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Numerical two-phase flows study in channels with variable cross-section

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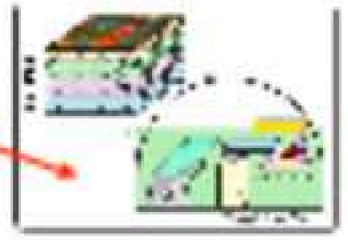
Outline

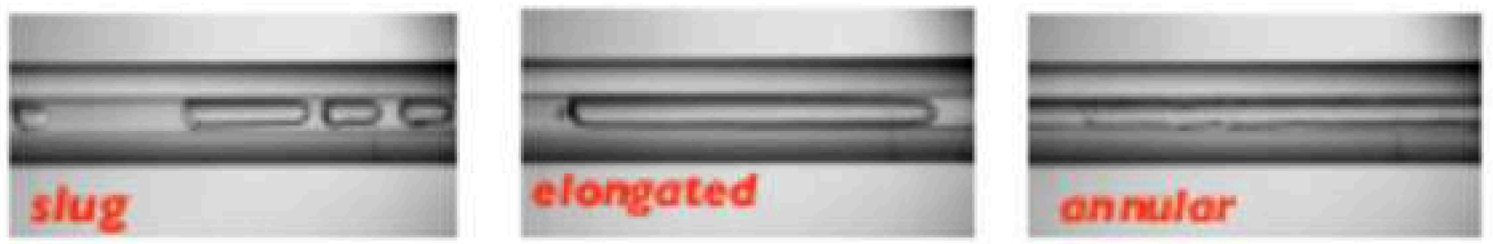
- Motivation;
- Numerical setup (*non-primitive* and *primitive variables*);
  - equations in axisymmetric coordinates;
  - sharp interface description for 2-phase flows;
- Some verifications/validations;
- Results: properties limits and bubble shape;
- Conclusions, further steps and key points.

Motivations

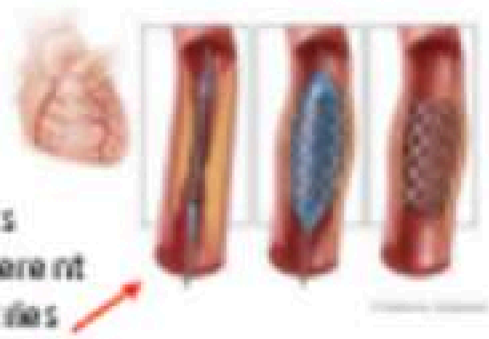
- cooling of electronics for new generation of stack microprocessors;

microchannels with different cross-sectional geometries





- cardiovascular artery disease (CAD);



stents with different geometries

Overview of Numerical Features

Finite Element code's features:

number of phases	1- and 2-phases (droplets and bubbles)
coordinate system	2D,3D and axisymmetric
pressure, diffusive terms	Galerkin method
convective terms	ALE (moving mesh) and SL methods
time discretization	1st./2nd. order forward differences
finite elements	linear, mini, quad, quad+bubble, cubic
linear systems	Projection method - LU
interface in 2-phase flows	Sharp transition, Geometric curvature
remeshing	insertion/contraction/flipping

Axi $\psi - \omega$ Eqs.

(ALE-FE Conjugated Heat-Transfer)

$$\frac{\partial \omega_z}{\partial t} + \mathbf{c}\cdot\nabla\omega_z = \frac{\omega_z v_r}{r} + \frac{1}{\mathrm{Re}}\left[\frac{\partial}{\partial r}\left(\frac{1}{r}\frac{\partial r\omega_z}{\partial r} + \frac{\partial^2 \omega_z}{\partial z^2}\right)\right]$$

$$\frac{\partial}{\partial r}\left(\frac{1}{r}\frac{\partial \psi}{\partial r}\right) + \frac{\partial^2}{\partial z^2}\left(\frac{\psi}{r}\right) = -\omega_z$$

$$\frac{\partial T}{\partial t} + \mathbf{c}\cdot\nabla T = \frac{1}{\mathrm{RePr}}\left[\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial T}{\partial r}\right) + \frac{\partial^2 T}{\partial z^2}\right]$$

Auxiliary:

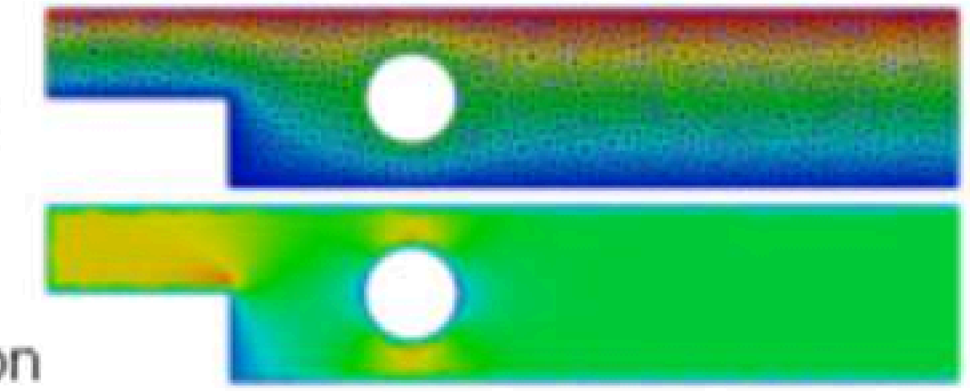
$$\mathbf{v} = (v_z, v_r) = \left(\frac{1}{r}\frac{\partial \psi}{\partial r}, -\frac{1}{r}\frac{\partial \psi}{\partial z}\right)$$

$$\omega_z = \frac{\partial v_r}{\partial z} - \frac{\partial v_z}{\partial r}$$

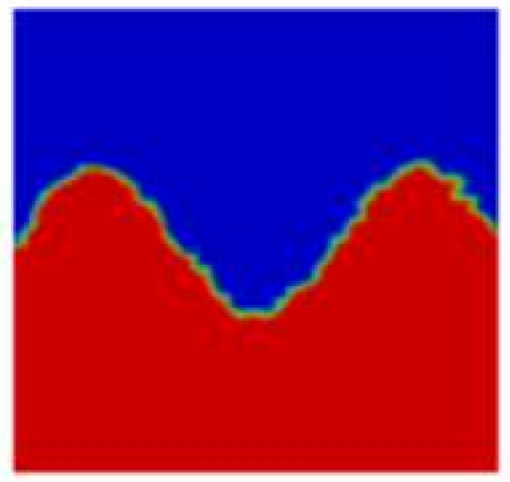
ALE formulation: $\frac{\partial \omega_z}{\partial t} + (\mathbf{v} - \hat{\mathbf{v}})\cdot\nabla\omega_z \begin{cases} \hat{\mathbf{v}} = \mathbf{v} \rightarrow \text{Lagrangian} \\ \hat{\mathbf{v}} = 0 \rightarrow \text{Eulerian} \end{cases}$

Validations

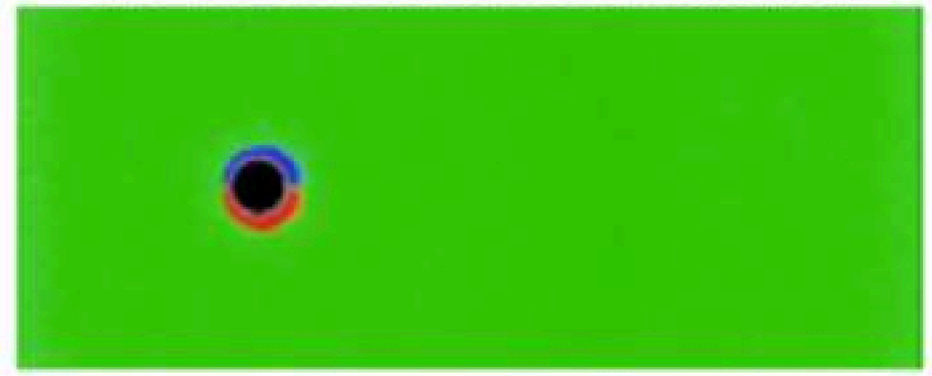
2D Backward facing step with hole



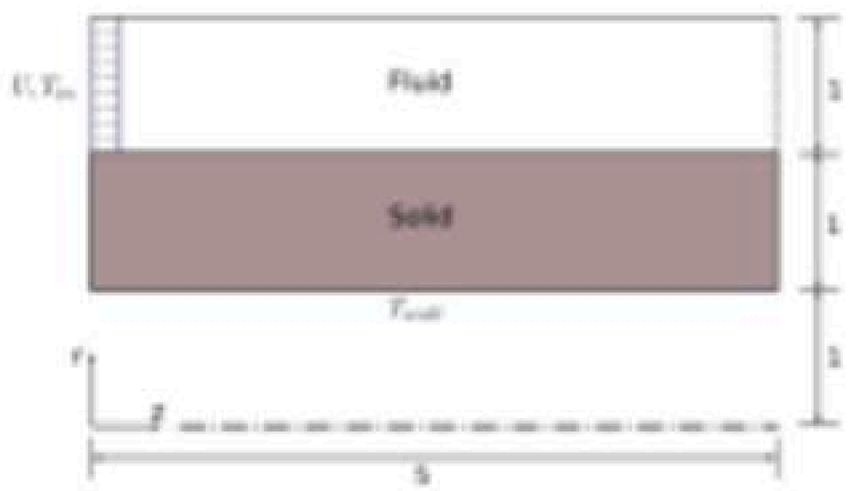
2D Natural Convection

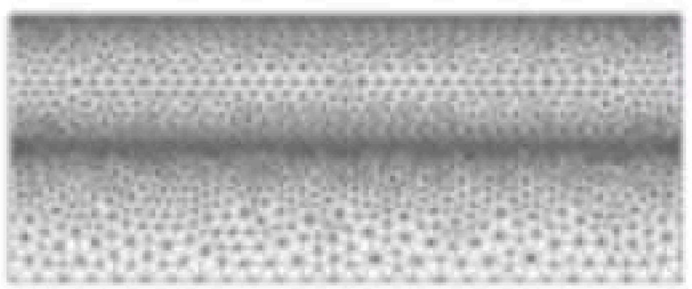


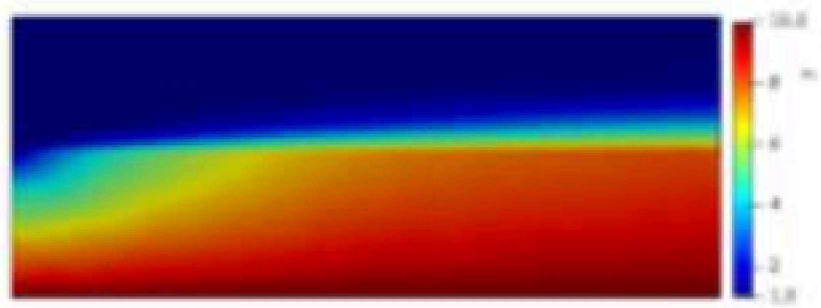
2D Vortex-Induced Vibration

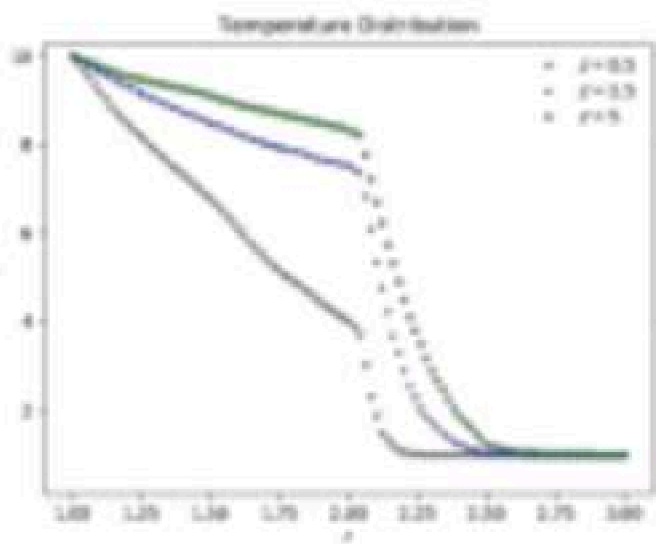


Results for Axisymmetric Conjugated Heat Transfer









Axi Navier-Stokes Eqs.

(ALE-FE 2-phase flows)

$$\rho(\mathbf{x})\left[\frac{\partial \mathbf{v}}{\partial t} + \mathbf{c}\cdot\nabla\mathbf{v}\right] = -\nabla p + \frac{1}{\mathrm{N}^{1/2}}\nabla\cdot\mu(\mathbf{x})\left[\nabla\mathbf{v} + \nabla\mathbf{v}^T\right] + \rho(\mathbf{x})\mathbf{g} + \frac{1}{\mathrm{Eo}}\mathbf{f}_{st}$$

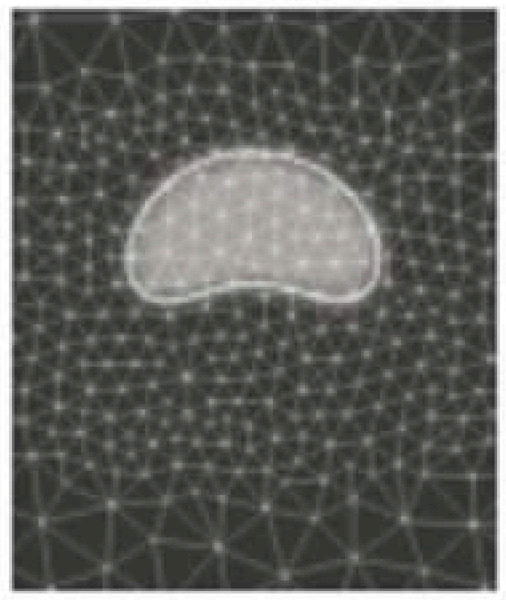
$$\nabla\cdot\mathbf{v} = 0$$

where: $\nabla^T = [\frac{\partial}{\partial r}; \frac{\partial}{\partial x}]$ $\quad \nabla\cdot = [\frac{1}{r}\frac{\partial}{\partial r}r; \frac{\partial}{\partial x}]$ $\quad \mathbf{f}_{st} = \kappa\mathbf{n}\delta$

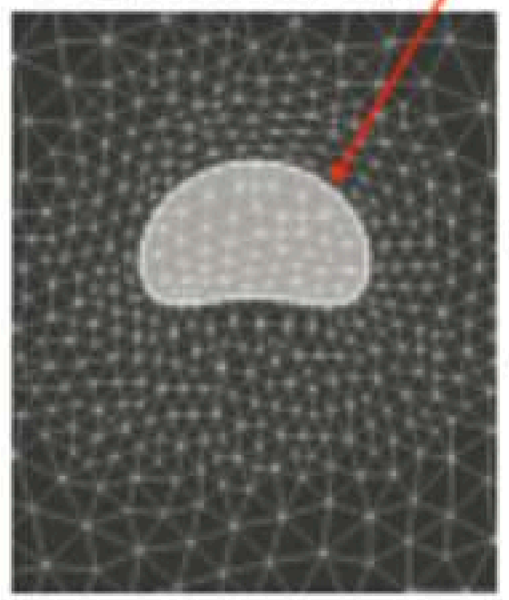
ALE formulation: $\frac{\partial \mathbf{v}}{\partial t} + (\mathbf{v} - \hat{\mathbf{v}})\cdot\nabla\mathbf{v} \begin{cases} \hat{\mathbf{v}} = \mathbf{v} \rightarrow \text{Lagrangian} \\ \hat{\mathbf{v}} = 0 \rightarrow \text{Eulerian} \end{cases}$

Interface definition

Uncoupled approach (interface and background mesh disconnected) *Level-Set, VOF, Inter. Tracking, ALE



Coupled approach (interface and background mesh connected) Lagrangian, *ALE (present work)



sharp transition across phases for fluid properties

surface tension calculation (Frenet-Serret)

$$\kappa_{2d}\,\vec{n} = \frac{d\vec{t}}{ds} \approx \frac{\vec{t}_2 - \vec{t}_1}{\Delta s}$$

$$\kappa = \kappa_{2d} + \frac{1}{R} = \kappa_{2d} + \frac{\sin(\phi)}{r}$$

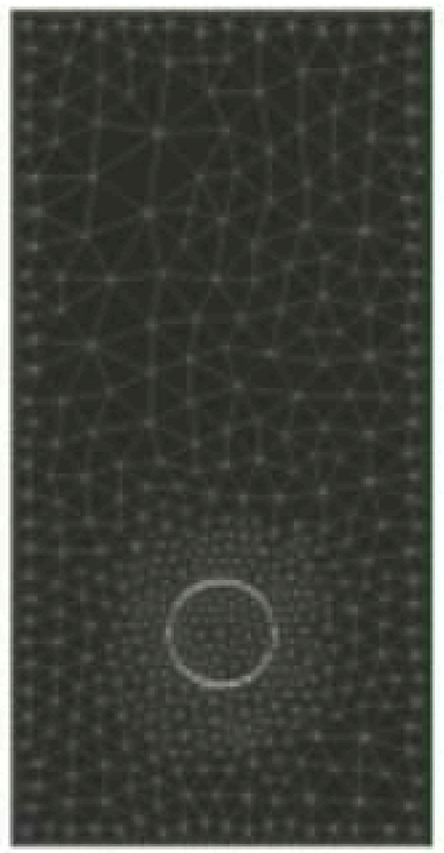
The method in action

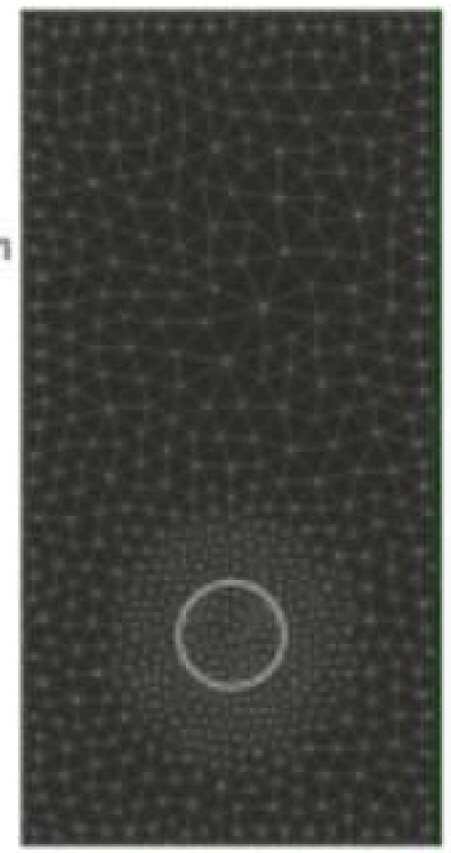
Coupled approach

- sharp transition
- Lagrangian motion of interface
- remeshing is required
- explicit location of interface

Uncoupled approach

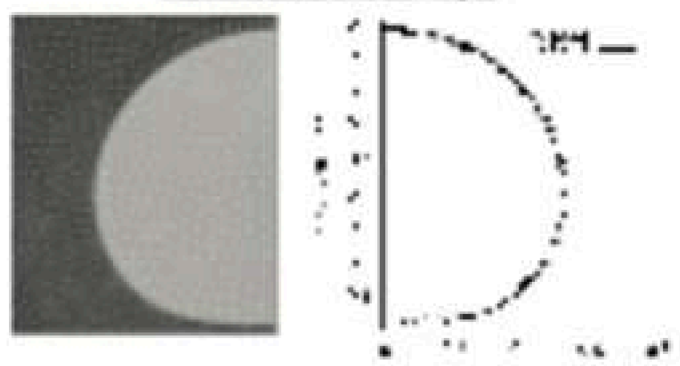
- smooth transition
- more nodes are required
- implicit location of interface



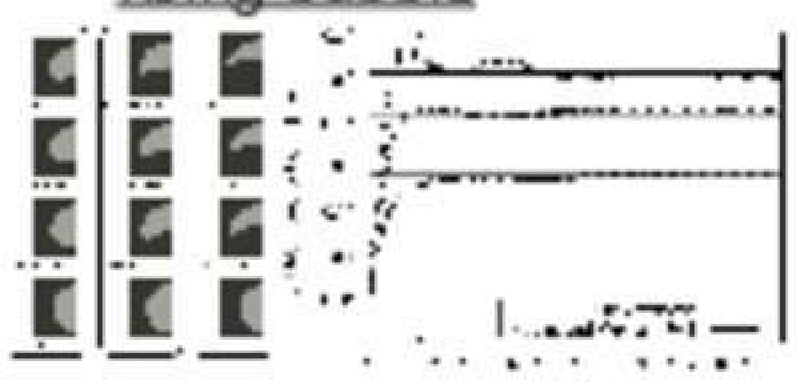


Validations

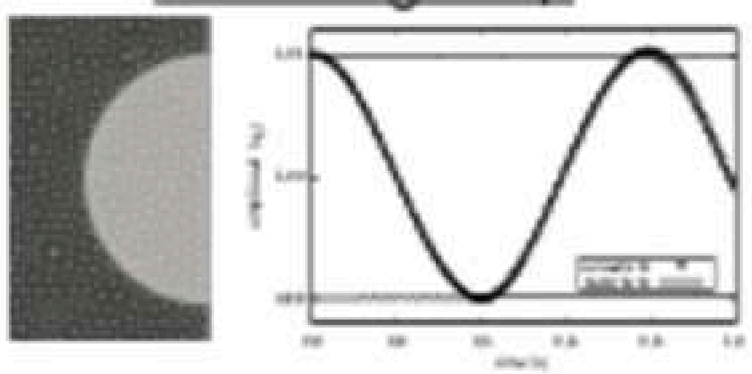
sessile drop



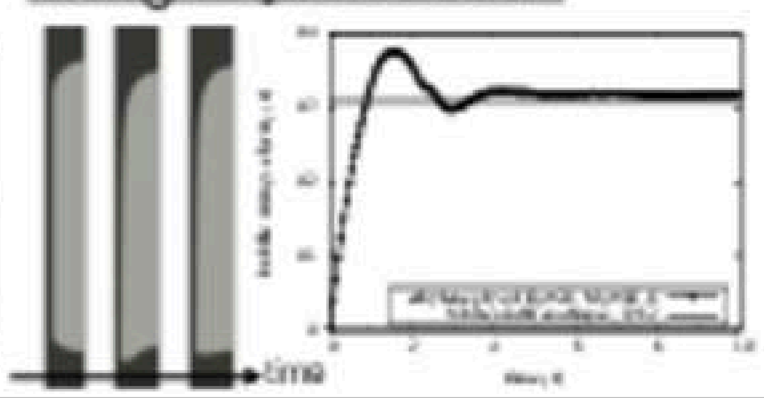
rising bubble



oscillating drop

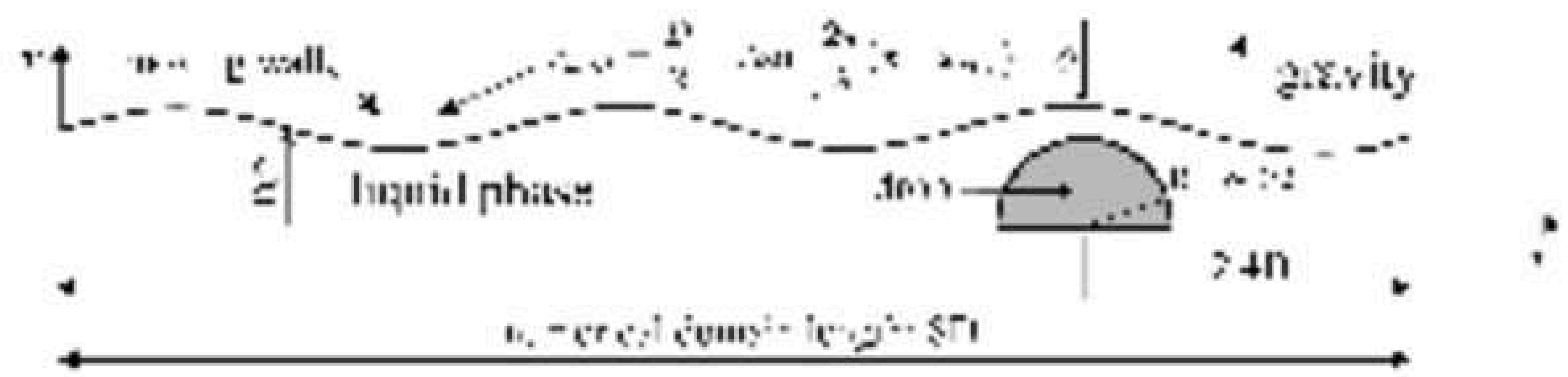


rising Taylor bubble



Geometries

Corrugated channel



wall moves as: $r_{wall} = \frac{D}{2} + A\sin\left\{\frac{2\pi}{\lambda}(x + x_{ref}) - \phi\right\}$

where x_{ref} is bubble's nose position

Properties limits

system	μ_{out}	μ_{in}	ρ_{out}	ρ_{in}	σ	ω	N	Eo	Mo
–	$(Pa.s)$	$(Pa.s)$	(kg/m^3)	(kg/m^3)	(N/m)	(Hz)	[–]	[–]	[–]
GW1	450E-3	238E-3	1250	967	0.0240	25.30	75.7	51.1	23.3
● GW3	450E-3	530E-3	1250	995	0.0105	0.01	75.7	116.8	277.9
GW5	450E-3	97E-3	1250	950	0.0057	12.39	75.7	49.1	20.6
GW8	450E-3	607E-3	1250	993	0.0250	25.63	75.7	49.1	20.6
WG1	190E-3	238E-3	1230	967	0.0230	24.85	411.1	52.5	0.8
WG2	67E-3	83E-3	1200	970	0.0019	7.18	3146.9	619.6	24.0
WG4	93E-3	104E-3	1220	990	0.0257	26.15	1688.2	46.6	0.04
● DEGG3	28E-3	530E-3	1110	995	0.0032	9.41	15416.9	340.3	0.16
DEGG10	28E-3	63E-3	1110	975	0.0016	6.69	15416.9	680.6	1.33
DEGG11	87E-3	157E-3	1160	968	0.0050	11.74	1744.0	227.6	3.8
● DEGG12	87E-3	115E-3	1160	966	0.0042	10.76	1744.0	270.9	6.53

spherical bubble frequency: $\omega^2 = \dfrac{n(n+1)(n-1)(n+2)\sigma}{[(n+1)\rho_{in} + n\rho_{out}]R^3}$

U. Olgac, A. D. Kayaalp, M. Muradoglu 2006

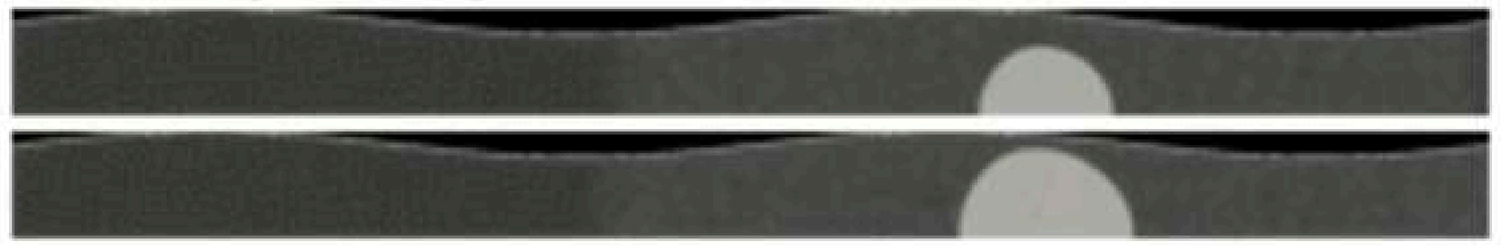
M. Hemmat & A. Borhan, 1996

Results for A=0.07D

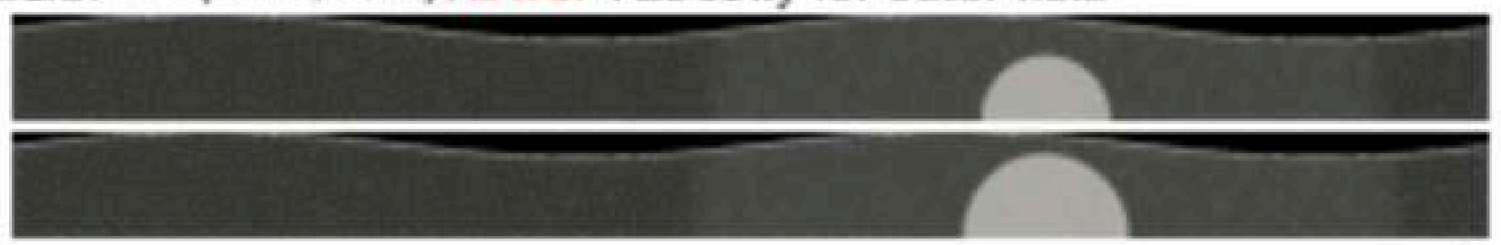
(I)

GW3: $\kappa = \{0.78, 0.97\}$, higher viscosity for outer fluid

DEGG 12: $\kappa = \{0.73, 0.95\}$

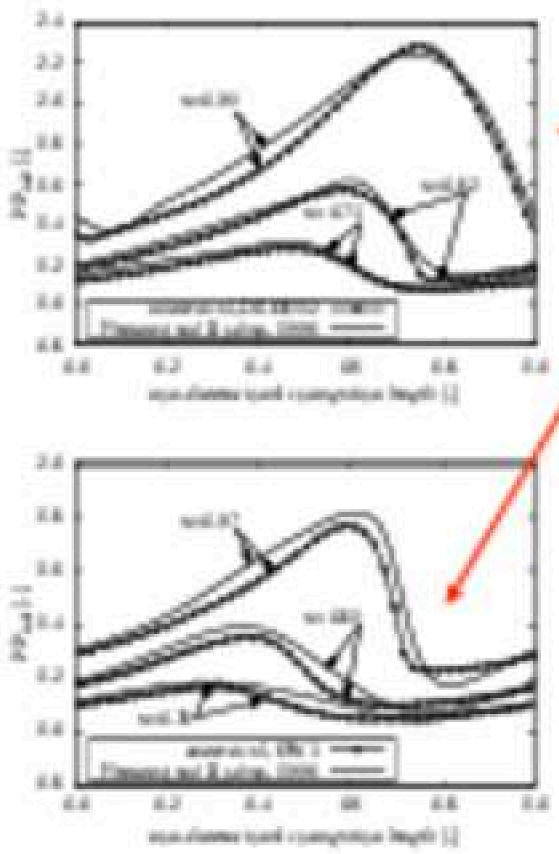


DEGG3: $\kappa = \{0.70, 0.90\}$, lower viscosity for outer fluid

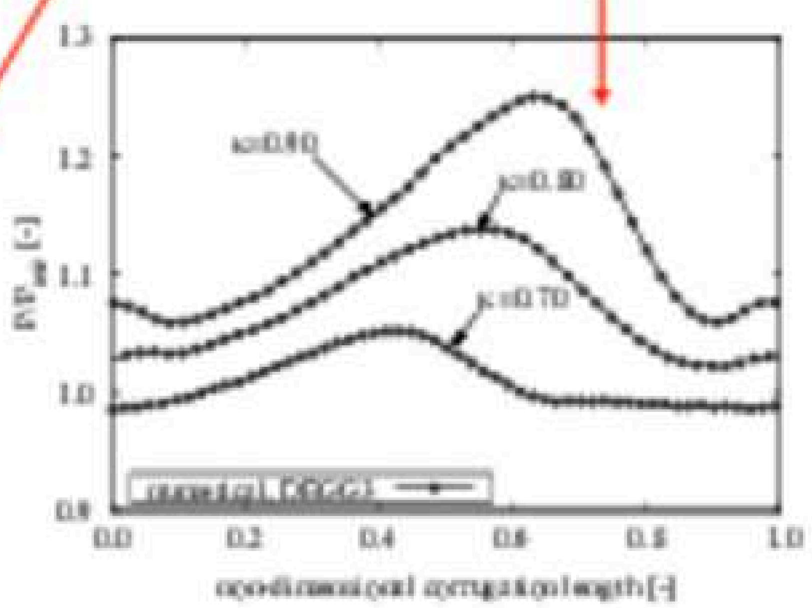


Comparisons

(II)



Comparison with *Hemmat and Borhan, 1996* experiments. Additionally, **new** results for DEGG3



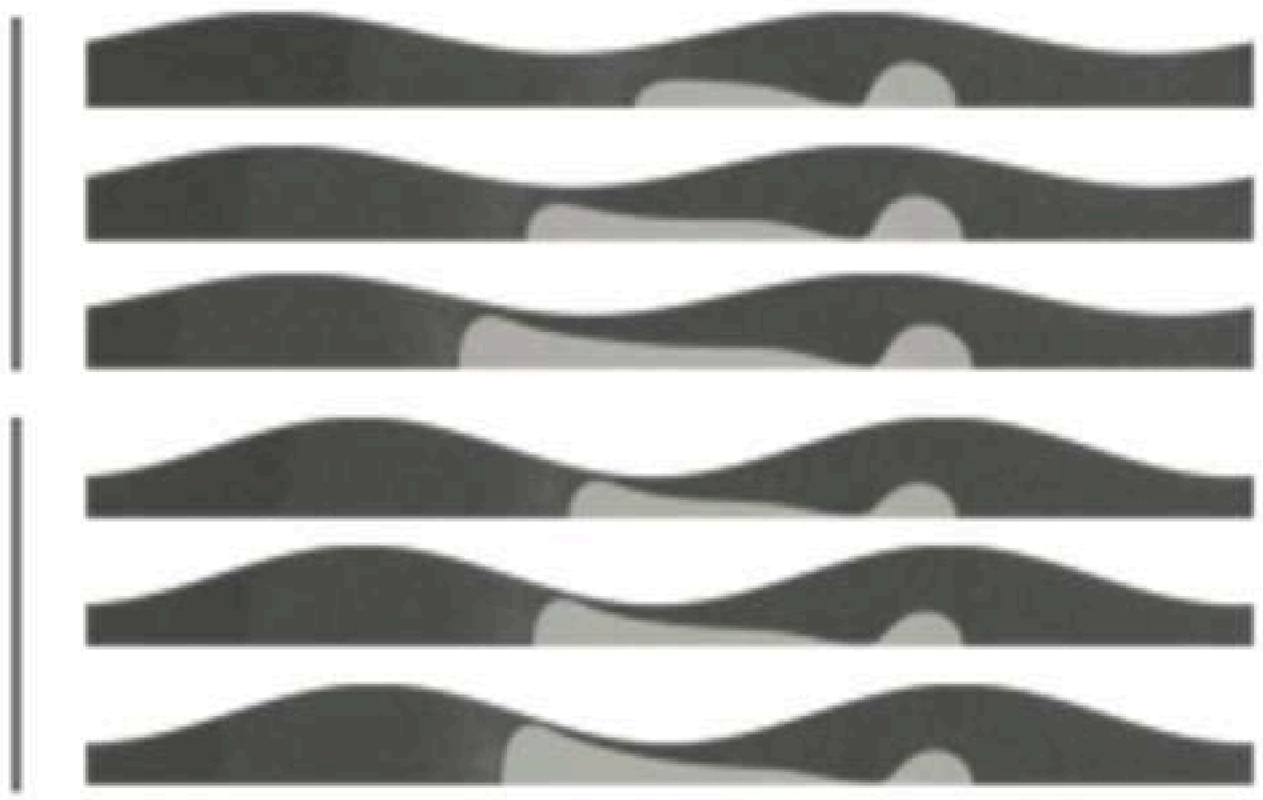
Results

(III)

DEGG 12: k={0.73,0.82,0.95}

A=0.14

A=0.21



Conclusions/Further steps/Key points

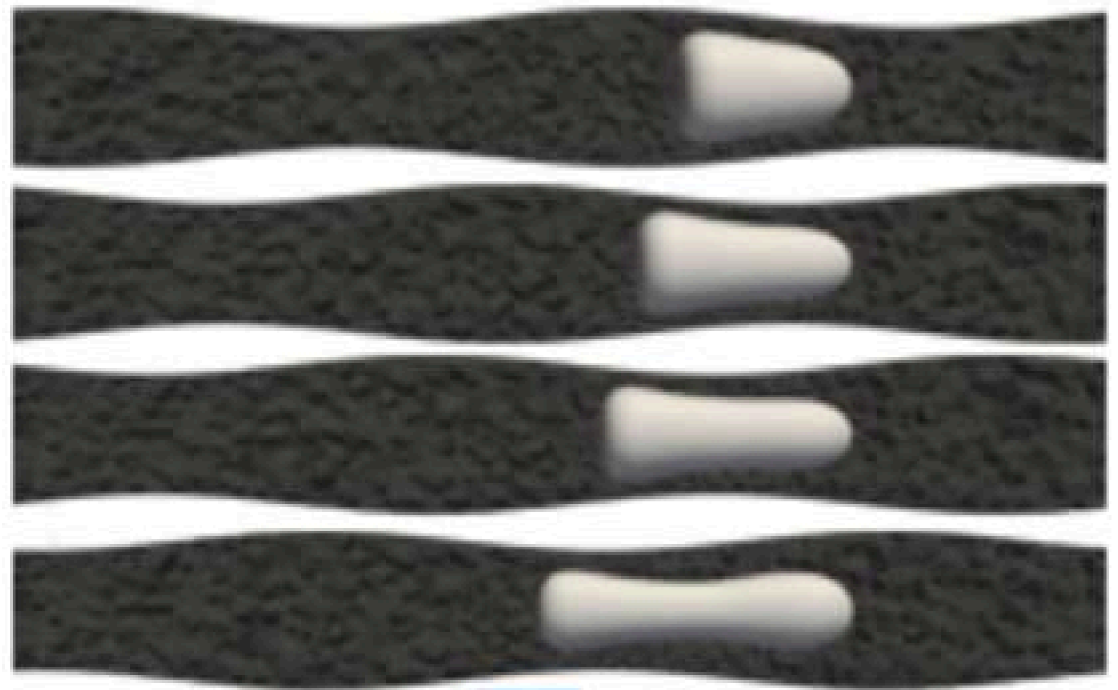
- moving mesh/boundary technique facilitates study of **periodic** and **very long** geometries and can be easily extend to any ALE CFD method
- study about bubble dynamics in two-phase systems with long periodic channels;
- numerics evaluated several flow parameters as bubble shape, capillary effects, bubble velocity and liquid film thickness;
- bubble's resonance frequency vs channel pattern;
- effects of oscillation and perturbation on bubble's path;
- 2-phase fluid-structure interactions.

- when does bubble break up in corrugated channels occurs?
- is CFD a *reasonable* approach for modeling bubble **brakup**/**coalescence**?

Thanks!

on-going 3D simulations

time



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