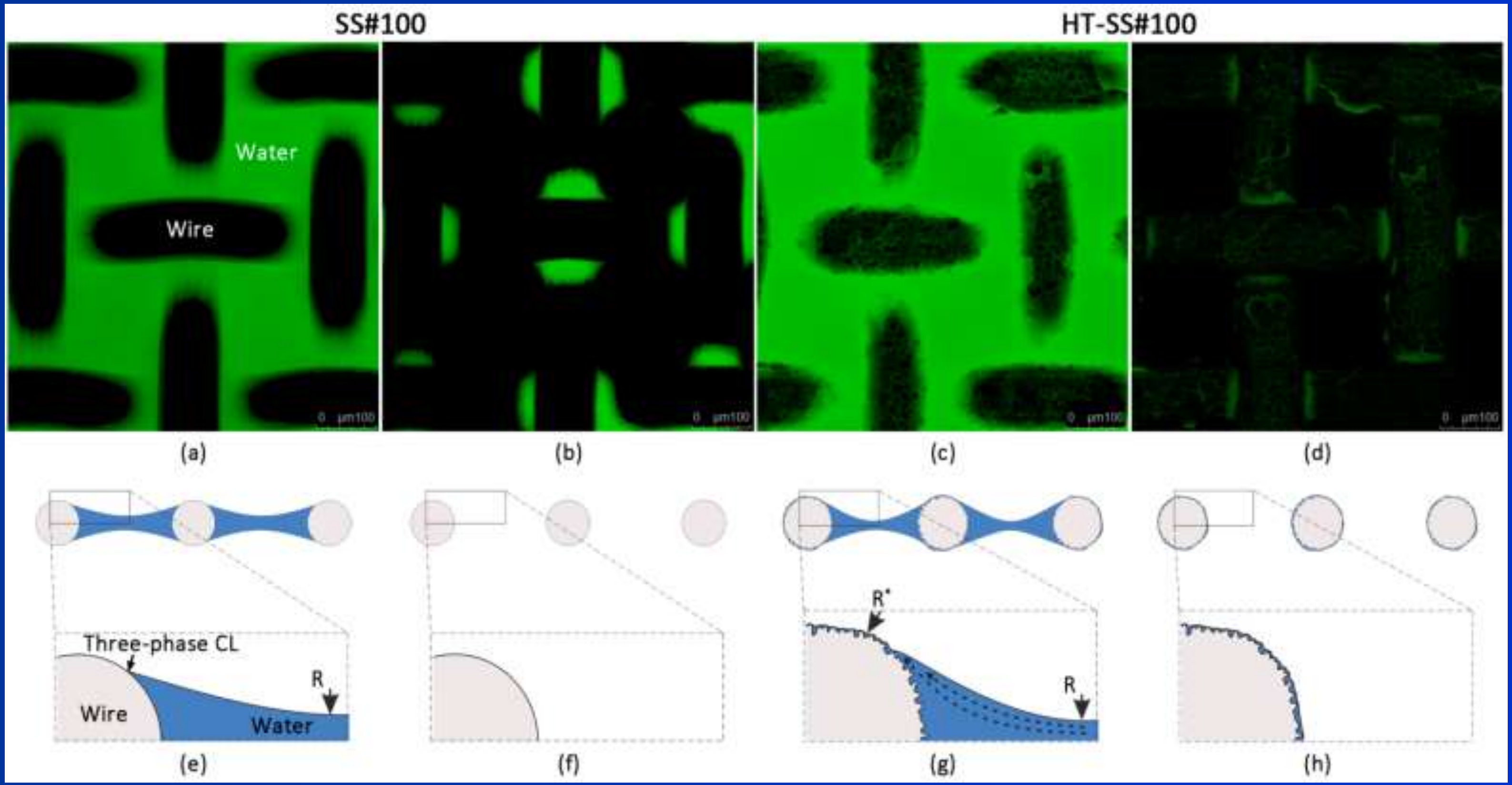
Evaporation Mechanism



Hydrophobic nature of untreated meshes – CL motion – No liquid at the wires

Larger pore spacing in untreated meshes – High meniscus RoC at ruptures

Untreated meshes take lower time to evaporate than HT mesh

HT meshes – completely wetting – secondary pores – increased pore saturation

Summary and Outlook

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Summary and Outlook

- Fluid-fluid and Fluid solid interfaces are ubiquitous in engineering systems
- Discerning thermo-hydrodynamics of interfaces poses challenging problems
- Local level transport is intrinsically linked with the system level performance
- Multiple-scales/physics interact manifesting a hierarchical problem definition (nano → micro → macro)
- To be meaningful, experiments require strict control of boundary conditions
- Several probing tools → effective exploitation needed to discern local physics
- Interdisciplinary skills need to be groomed in students → cooperation/sharing
- Interesting transport physics awaits exploration and translation into products!