Computing Complex Flows using a Front Tracking Method

Grétar Tryggvason
Worcester Polytechnic Institute

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DNS of Multiphase Flows
Outline

Motivation

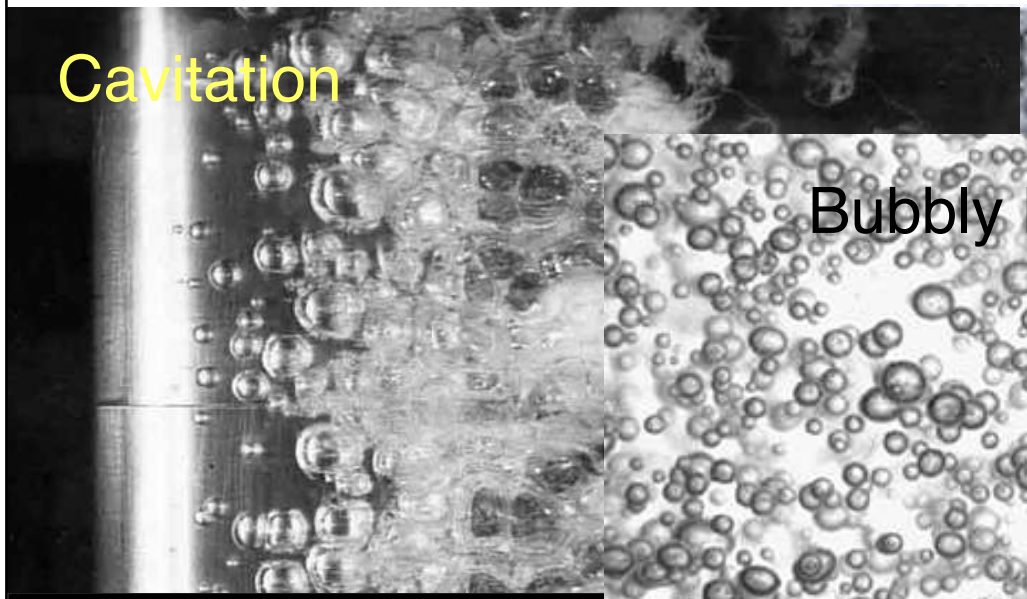
Numerical approach

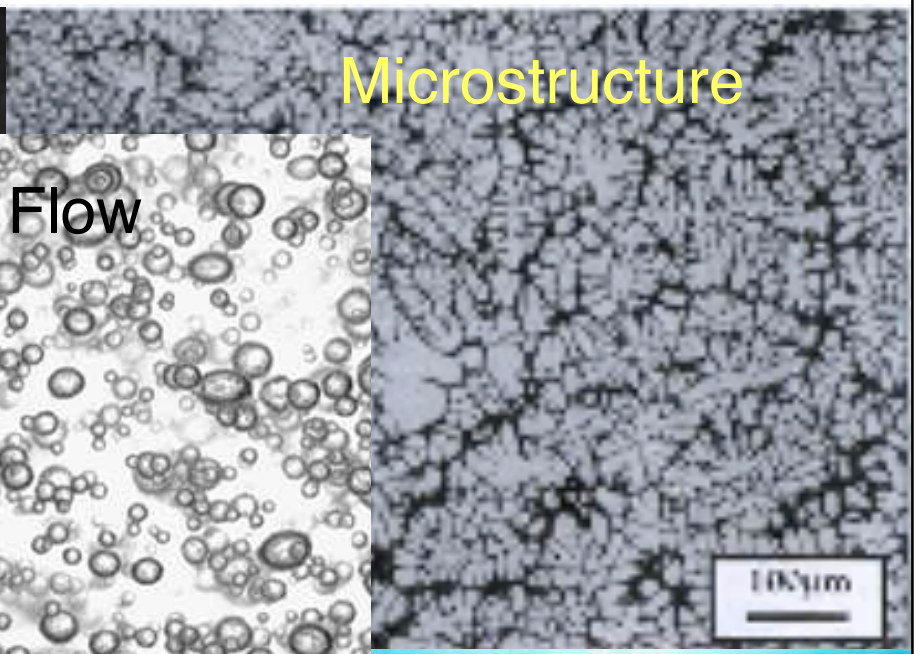
Simulations of bubbly channel flows

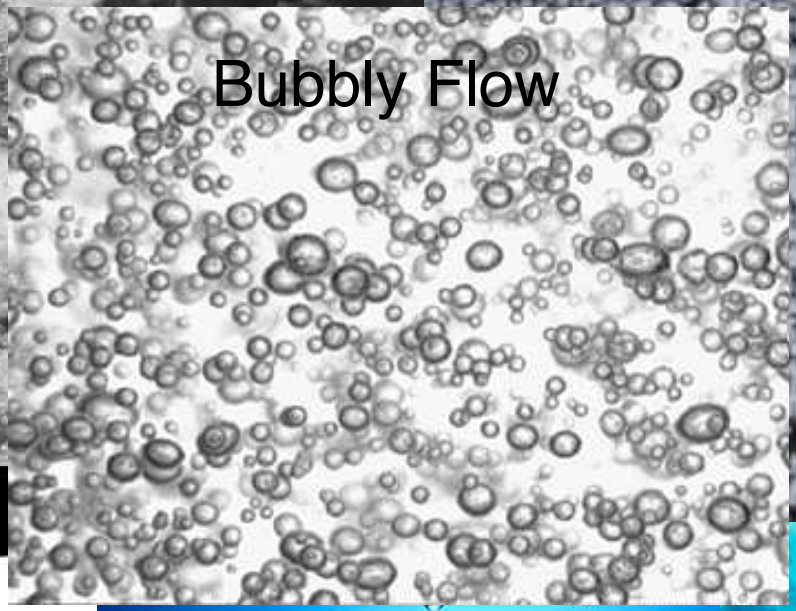
More complex systems
- Other fields
- Boiling
- Multiscale issues

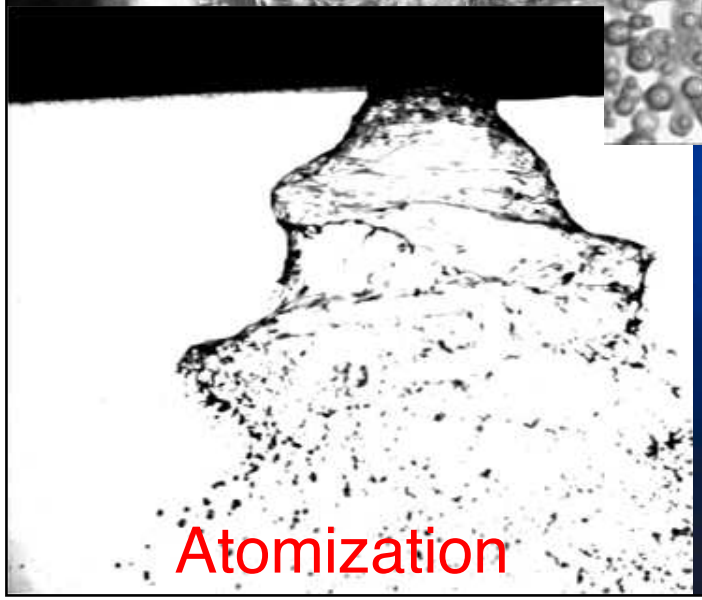
Outlook and current issues

DNS of Multiphase Flows
Motivation and Goals









DNS of Multiphase Flows
Motivation and Goals

The goal is to simulate accurately the smallest continuum scales for multiphase systems that are sufficiently large so that meaningful averages can be obtained and the results used to help generate insight and closure models for engineering tools

Example: The "two-fluid model"

$$\frac{\partial}{\partial t}\varepsilon_p\rho_p + \nabla\cdot\left(\varepsilon_p\rho_p\mathbf{u}_p\right) = \dot{m}_p$$

$$\frac{\partial}{\partial t}\left(\varepsilon_p\rho_p\mathbf{u}_p\right) + \nabla\cdot\left(\varepsilon_p\rho_p\mathbf{u}_p\mathbf{u}_p\right) = -\varepsilon_p\nabla p_p$$

$$+\nabla\cdot\left(\varepsilon_p\mu_p\mathbf{D}_p\right) + \varepsilon_p\rho_p\mathbf{g} + \nabla\cdot\left(\varepsilon_p\rho_p < uu >\right) + \mathbf{F}_{\text{int}}$$

Equations for the average motion of each constituent

Reynolds stresses

interfacial forces

Volume average of f_i

$$\langle f_i\rangle = \frac{1}{\varepsilon_i Vol}\int_V \chi_i(\boldsymbol{x},t) f_i(\boldsymbol{x},t)dv$$

Characterization of the interface

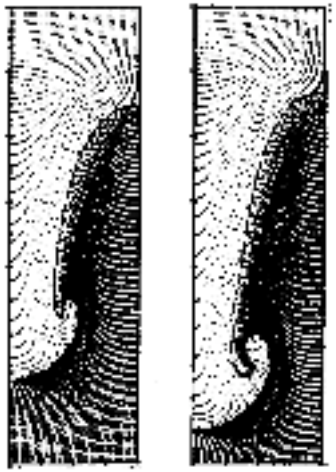
$$\frac{1}{Vol}\int_s \boldsymbol{nn}\,da \qquad \frac{1}{Vol}\int_s \boldsymbol{nnnn}\,da$$

Structure functions, turbulent quantities, etc.

Computational Approach

CFD of Multiphase Flows—one slide history

BC: Birkhoff and boundary integral methods for the Rayleigh-Taylor Instability



From: B. Daly (1969)

65’ Harlow and colleagues at Los Alamos: The MAC method

75’ Boundary integral methods for Stokes flow and potential flow

85’ Alternative approaches (body fitted, unstructured, etc.)

95’ Beginning of DNS of multiphase flow. Return of the “one-fluid” approach and development of other techniques

DNS of Multiphase Flows
Numerical Method

Conservation of Momentum

$$\rho\frac{\partial \boldsymbol{u}}{\partial t}+\rho\nabla\cdot\boldsymbol{uu}=-\nabla p+\boldsymbol{f}+\nabla\cdot\mu\left(\nabla\boldsymbol{u}+\nabla^{T}\boldsymbol{u}\right)+\int_{F}\sigma\kappa\mathbf{n}\delta\left(\boldsymbol{x}-\boldsymbol{x}_{f}\right)da$$

Singular interface term

Conservation of Mass

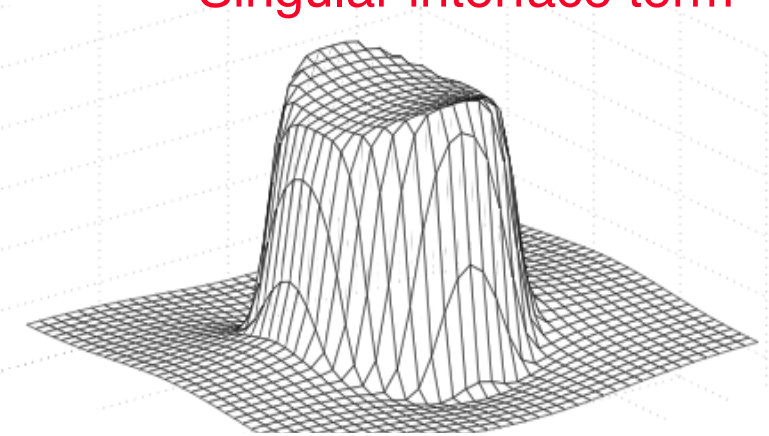
$$\nabla\cdot\boldsymbol{u}=0$$

Incompressible flow

Equation of State:

$$\frac{D\rho}{Dt}=0;\quad\frac{D\mu}{Dt}=0$$

Constant properties



Oscillating drop: pressure

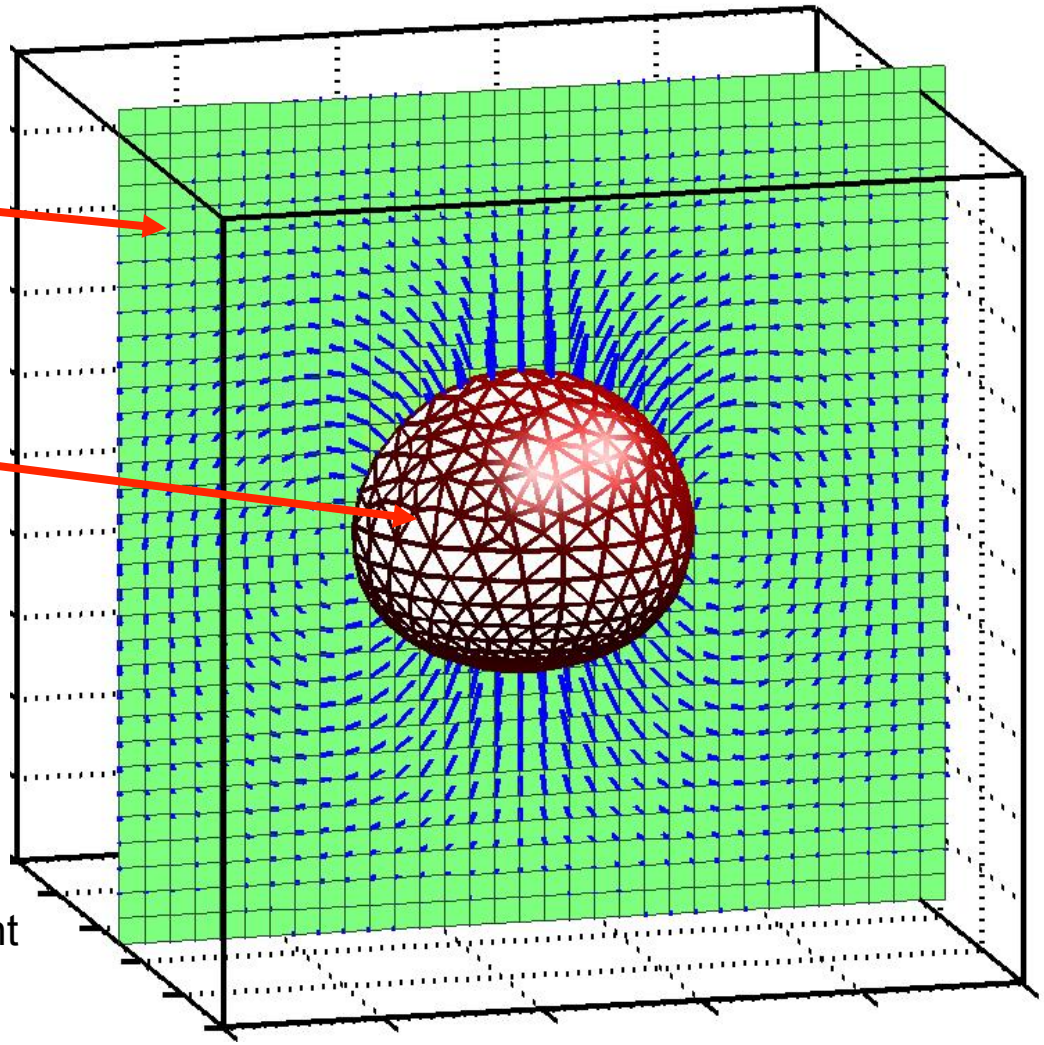
The conservation equations are solved on a regular fixed grid and the front is tracked by connected marker points.
The “one fluid” formulation of the conservation equations is the starting point for several numerical methods, including MAC, VOF, level sets, and front tracking.

Front Tracking

Fixed grid used for the solution of the Navier-Stokes equations

Tracked front to advect the fluid interface and find surface tension

The method has been used to simulate many problems and extensively tested and validated



S.O. Unverdi, G. Tryggvason. "A Front Tracking Method for Viscous Incompressible Flows." *J. Comput. Phys,* 100 (1992), 25-37.

DNS of Multiphase Flows
Interpolating from grid

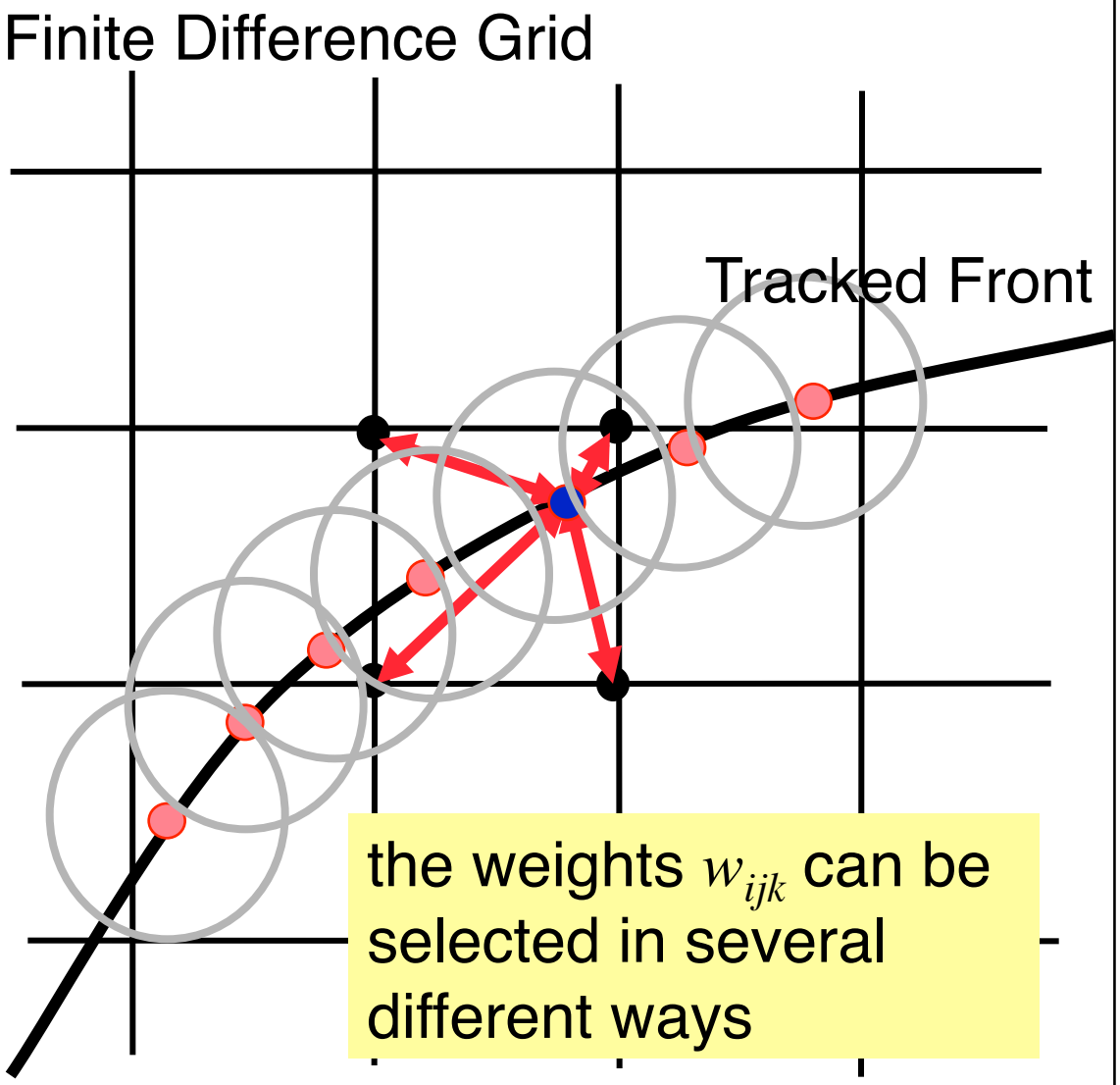
The velocities are interpolated from the grid:

$$\phi_l = \sum \phi_{ijk} w_{ijk}$$

The front values are distributed onto the grid by

$$\phi_{ijk} = \sum \phi_l w_{ijk} \frac{\Delta s_l}{h^3}$$

On the front: per length
On the grid: per volume



DNS of Multiphase Flows
Numerical Method

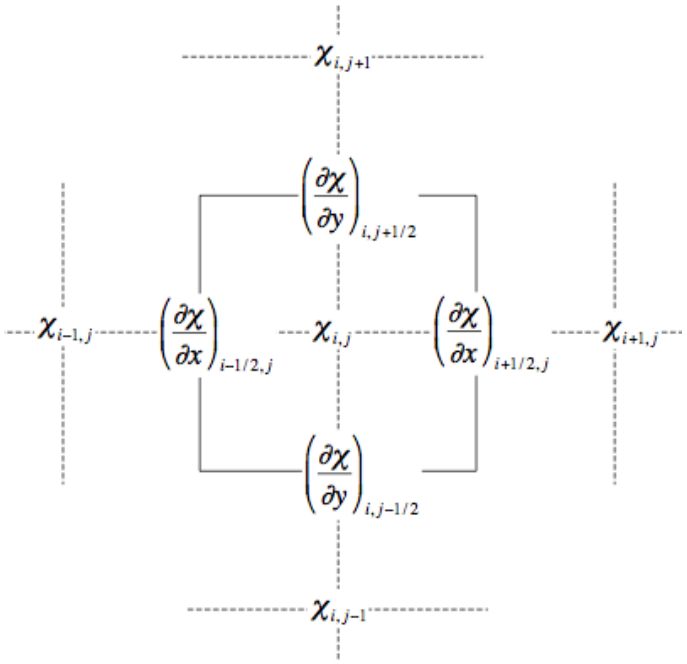
Construction of the density from the gradient

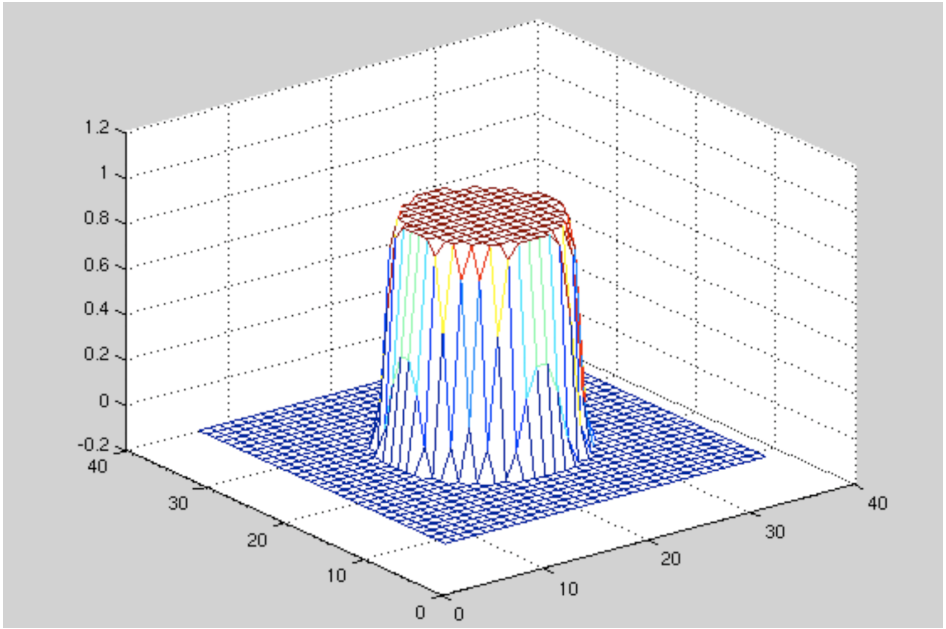
$$\chi_{i,j} = \chi_{i-1,j} + \Delta x \left(\partial\chi/\partial x\right)_{i+1/2,j}$$

$$\chi_{i,j} = \frac{1}{4}\left(\chi_{i+1,j} + \chi_{i-1,j} + \chi_{i,j-1} + \chi_{i,j+1} + \right.$$

$$\left. \Delta x \left(\partial\chi/\partial x\right)_{i+1/2,j} - \Delta x \left(\partial\chi/\partial x\right)_{i-1/2,j} + \Delta y \left(\partial\chi/\partial y\right)_{i,j+1/2} - \Delta y \left(\partial\chi/\partial y\right)_{i,j-1/2}\right)$$

Solved in a narrow band around the interface



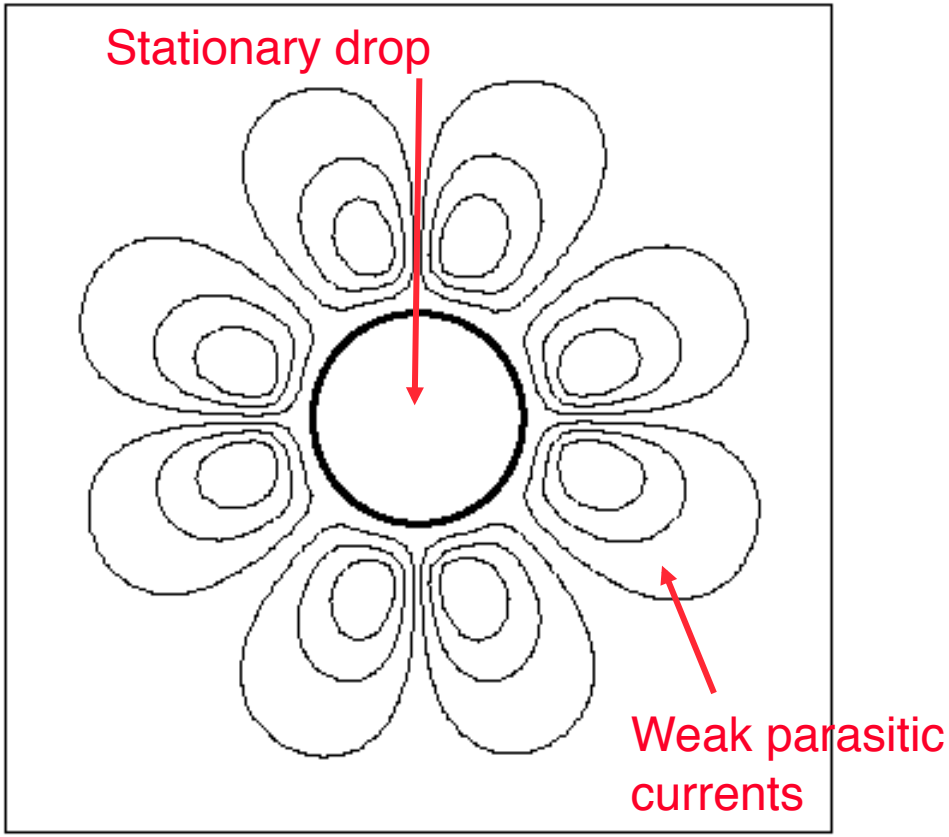


Parasitic Currents

The regular grid induces a small anisotropy. These currents are typically small in immersed boundary methods.

At steady state the pressure gradient should be balanced by surface tension

$$\nabla_h p + \mathbf{f}_\sigma^n = 0$$



DNS of Multiphase Flows
Numerical Method—Surface Tension

Surface tension can be added in several ways:

$$\mathbf{f}_{ij} = (\sigma\kappa)_{ij} \nabla I_{ij}$$

grid-grid

Curvature and normal vector computed directly on the fixed grid—marker function

$$\mathbf{f}_{ij} = (\sigma\kappa)^f_{ij} \nabla I^f_{ij}$$

front-front

Curvature and normal vector computed on the front, distributed to the fixed grid —our original approach

$$\mathbf{f}_{ij} = (\sigma\kappa)^f_{ij} \nabla I_{ij}$$

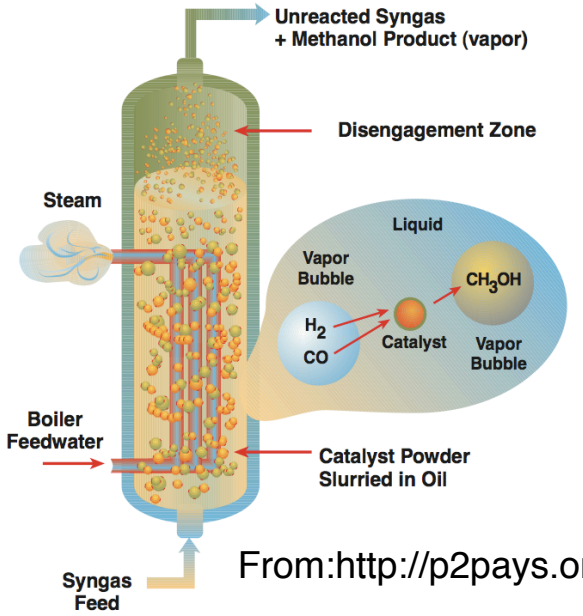
front-grid

Curvature computed on the front, distributed to the fixed grid. Normal vector computed on the grid

The last approach seems to combine the accuracy of tracking with the possibility of balancing pressure exactly

Bubbly Flows

DNS of Multiphase Flows
Why Multiphase Flows are Important!



Liquid Phase Methanol (LPMEOH™) Process

From:http://p2pays.org/ref/16/15865.pdf

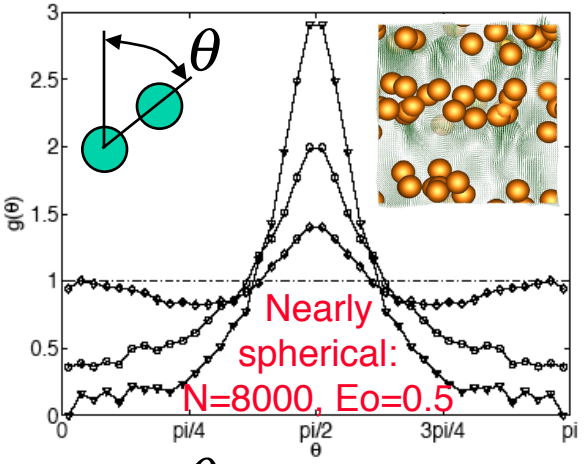
Examples of Applications of Bubble Columns

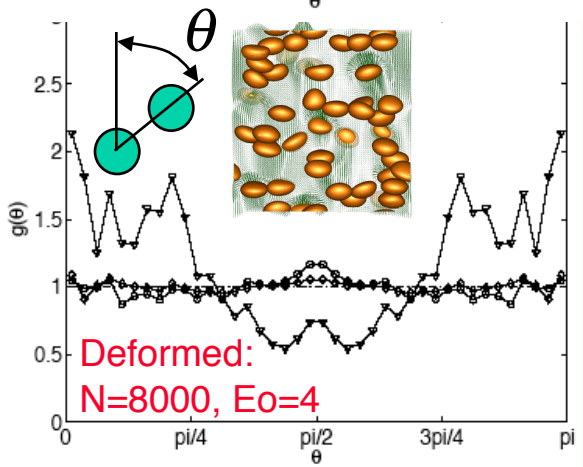
Process	Methods and/or Reactants
Acetone	Oxidation of cumene
Acetic acid	Oxidation of acetaldehyde
	Oxidation of sec-butanol
	Carbonylation of methanol
Acetic anhydride	Oxidation of acetaldehyde
Acetaldehyde	Partial oxidation of ethylene
Acetophenone	Oxidation of ethylbenzene
Barium chloride	Barium sulfide and chlorine
Benzoic acid	Oxidation of toluene
Bleaching powder	Aqueous calcium oxide and chlorine
Bromine	Aqueous sodium bromide and chlorine
Butene	Absorption in aqueous solutions of sulfuric acid
Carbon Dioxide	Absorption in ammoniated brine
Carbone tetrachloride	Carbon disulphide and chlorine
Copper oxychloride	Oxidation of cuprous chloride
Cumene	Oxidation of phenol
Cupric chloride	Copper and cupric acid or hydrochloric acid
Dichlorination	Oxychlorination of ethylene
Ethyl benzene	Benzene and ethylene
Hexachlorobenzene	Benzene and chlorine
Hydrogen peroxide	Oxidation of hydroquinone
Isobutylene	Absorption in aqueous solutions of sulfuric acid
Phtalic acid	Oxidation of xylene
Phenol	Oxidation of cumene
Potassium bicarbonate	Aqueous potassium carbonate
Sodium bicarbonate	Aqueous sodium carbonate
Sodium metabisulphides	Carbon dioxide, aqueous sodium carbonate, and sulfur dioxide
Thiuram disulphides	Dithiocarbamates, chlorine, and air
Vinyl acetate	Oxidation of ethylene in acetic acid solutions
Water	Wet oxidation of waste water

After: S. Furusaki, L.-S. Fan, J. Garside. **The Expanding World of Chemical Engineering** (2nd ed), Taylor & Francis 2001

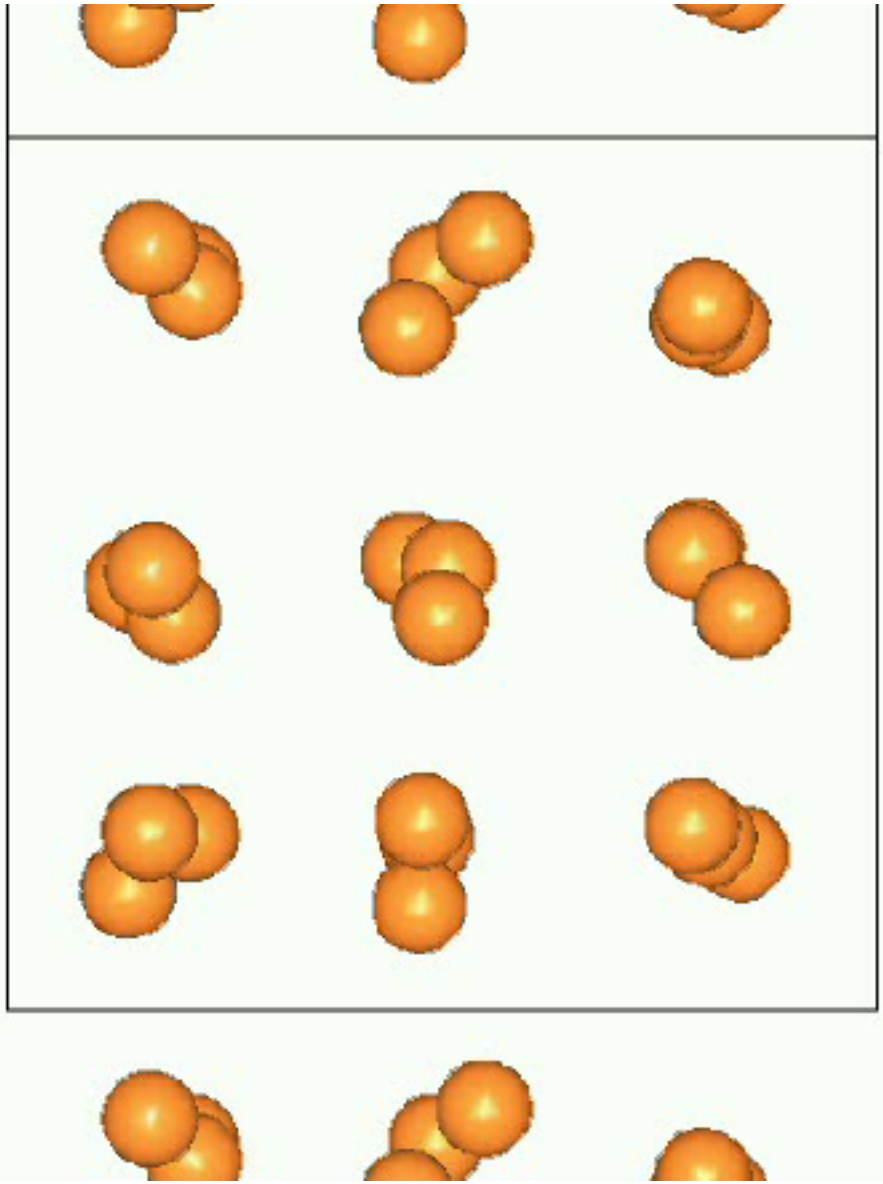
DNS of Multiphase Flows
Applications of DNS to bubbly flows

Angular pair probability distribution



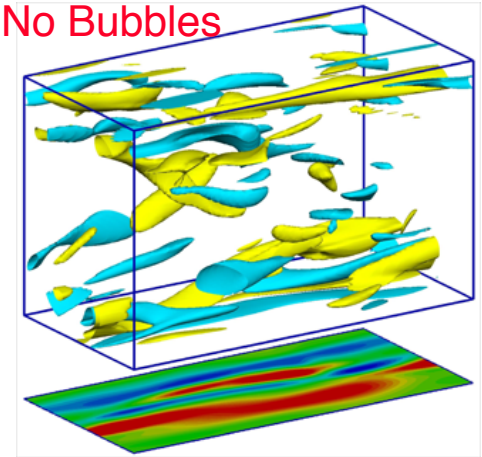


$$G(\bar{r}) = \frac{V}{N(N-1)} \left\langle \sum_i \sum_{j \neq i} \delta(\bar{r} - \bar{r}_{ij}) \right\rangle$$

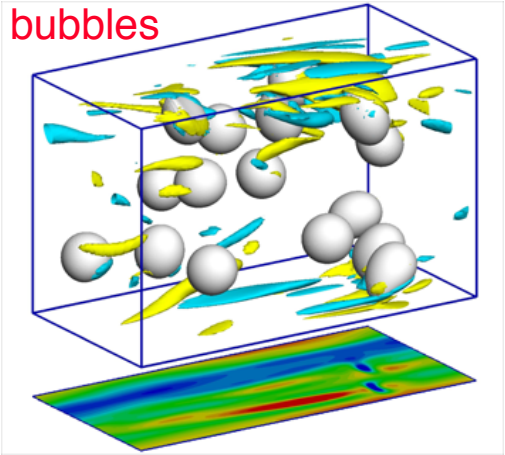


DNS of Multiphase Flows
Bubble Induced Drag Reduction

No Bubbles

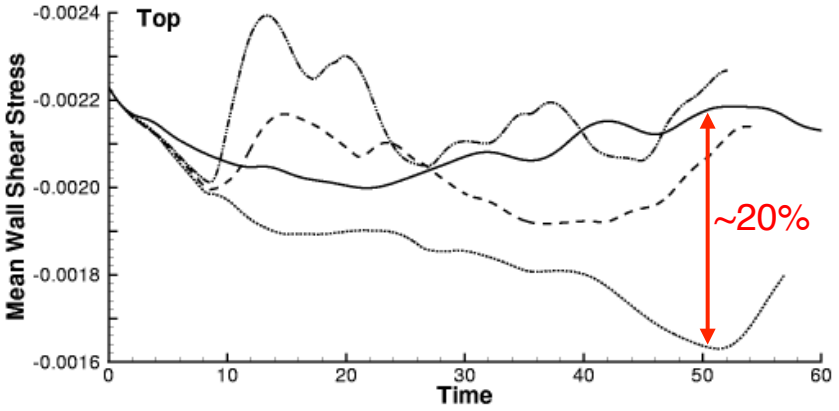


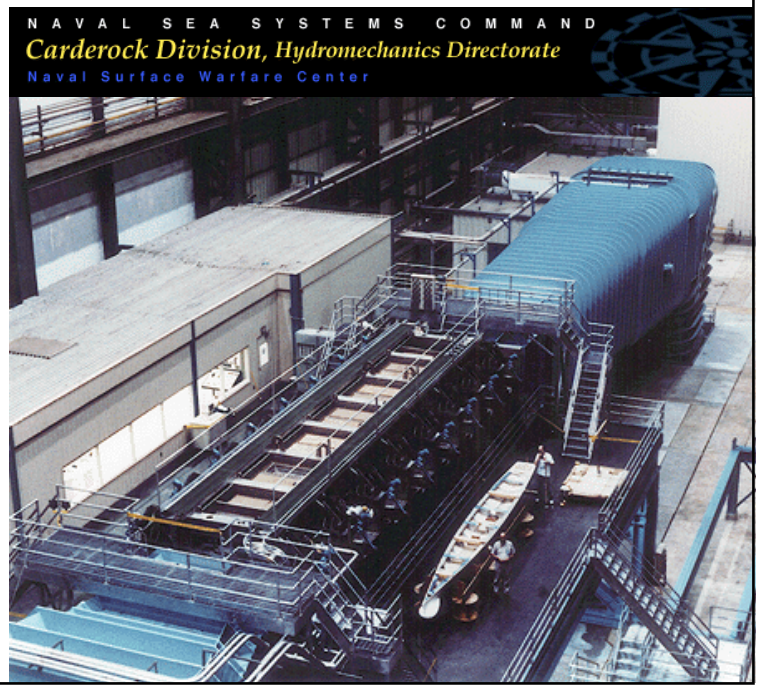
Slightly deformable bubbles



Experiment:
d^+=120; We=0.686
Simulations:
d^+=54; We=0.203-0.405

DNS of bubbles injected near the wall in a a turbulent channel flow show that the deformability of the bubbles plays a major role. Bubbles with a deformability comparable to what is seen experimentally (S. L. Ceccio, taken in the LCC) can lead to drag significant drag reduction, but only for a short time. The simulations clarified the turbulent modification and showed that less deformable bubbles can lead to an increase in the wall drag.



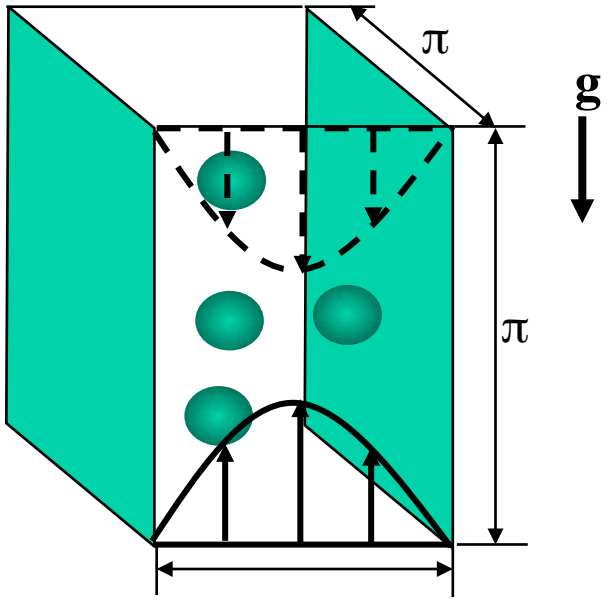


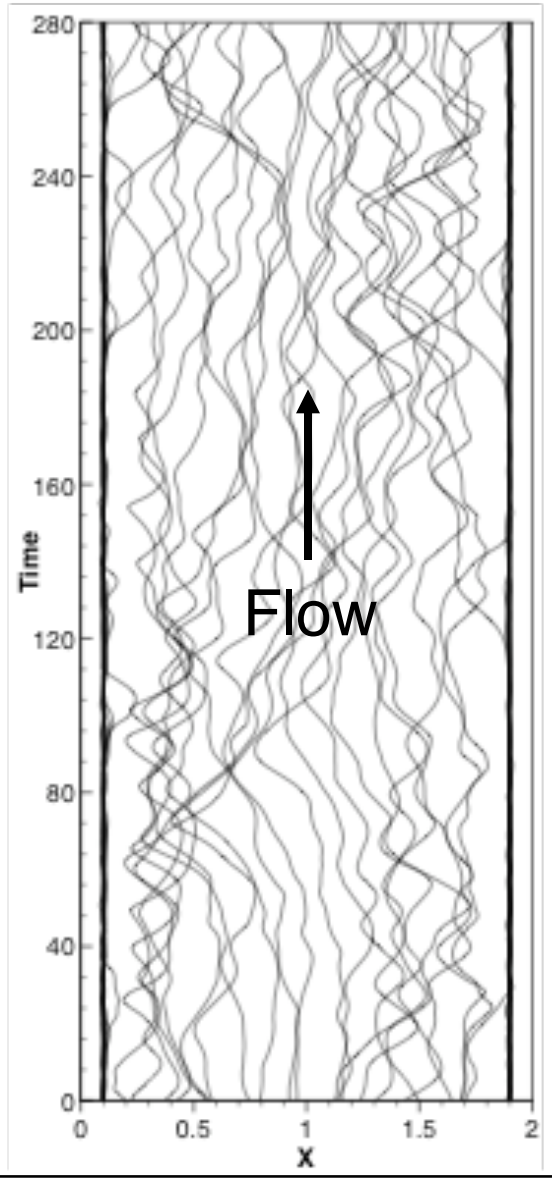
Bubbly Flows in Vertical Channels

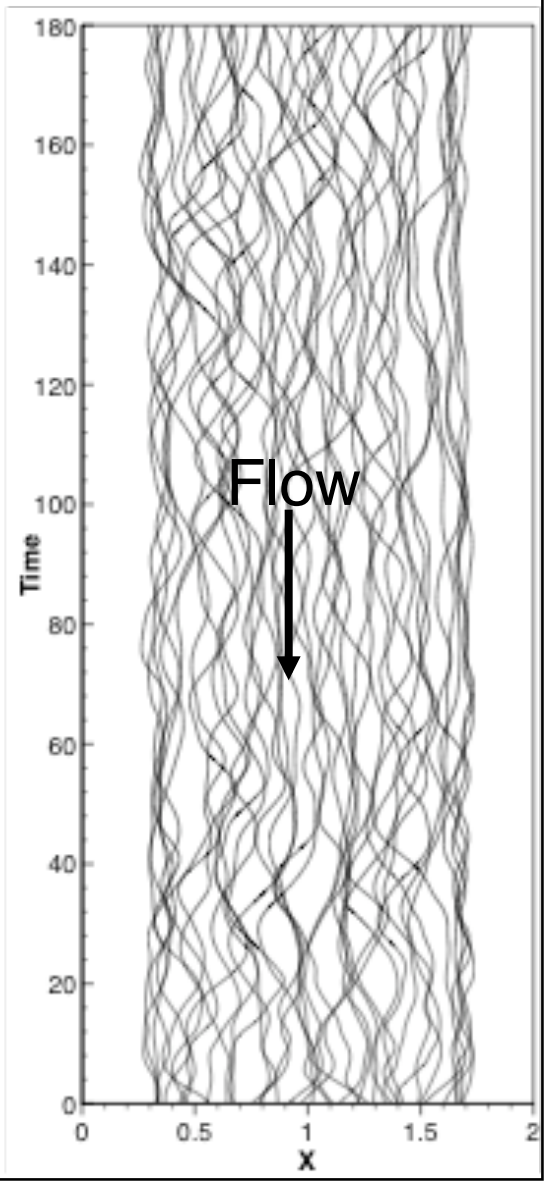
(with S. Biswas & J. Lu)

DNS of Multiphase Flows
Bubbles in Laminar Channel Flows

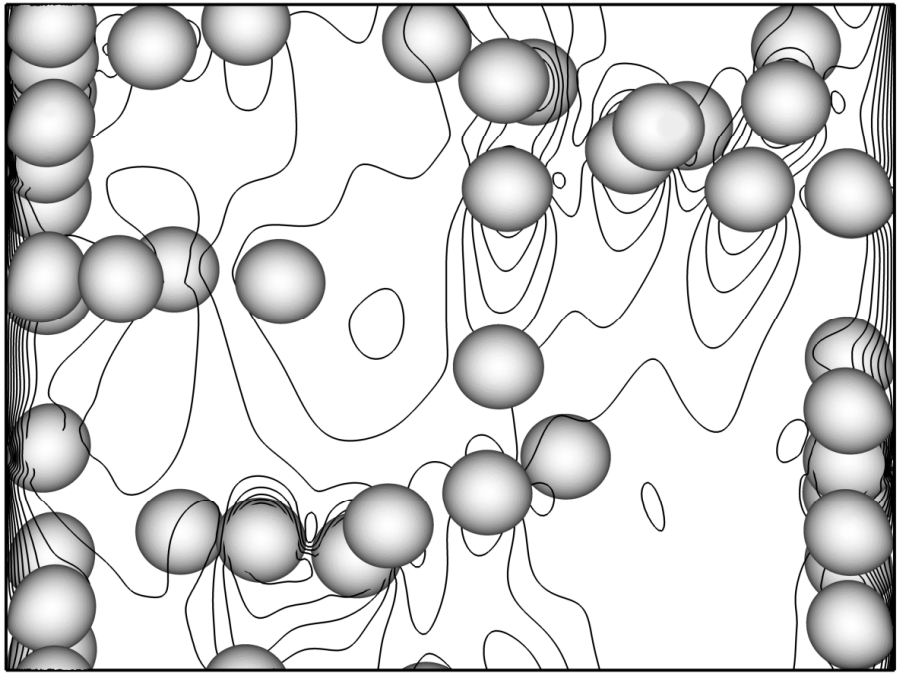
The path of bubbles. The cross-channel coordinate versus time for the upflow (left) and the downflow (right) at approximately steady state.



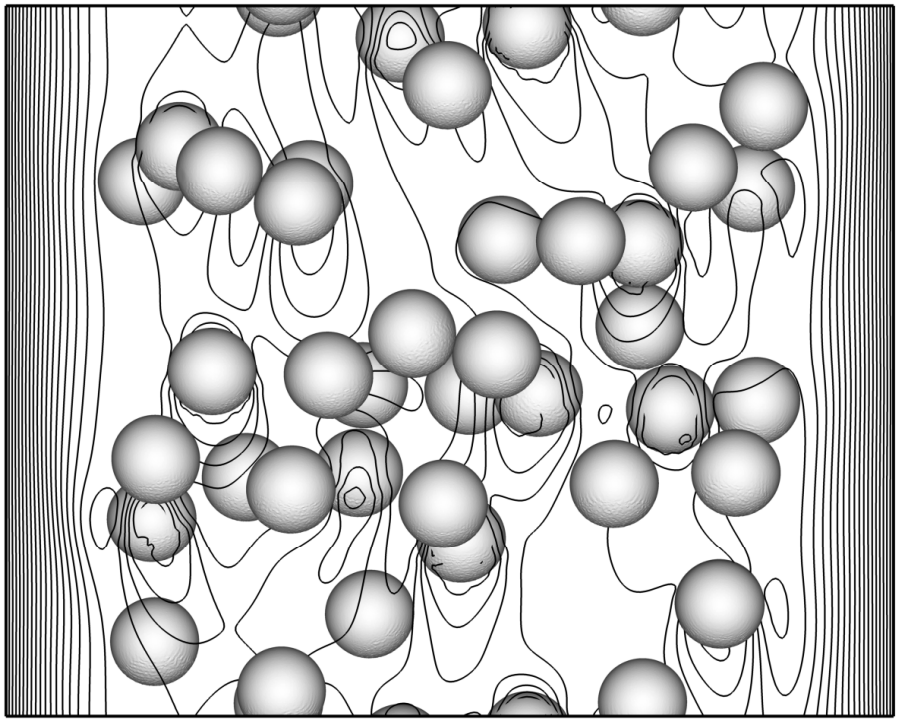




DNS of Multiphase Flows
Bubbles in Laminar Channel Flows



Upflow

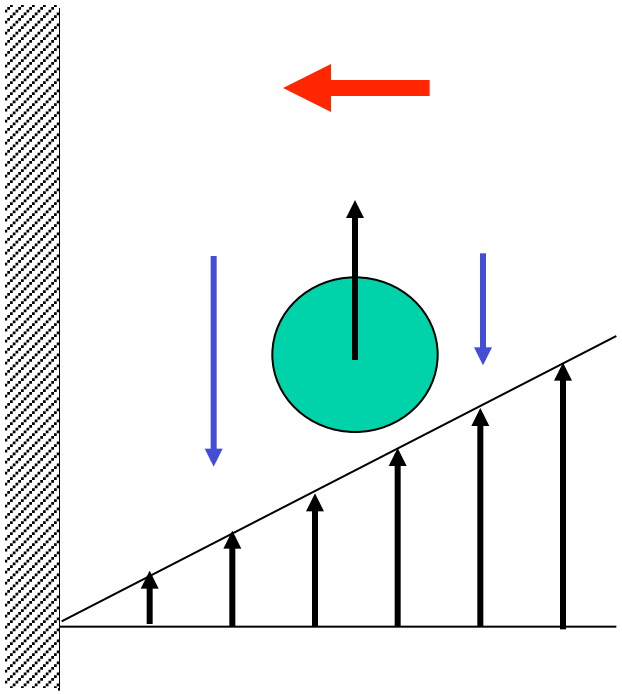


Downflow

The bubble distribution and isocontours of the vertical velocity in the middle plane for upflow on the left and dowflow on the right. The velocity contours are plotted with 0.05 intervals.

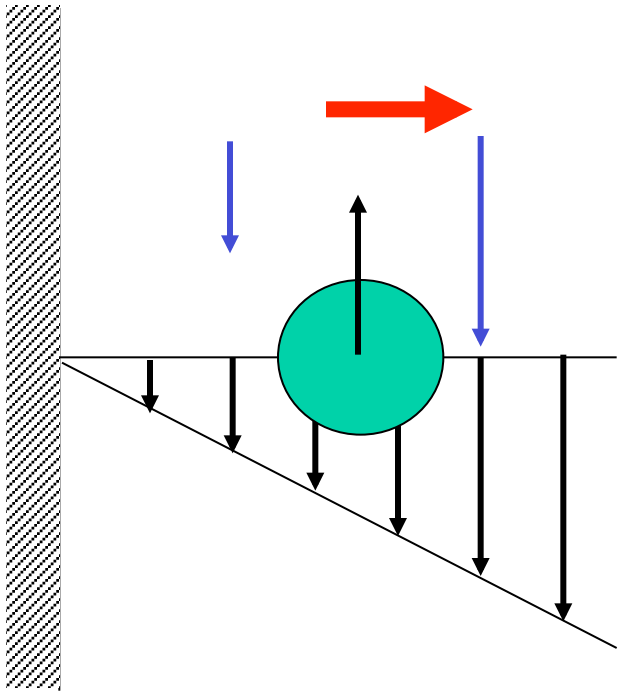
For a nearly spherical bubble

Lift toward wall



Upflow

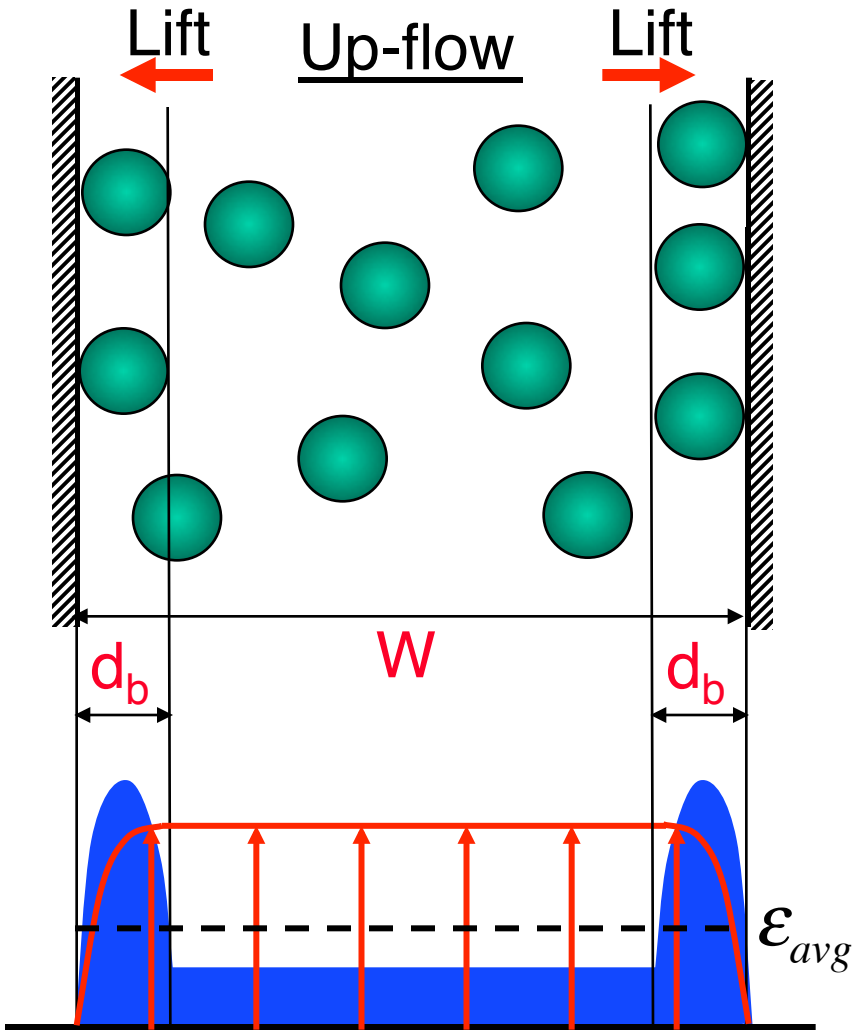
Lift away from wall

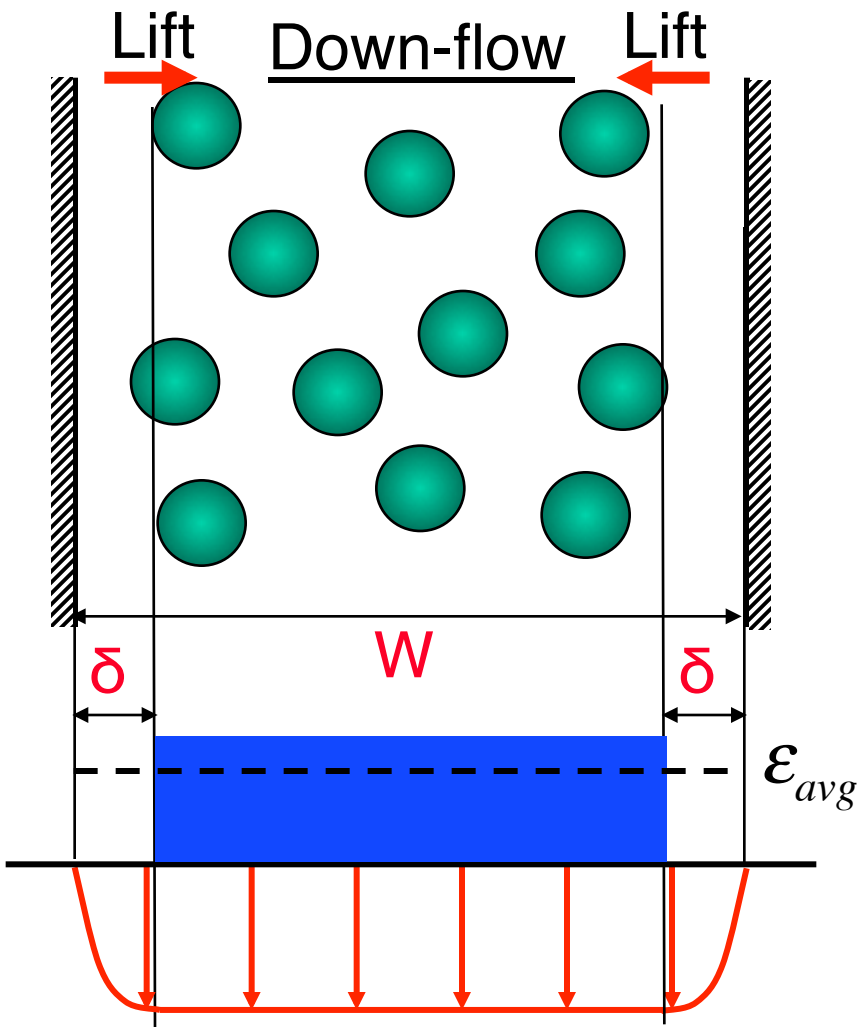


Downflow

DNS of Multiphase Flows
Bubbles in Laminar Channel Flows

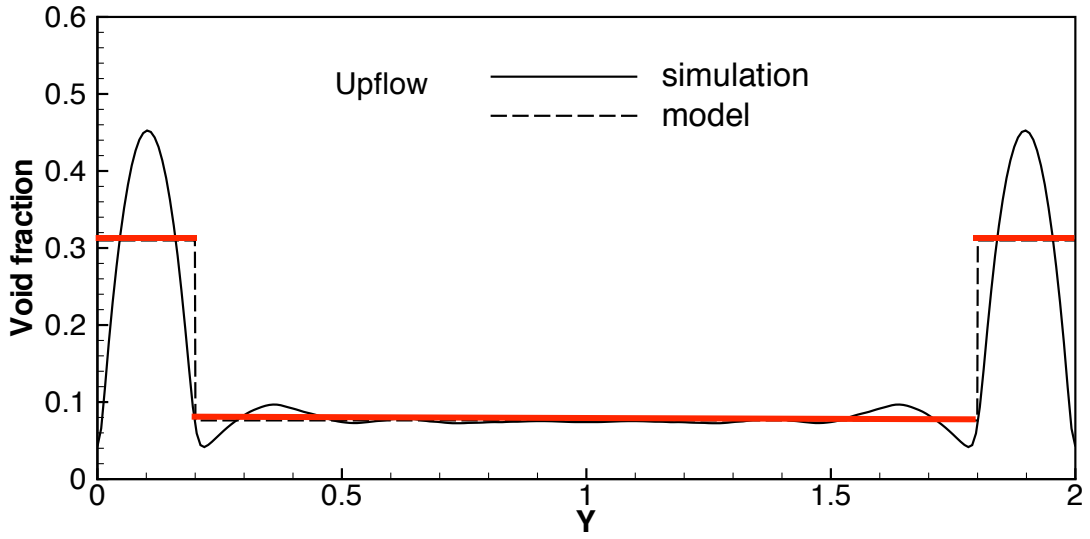
Simple two-fluid model for laminar multiphase flow

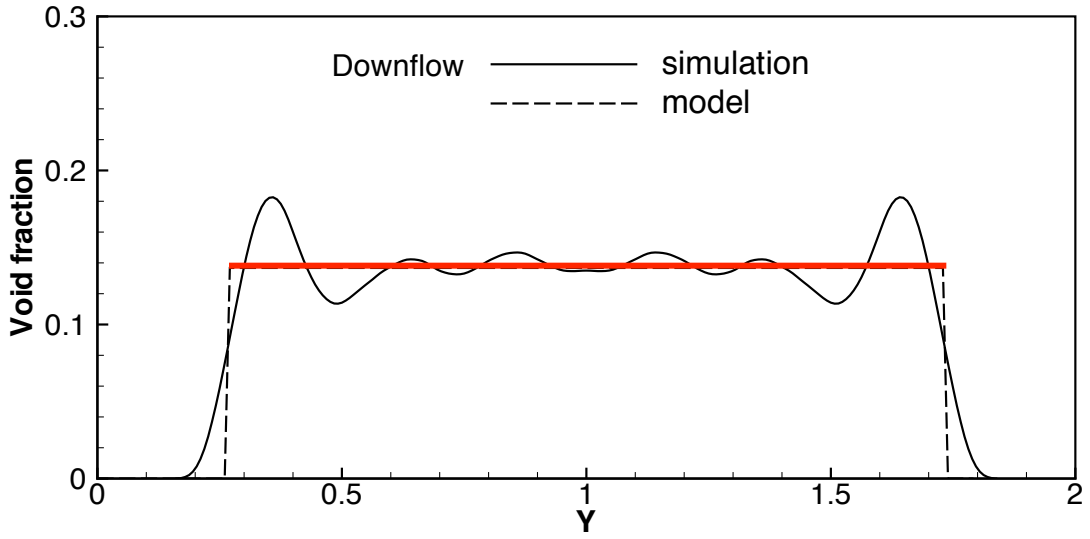




DNS of Multiphase Flows
Bubbles in Laminar Channel Flows

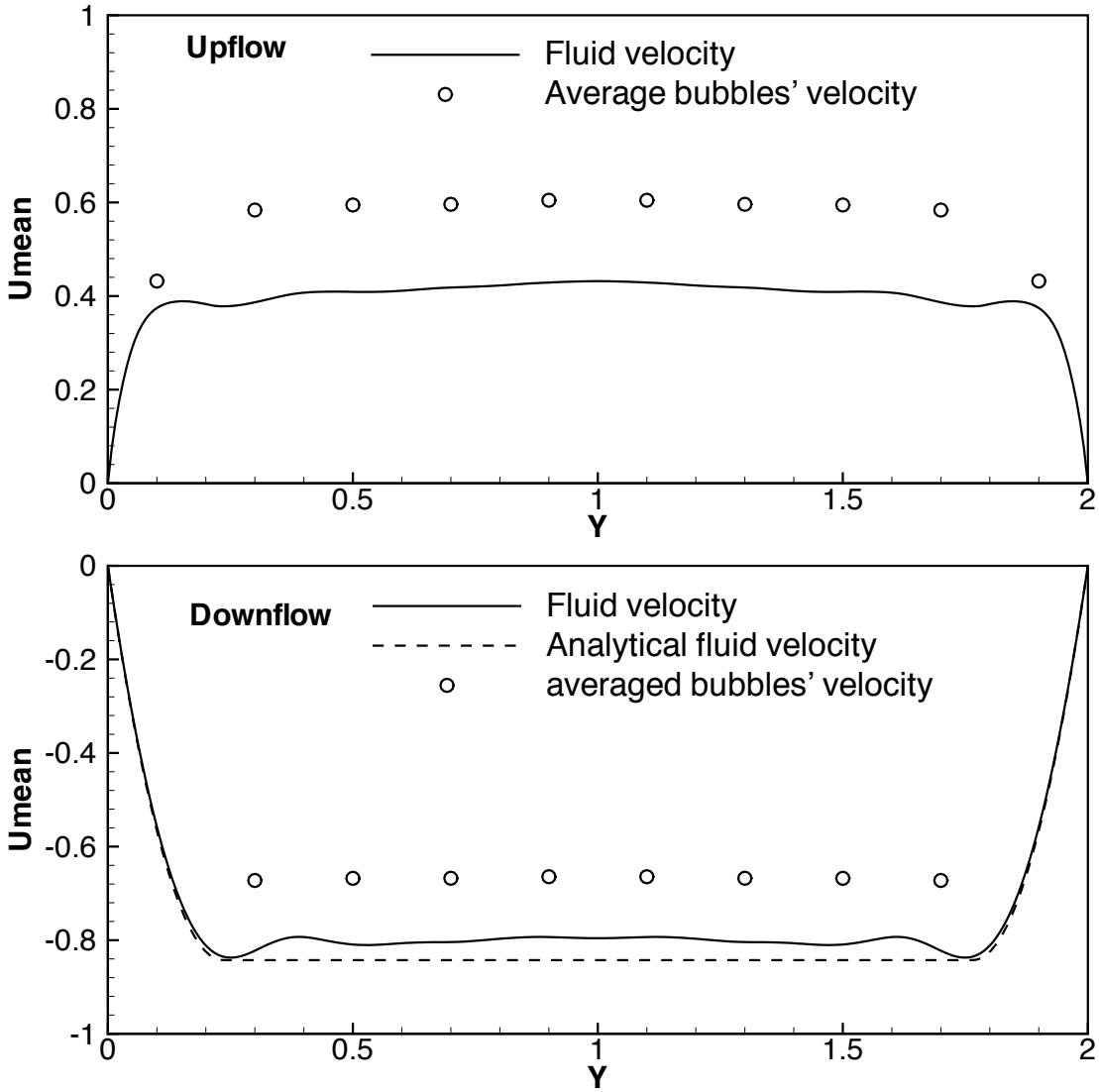
The average void fraction profile across the channel for the upflow (top) and the downflow (bottom). The solid lines denote the results from the simulations and the dashed lines are the analytical results.





DNS of Multiphase Flows
Bubbles in Laminar Channel Flows

The average vertical liquid velocity profile across the channel for the upflow (top) and the downflow (bottom). The solid lines are the simulated results, averaged over 80 time units. The dashed line is the analytical results for the downflow. The circles represent the average bubble velocities in 10 equal sized bins across the channel.

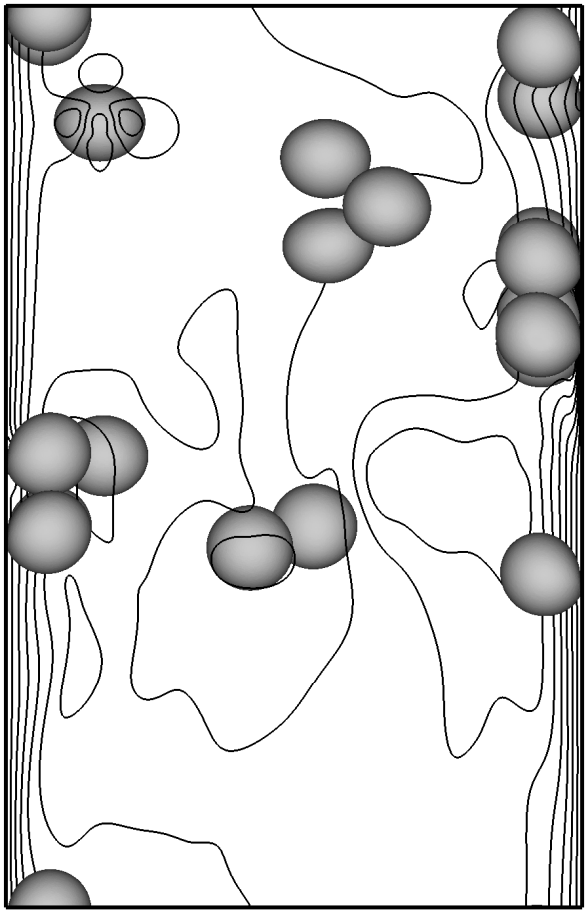


Effect of Bubble Deformability for Turbulent Upflow

(with J. Lu)

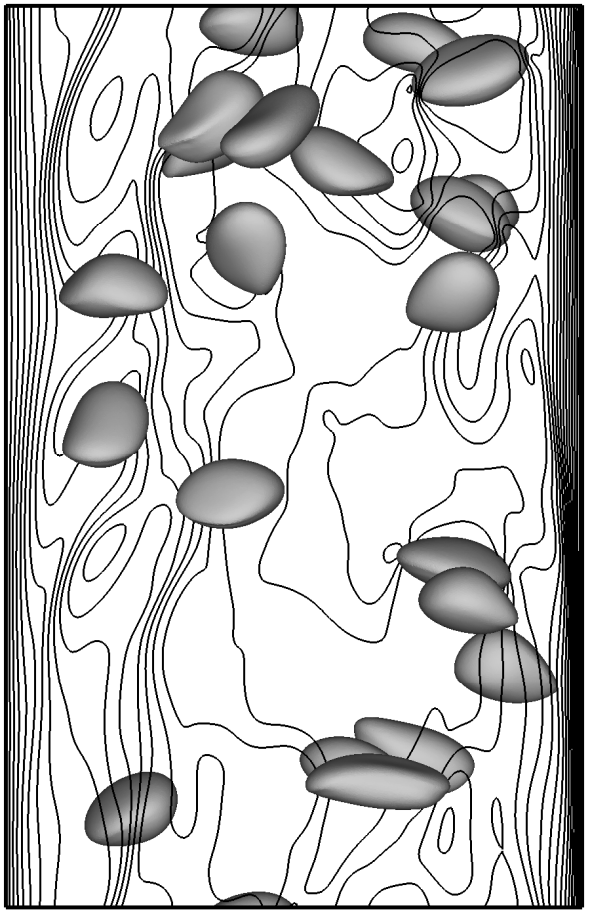
DNS of Multiphase Flows
Turbulent Upflow: Effect of Deformability

The bubbles and iso-contours of the instantaneous vertical velocity in a plane through the middle of the channel for the upflow of nearly spherical (left) and much more deformable (right) bubbles at one time when the flow is approximately at steady state.



$M=1.54 \times 10^{-10}$

Eo=0.45

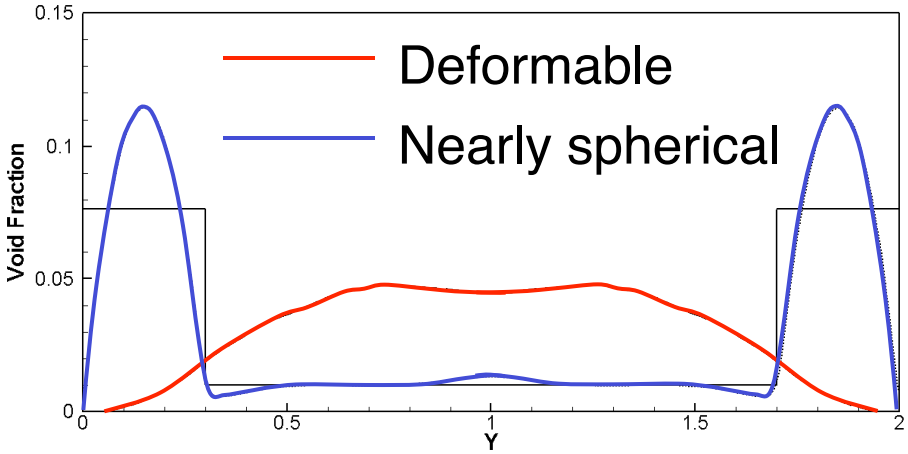


$M=1.54 \times 10^{-7}$

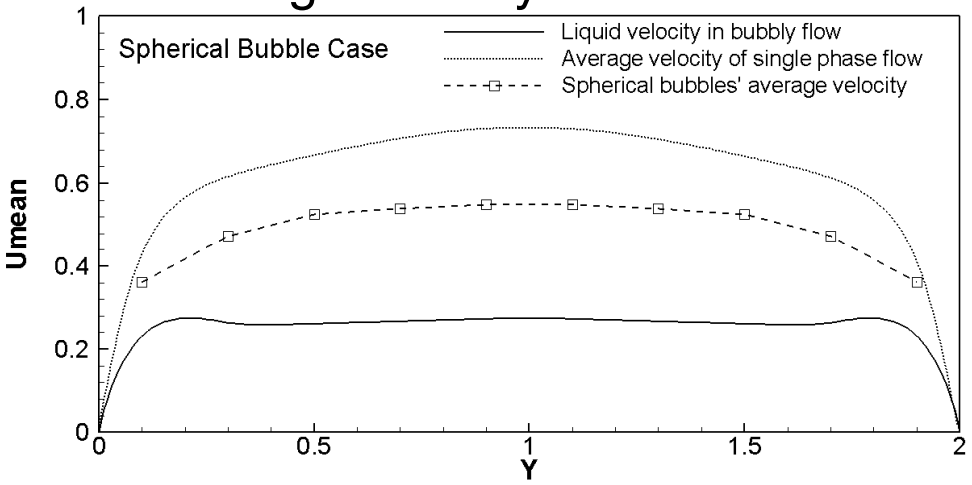
Eo=4.5

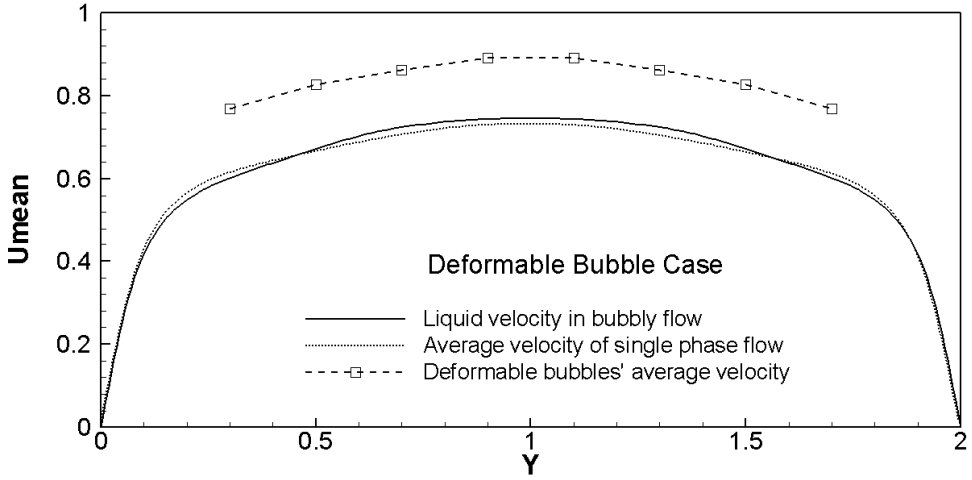
DNS of Multiphase Flows
Turbulent Upflow: Effect of Deformability

Void fraction



Average velocity





The void fraction has major influence of the flow behavior. The void fraction is plotted above and the velocity profiles to the right, along with the velocity from flow without bubbles (rescaled to account for the change in average density). The wall peak in the void fraction for nearly spherical bubbles results in a reduction in the flow rate.

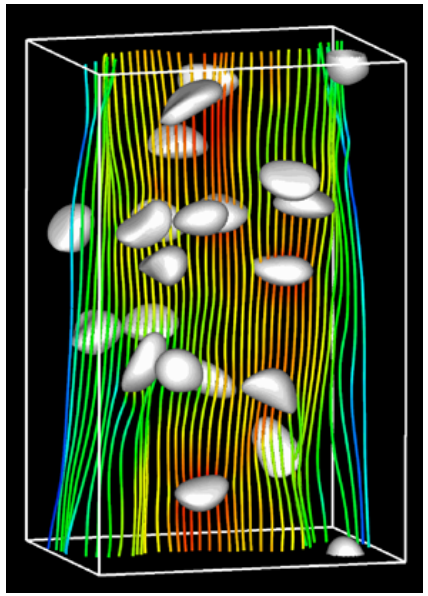
DNS of Multiphase Flows
Bubbly flows in channels—Summary

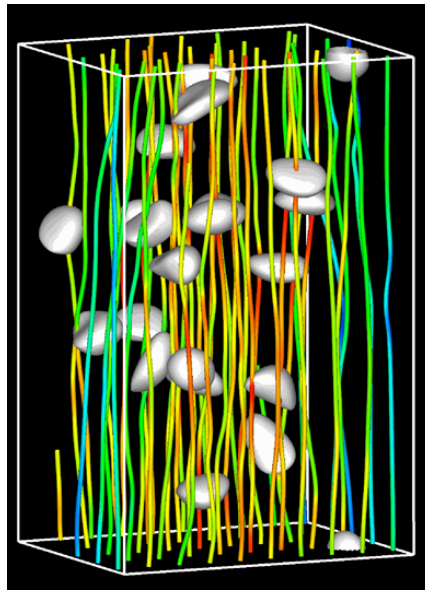
For nearly spherical bubbles the flow consists of a homogeneous core where the mixture is in hydrostatic equilibrium and a wall-layer.

For upflow the wall-layer is bubble rich and the total flow rate depends strongly on the deformability of the bubbles.

For downflow the wall-layer has no bubbles and the velocity profile is easily found for both laminar and turbulent flow. For downflow the exact size of the bubbles plays only a minor role, as long as they remain nearly spherical.

For upflow deformable bubbles stay away from walls, completely changing the flow structure





Additional Fields & Forces Temperature & Electricity

DNS of Multiphase Flows

Thermocapillary migration

The temperature is found by solving the energy equation

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

The temperature on the surface of the bubble or drop is found by interpolating it from the grid and surface tension is found by $\sigma = \sigma_o - \beta(T - T_o)$

Electrohydrodynamics of suspensions

The electric field is obtained from the equation for the conservation of current:

$$\cancel{\frac{Dq}{Dt}}^{0} = \nabla \cdot \sigma \mathbf{E}$$

neglecting the convection of charge

the charge accumulation is found by:

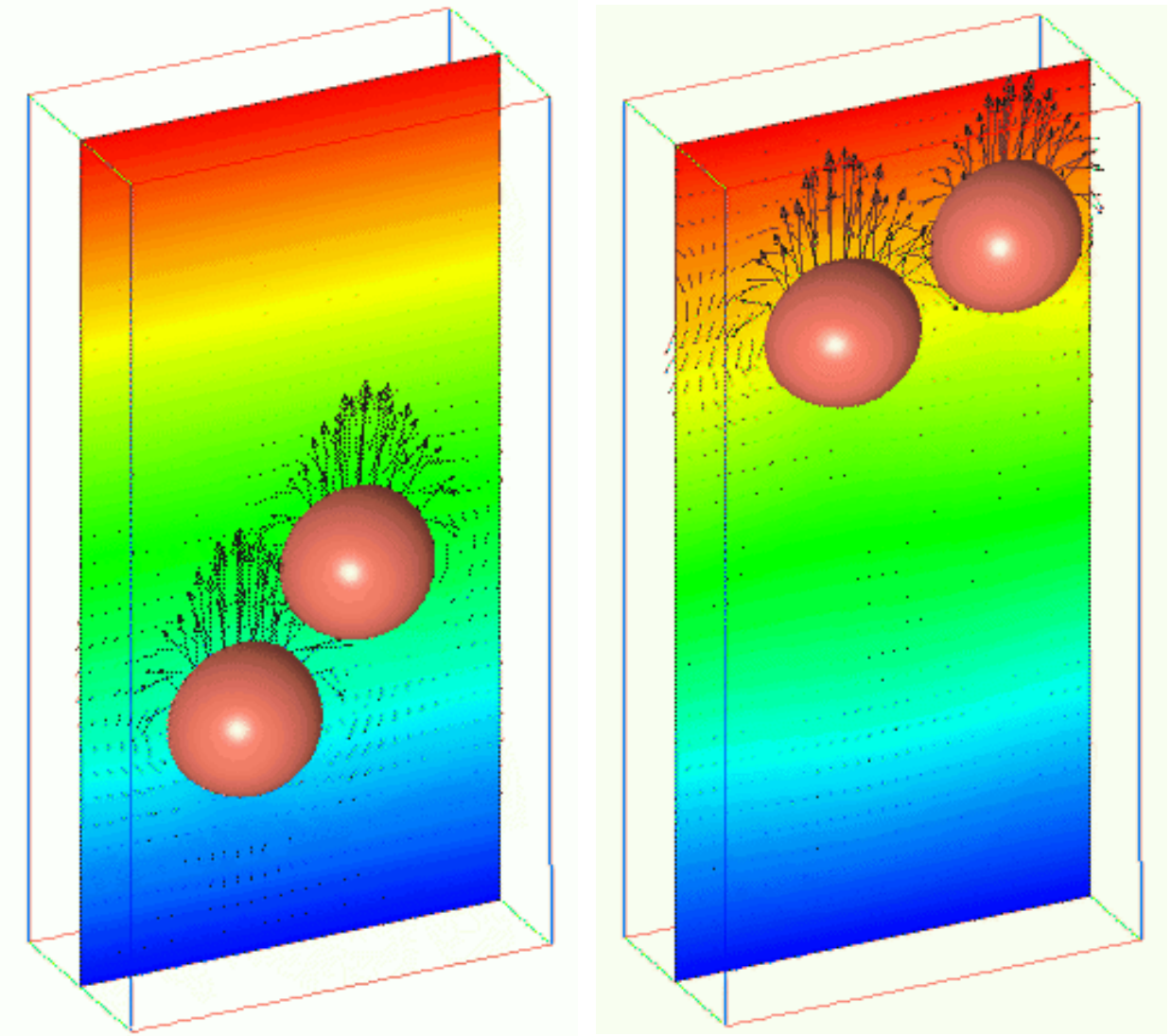
$$q = \nabla \cdot \varepsilon \mathbf{E}$$

The force on the fluid is then found by:

$$\mathbf{f} = q\mathbf{E} - \tfrac{1}{2}(\mathbf{E} \cdot \mathbf{E}) \nabla \varepsilon$$

DNS of Multiphase Flows
Thermocapillary migration

Thermocapillary motion of two three-dimensional bubbles. The top wall is hot and the bottom wall is cold. Initially the bubbles are placed near the cold wall. As they rise, the bubbles line up perpendicular to the temperature gradient.

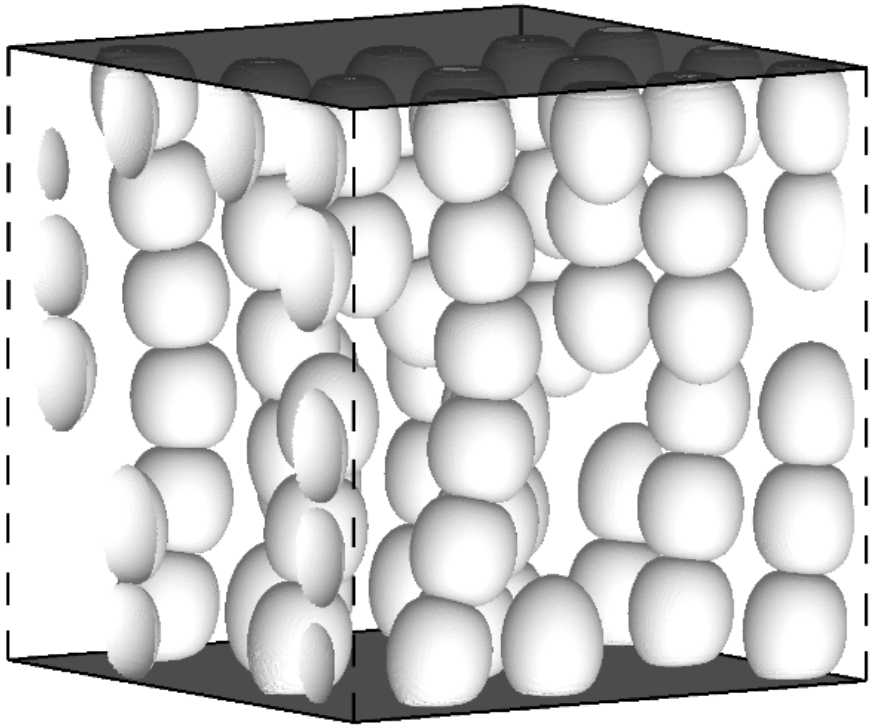


DNS of Multiphase Flows
Electrohydrodynamics

$\sigma_i/\sigma_o = 0.005$ $\quad \mathrm{Re} = 20$

$\varepsilon_i/\varepsilon_o = 0.01$ $\quad We = 0.0625$

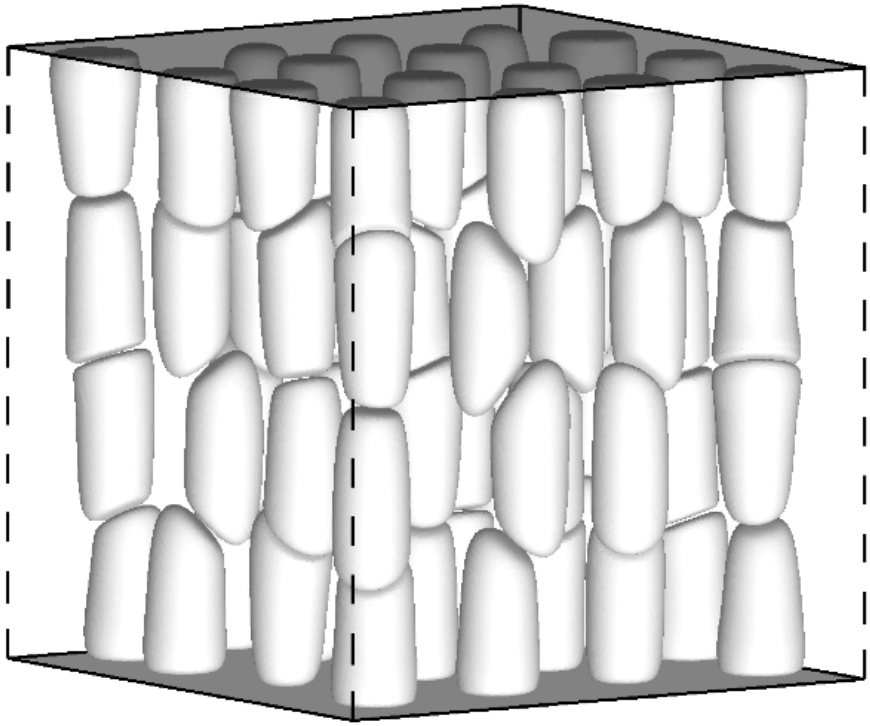
$\alpha = 20\%$ $\quad E^* = 0.0182$



$\sigma_i/\sigma_o = 0.01$ $\quad \mathrm{Re} = 20$

$\varepsilon_i/\varepsilon_o = 0.1$ $\quad We = 0.0625$

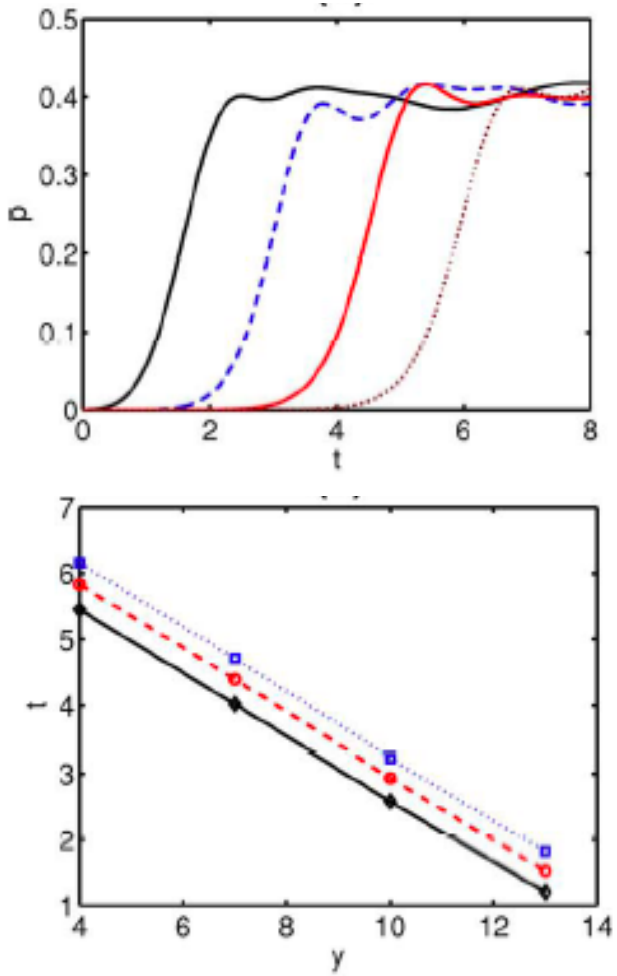
$\alpha = 20\%$ $\quad E^* = 0.04$

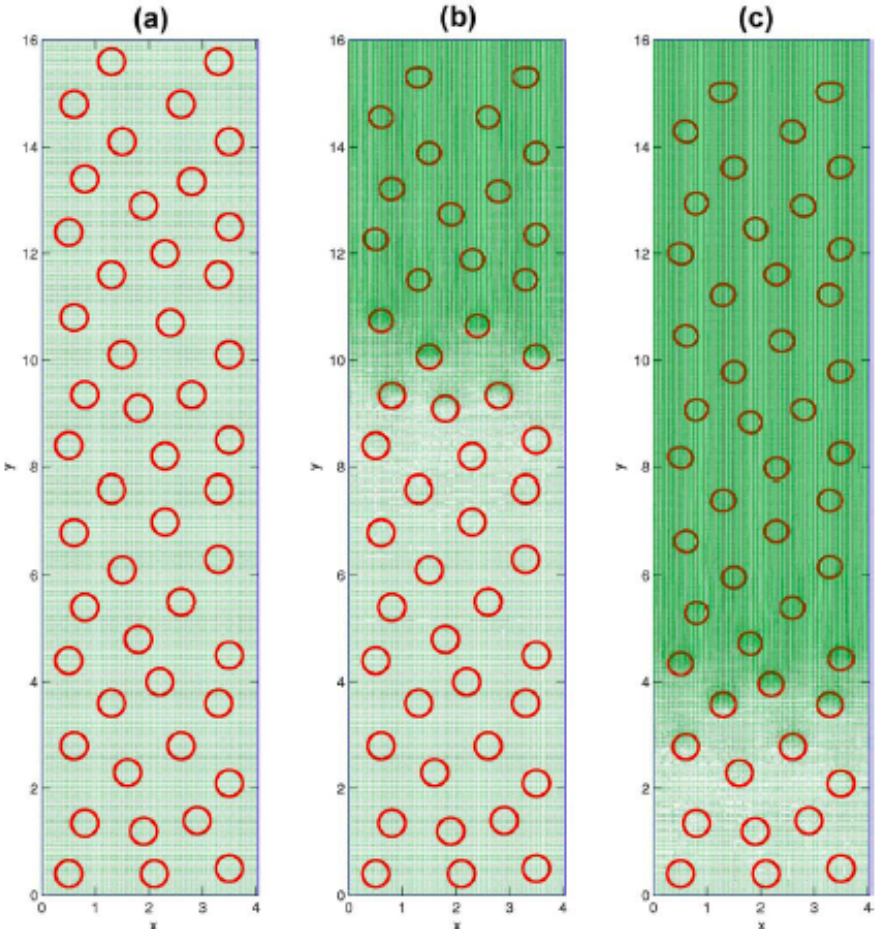


Cavitating Bubbly Clouds

DNS of Multiphase Flows
Shocks in bubbly liquid

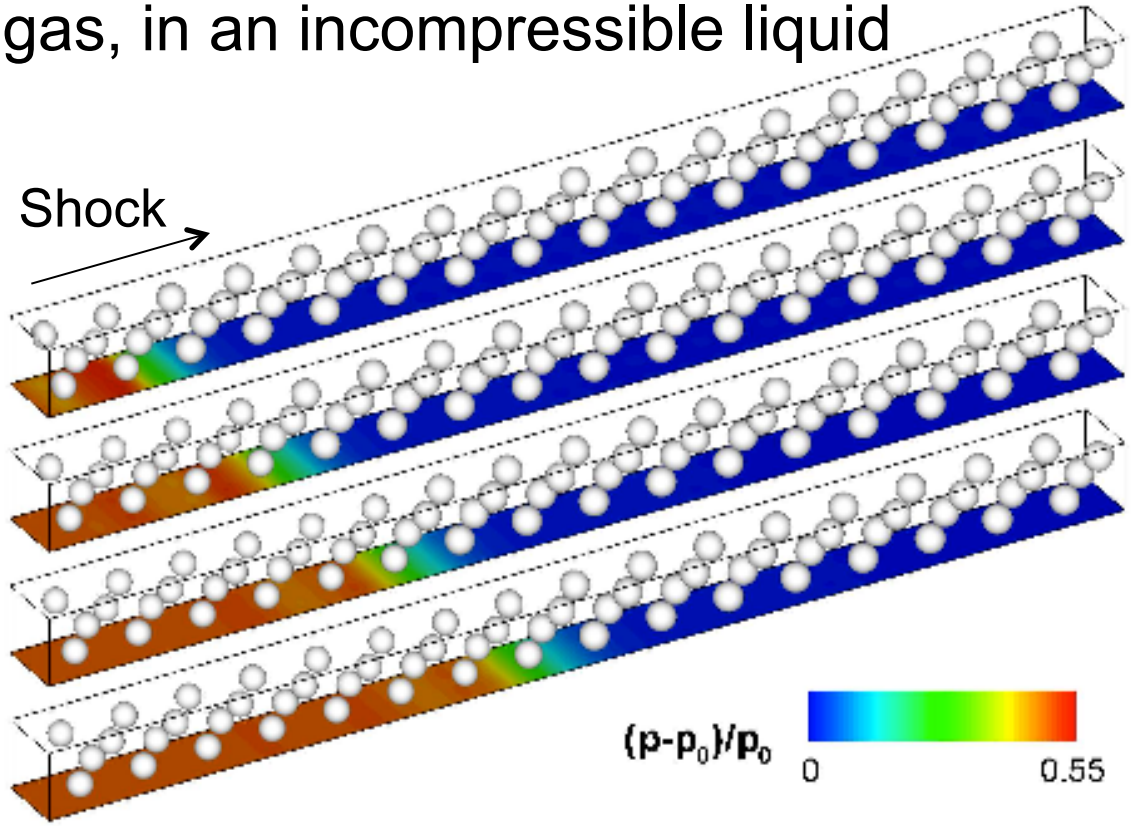
Polytropic gas inside the bubbles

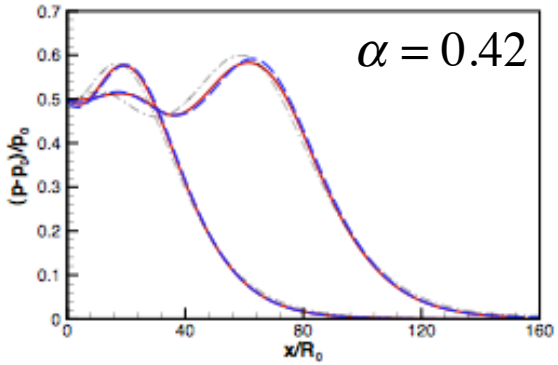


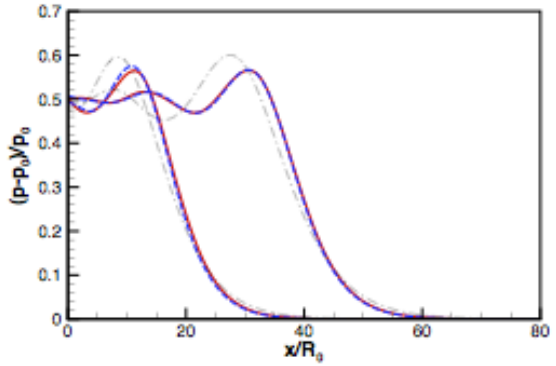


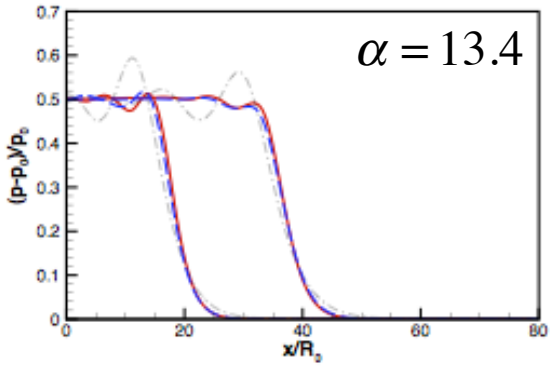
DNS of Multiphase Flows
Shocks in bubbly liquid

Compressible bubbles filled with ideal gas, in an incompressible liquid









C.F. Delale and G. Tryggvason. “Shock structure in bubbly liquids: Comparison of Direct Numerical Simulations and model equations.” *Shock Waves* 17 (2008), 433–440.

J. H. Seo, S. K. Lele and G. Tryggvason. “Investigation and modeling of bubble-bubble interactions effect in homogeneous bubbly flows.” *Physics of Fluids*, in press

Simulations of Boiling Flows

(with D. Juric, A. Esmaeeli & J. Lu)

DNS of Multiphase Flows
Governing Equations

$$\rho\frac{\partial \boldsymbol{u}}{\partial t}+\rho\nabla\cdot\boldsymbol{uu}=-\nabla p+\boldsymbol{f}+\nabla\cdot\mu\left(\nabla\boldsymbol{u}+\nabla^{T}\boldsymbol{u}\right)+\int_{F}\sigma\kappa\mathbf{n}\delta\left(\boldsymbol{x}-\boldsymbol{x}_{f}\right)da$$

$$\frac{\partial cT}{\partial t}+\mathbf{u}\cdot\nabla cT=\nabla\cdot k\nabla T+\int\dot{q}\delta(\mathbf{x}-\mathbf{x}_{f})dA$$ Energy equation

$$\dot{q}=k_{1}\frac{\partial T}{\partial n}\Big)_{1}-k_{2}\frac{\partial T}{\partial n}\Big)_{2}$$ Heat source

$$T_{l}=T_{v}=T_{sat}(p_{sys})$$ Thermodynamic

$$\nabla\cdot\mathbf{u}=\frac{1}{L}\left(\frac{1}{\rho_{v}}-\frac{1}{\rho_{f}}\right)\int\dot{q}\delta(\mathbf{x}-\mathbf{x}_{f})dA$$ Mass conservation

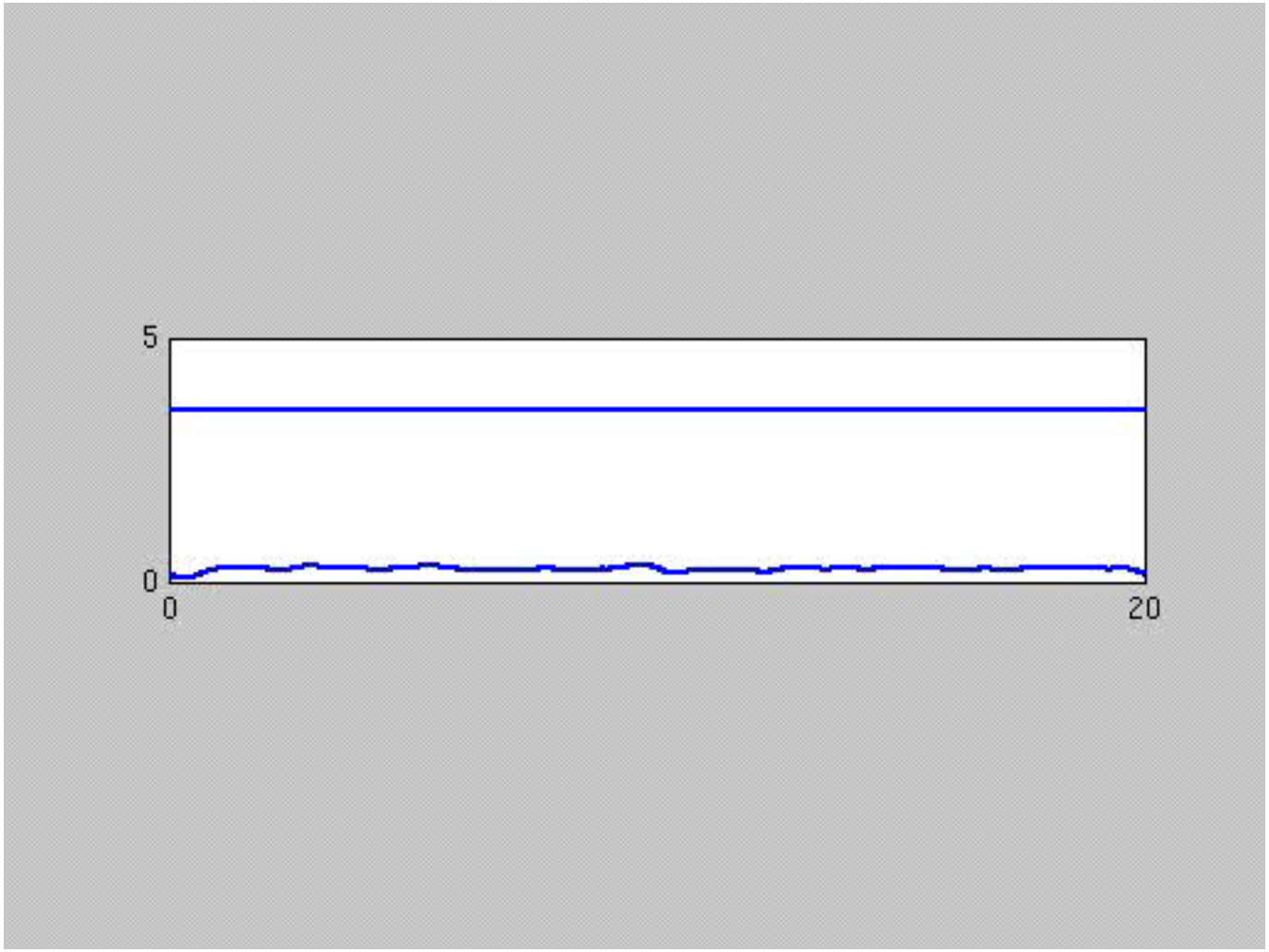
$$V_{n}=\frac{1}{2}(u_{l}+u_{v})-\frac{\dot{q}}{L}\left(\frac{1}{\rho_{v}}+\frac{1}{\rho_{f}}\right)$$

$$\frac{dx_{f}}{dt}=V_{n}\mathbf{n}+\mathbf{u}$$

} Velocity of bdry

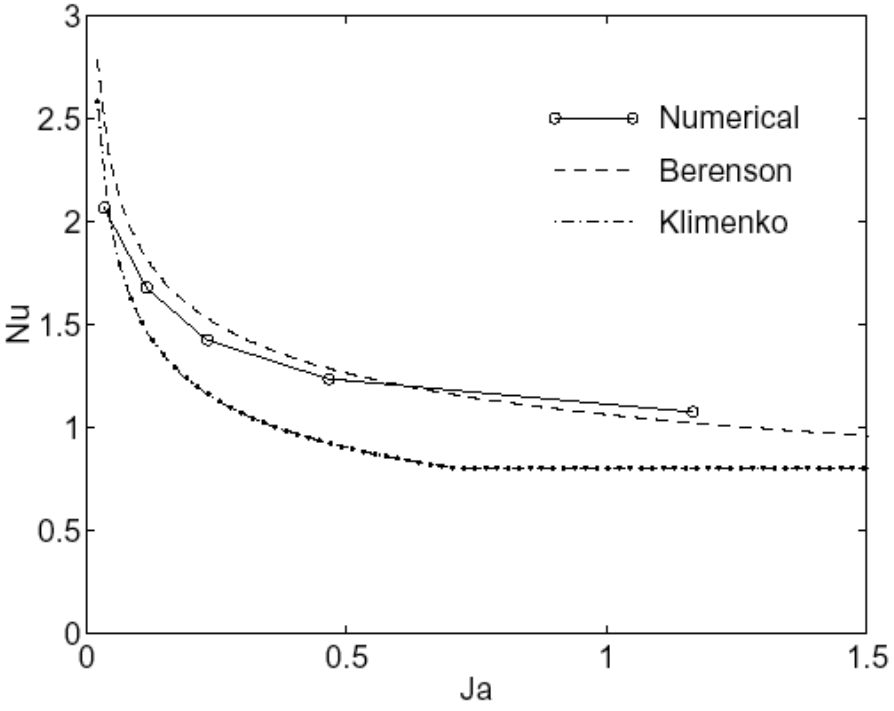
DNS of Multiphase Flows

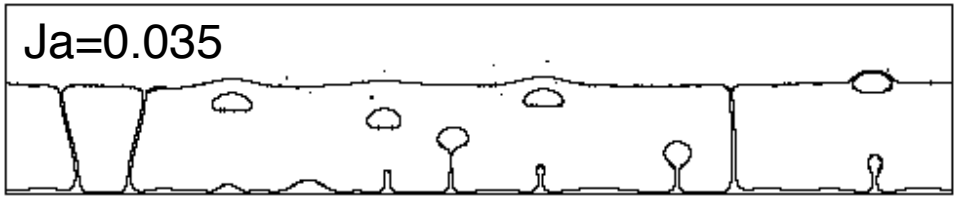
Boiling Flows

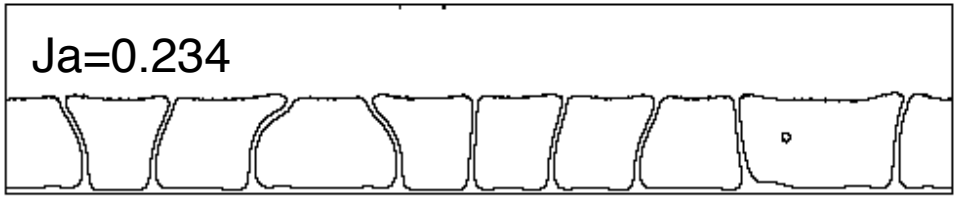


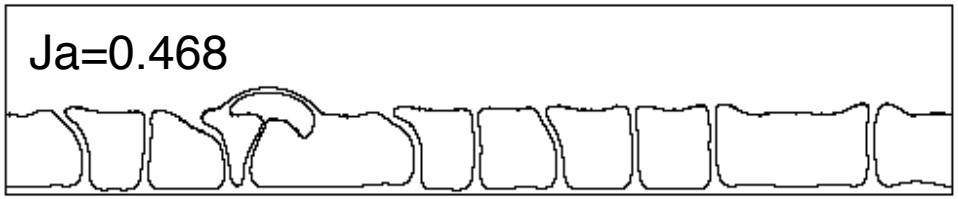
DNS of Multiphase Flows
Boiling Flows

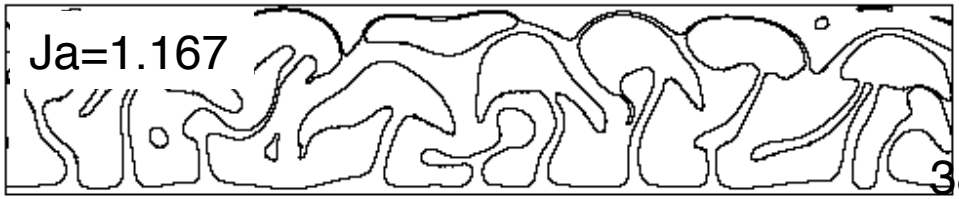
The effect of the Jacob number on the boiling for near critical film boiling





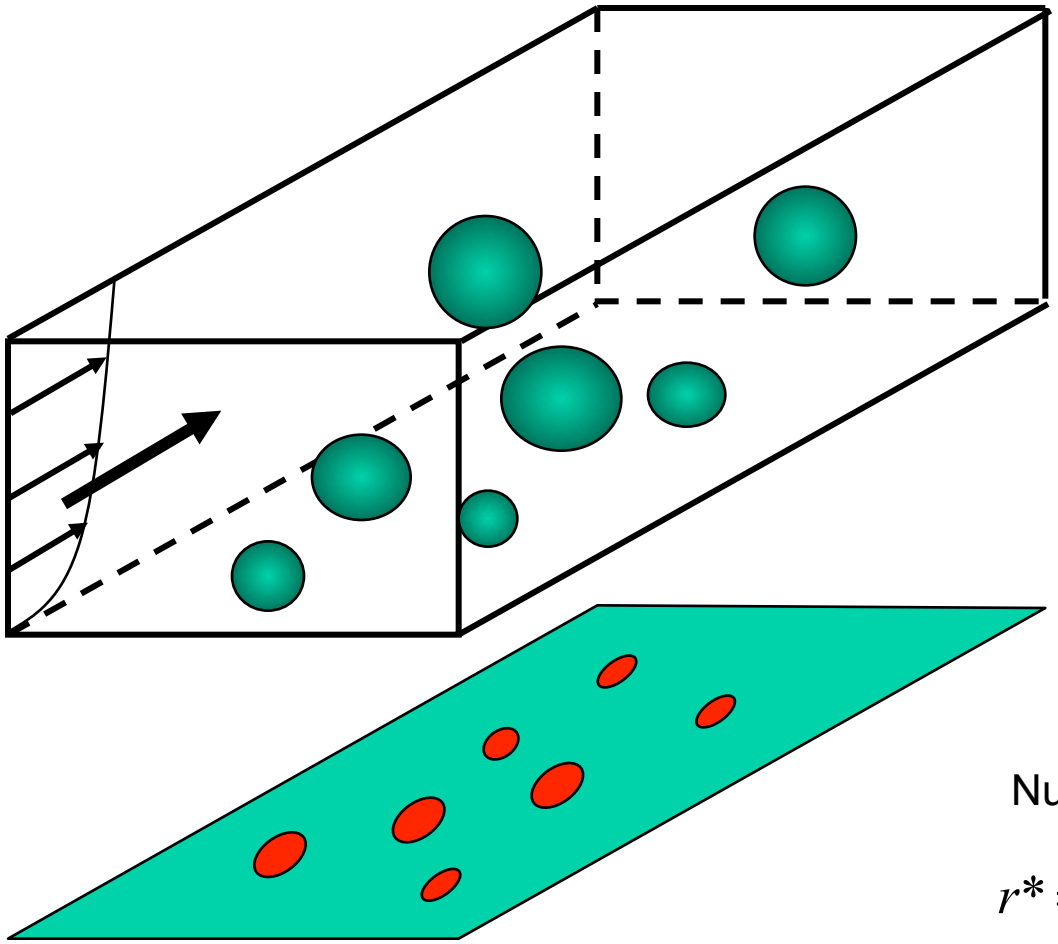






Nucleate Boiling

Nucleate Flow Boiling



Assumption : Surface nucleation characteristics determined by size distribution of potentially active sites

- Random spatial site distribution
- Random conical cavity size (mouth radius, r) distribution
- Assume vapor embryo radius = r
- Assume near wall liquid film is stationary

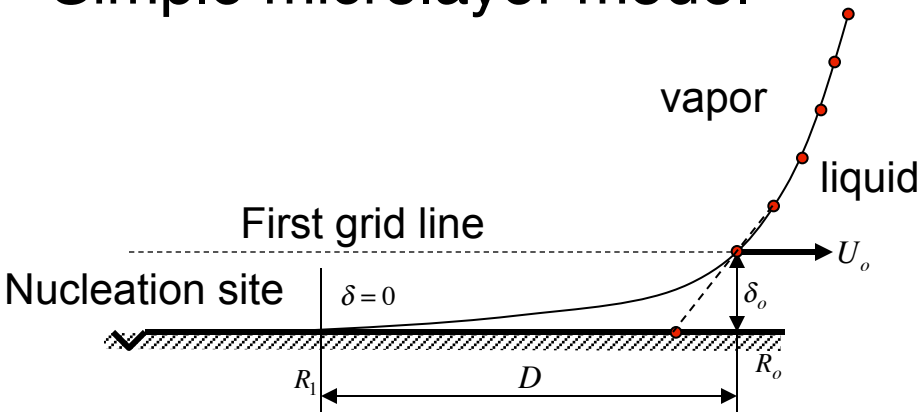
Nucleation site is active if $r_{min} > r^*$

$$r^* = \frac{2\sigma T_{sat} \upsilon_{lv}}{h_{lv}\left[T_l - T_{sat}\right]}$$

Carey (1992)

Simple microlayer model

Simple microlayer model



Evaporation of the film

$$\dot{q} = k\frac{T_w - T_f}{\delta} = k\frac{\Delta T}{\delta}$$ Heat transfer

$$\frac{d\delta}{dt} = -\frac{\dot{q}}{\rho_f L} = -\frac{k\Delta T}{\delta \rho_f L} = -\frac{\beta}{\delta}$$ Evaporation

$$\delta = \sqrt{\delta_o^2 - 2\beta t}$$ Integrate to find thickness

$$t_e = \delta_o^2 / 2\beta$$

$$D = U_o t_e = \frac{U_o \delta_o^2}{2\beta}$$ Find length of film

Total heat transfer to the microlayer

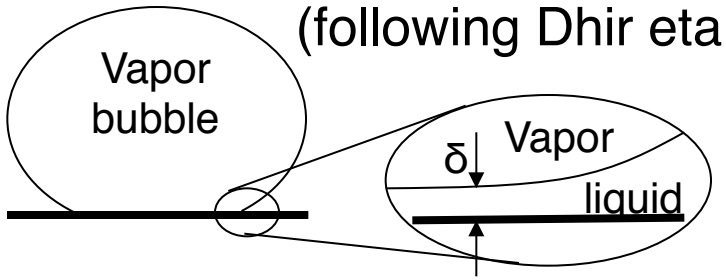
$$\dot{Q} = \int_0^D \dot{q}\, dx = \int_0^D \frac{k\Delta T}{\sqrt{\delta_o^2 - (2\beta/U_o)x}} dx = \frac{k\Delta T}{\delta_o}\int_0^D \frac{1}{\sqrt{1-\left(2\beta/\delta_o^2 U_o\right)x}} dx \rightarrow \dot{Q} = \delta_o U_o L \rho_f$$

Volume expansion $\dot{V} = \frac{\dot{Q}}{L}\left(\frac{1}{\rho_v} - \frac{1}{\rho_f}\right)$ Applied near the apparent contact

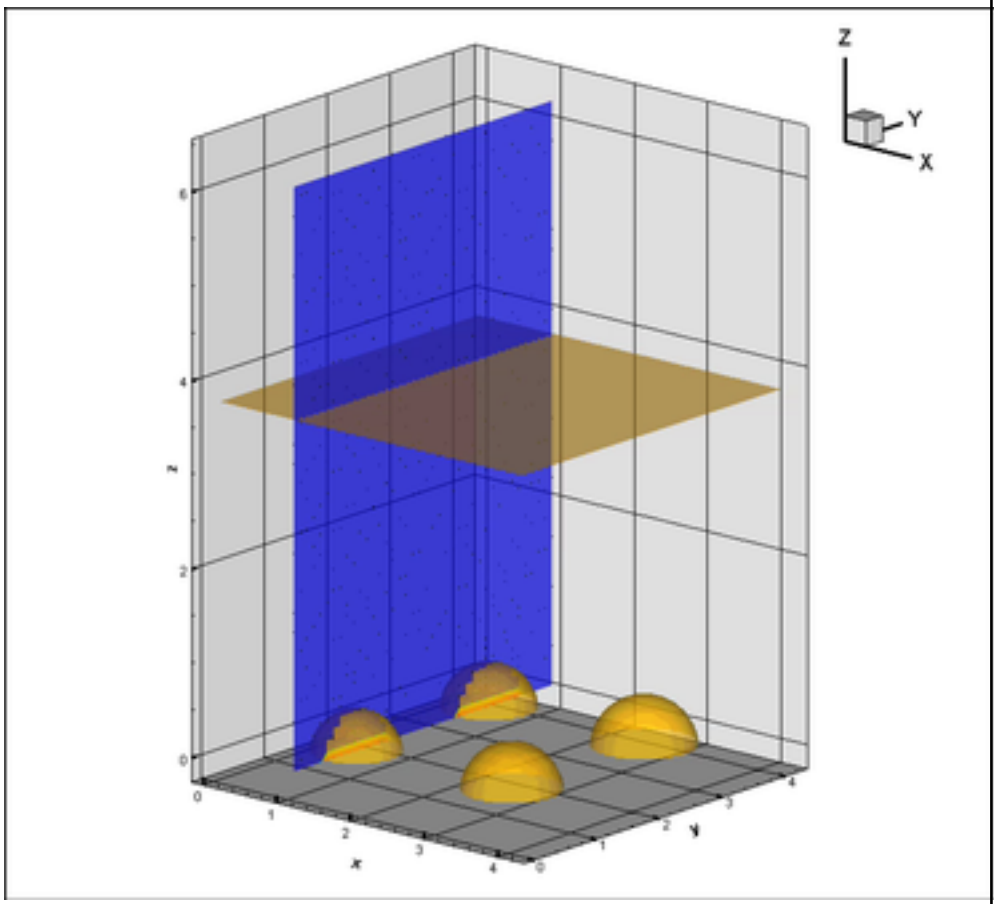
DNS of Multiphase Flows
Nucleate Boiling

Simulation of the generation of bubbles in a shallow pool. In addition to solving the energy equation, the latent heat and the volume expansion at the phase boundary must be included. Most simulations so far have been for film boiling. The nucleation of a vapor bubble and the evaporation in the microlayer must be addressed by multiscale modeling.

Microlayer modeling (following Dhir etal)



Movie from D. Juric



Water at 1atm, Tsat=373.15K; liquid/vapor density ratio=1605; viscosity ratio=23; thermal conductivity ratio=27; specific heat ratio=1; domain size: 10.5x10.5x15.75 mm; Wall superheat: 18K 40x40x60 grid resolution

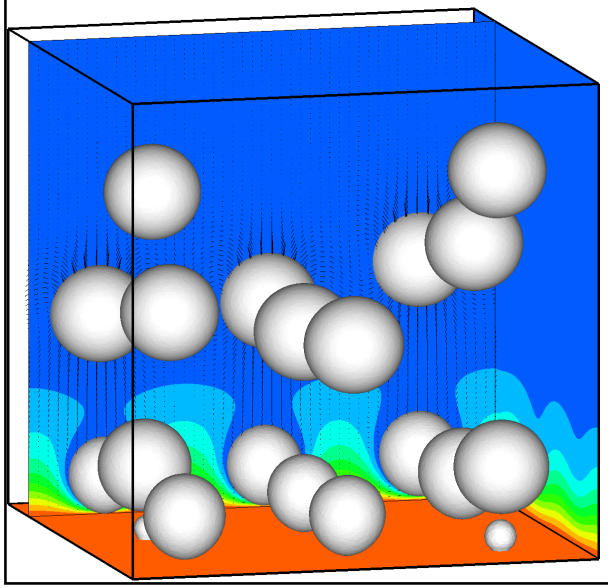
DNS of Multiphase Flows

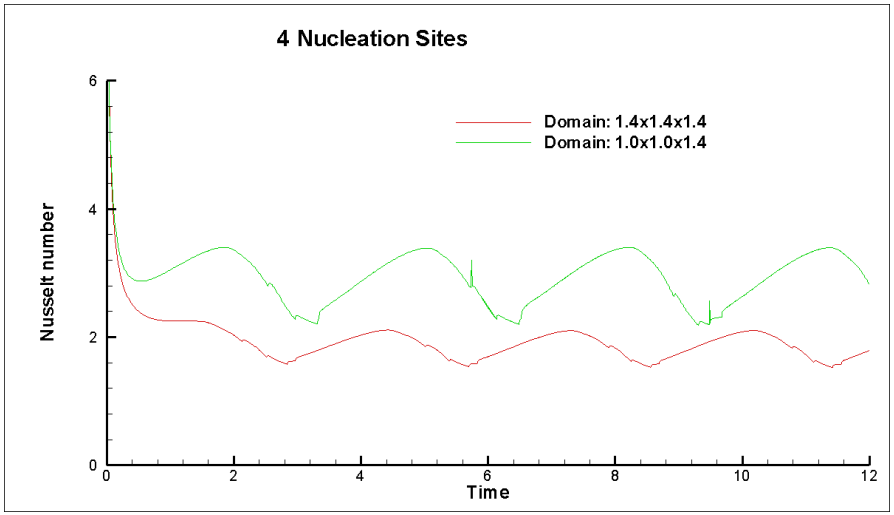
Nucleate Boiling

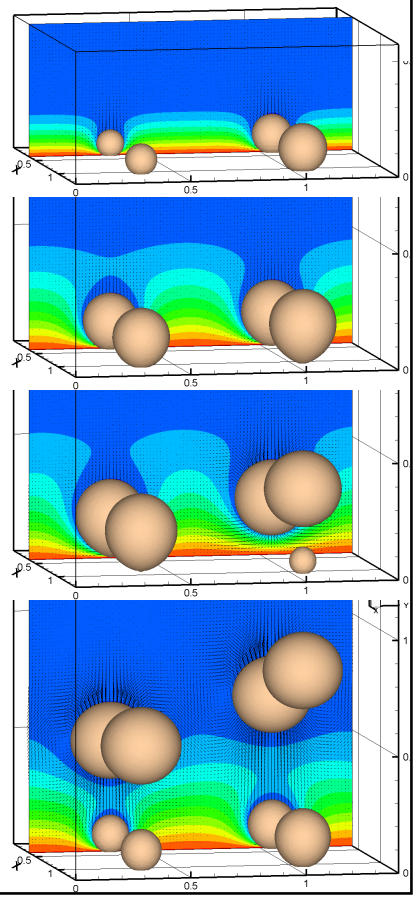
There appears to be no significant technical obstacles for conducting large scale simulations of nucleate flow boiling—however, some development works still needs to be done!

Such simulations should allow us to

- Assess the accuracy of the assumptions made in the modeling of the microlayer
- Use the simulations to make predictions about boiling under conditions where experiments are difficult or do not yield the necessary data.







Multiphase flow DNS with embedded multi-scale models

DNS of Multiphase Flows
Multiscale Issues

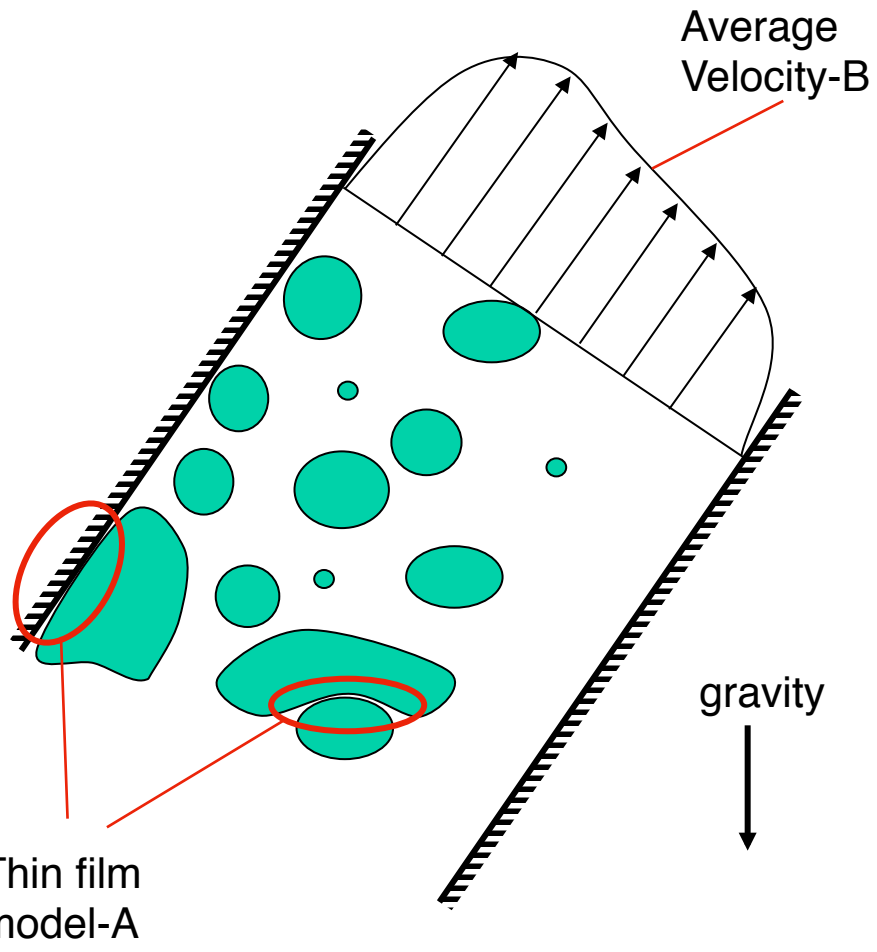
Some communities have defined two types of multi-scale problems.

Type A Problems: Dealing with Isolated Defects

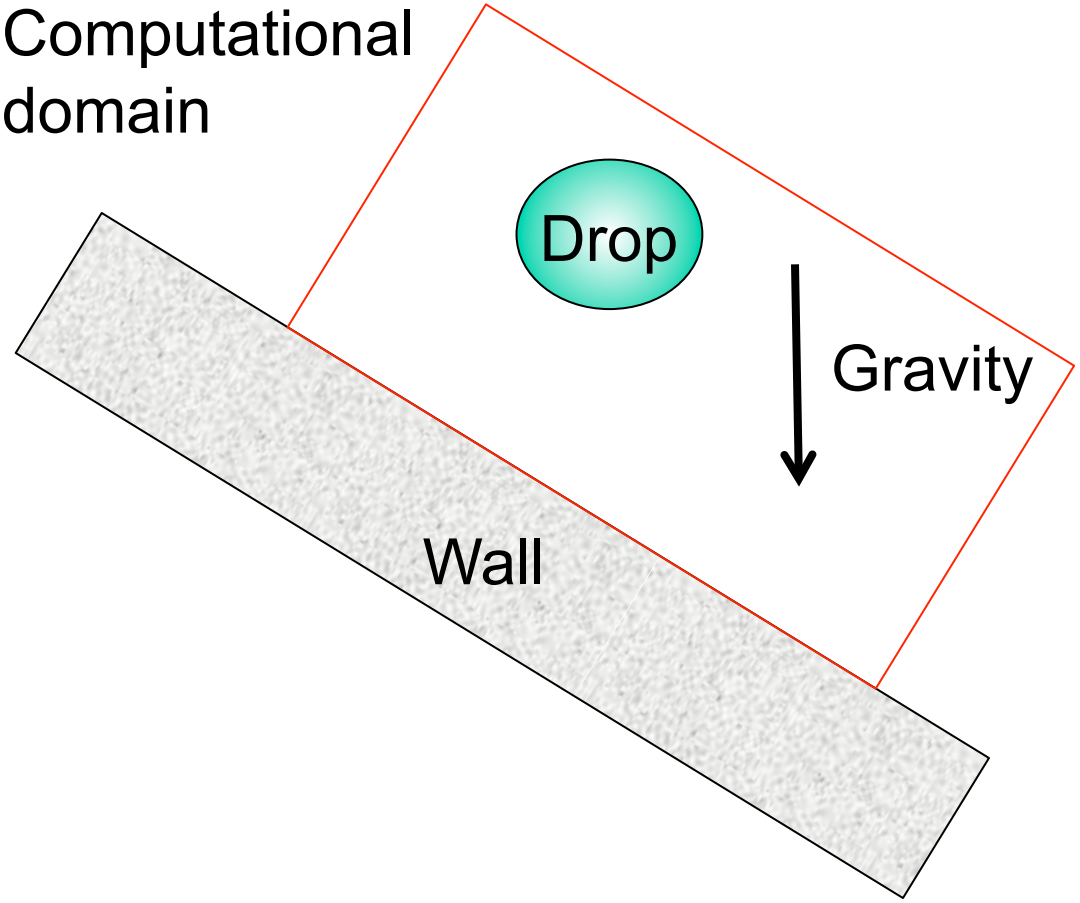
Type B Problems: Constitutive Modeling Based on the Microscopic Models

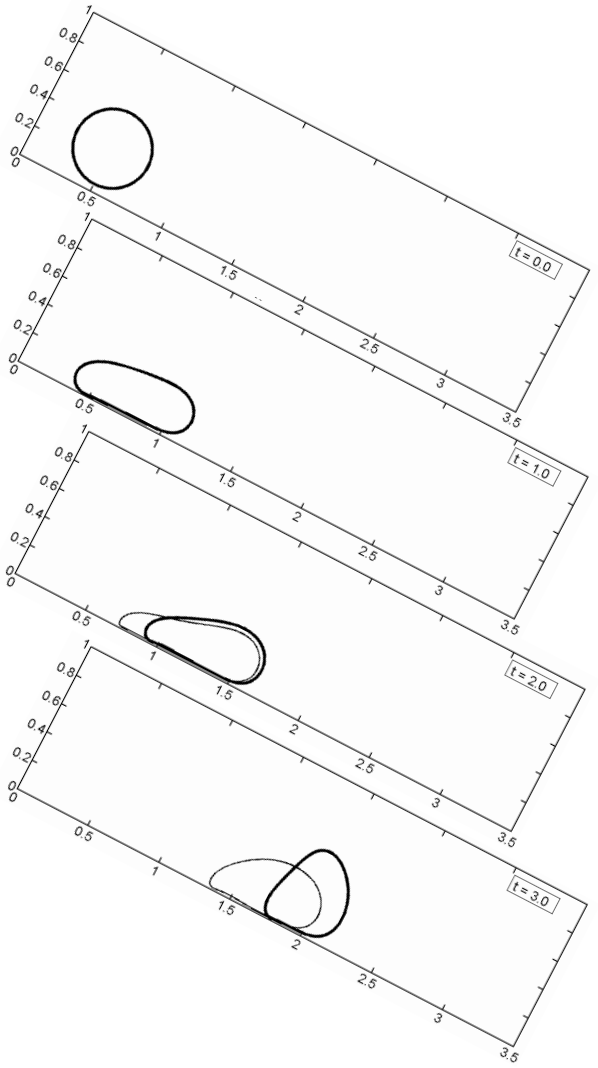
Reference: W. E and B. Enquist, The heterogeneous multiscale methods, *Comm. Math. Sci*. **1** (2003), 87—133.

Buoyant bubbles in an inclined channel flow



DNS of Multiphase Flows
DNS with multi-scale models





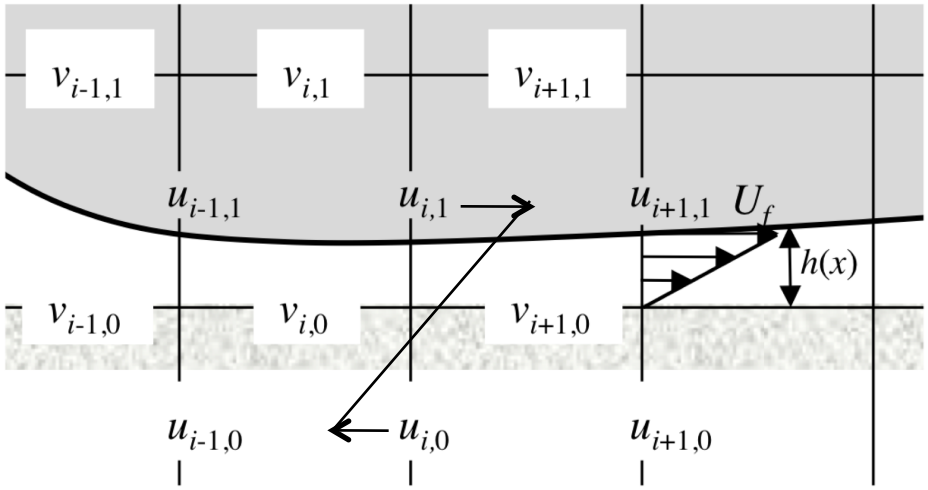
S. Thomas, A. Esmaeeli and G. Tryggvason. “Multiscale computations of thin films in multiphase flows.” *Int’l J. Multiphase Flow* 36 (2010), 71-77.

DNS of Multiphase Flows
DNS with multi-scale models

Film model—linear velocity profile

$$\frac{\partial h}{\partial t}+\frac{1}{2}\frac{\partial}{\partial x}\left(hU_f\right)=0;$$

$$\frac{\partial}{\partial t}\left(hU_f\right)+\frac{2}{3}\frac{\partial}{\partial x}\left(hU_f^2\right)=-\frac{2h}{\rho_o}\left(\frac{dp}{dx}\right)_f,$$



Wall shear and ghost velocity:

$$\tau_f=\mu_o\frac{U_f}{h} \rightarrow u_{i,0}=u_{i,1}-\frac{\tau_f\Delta y}{\mu_d}$$

1. Identify whether a grid points at a wall belong to a film or not.

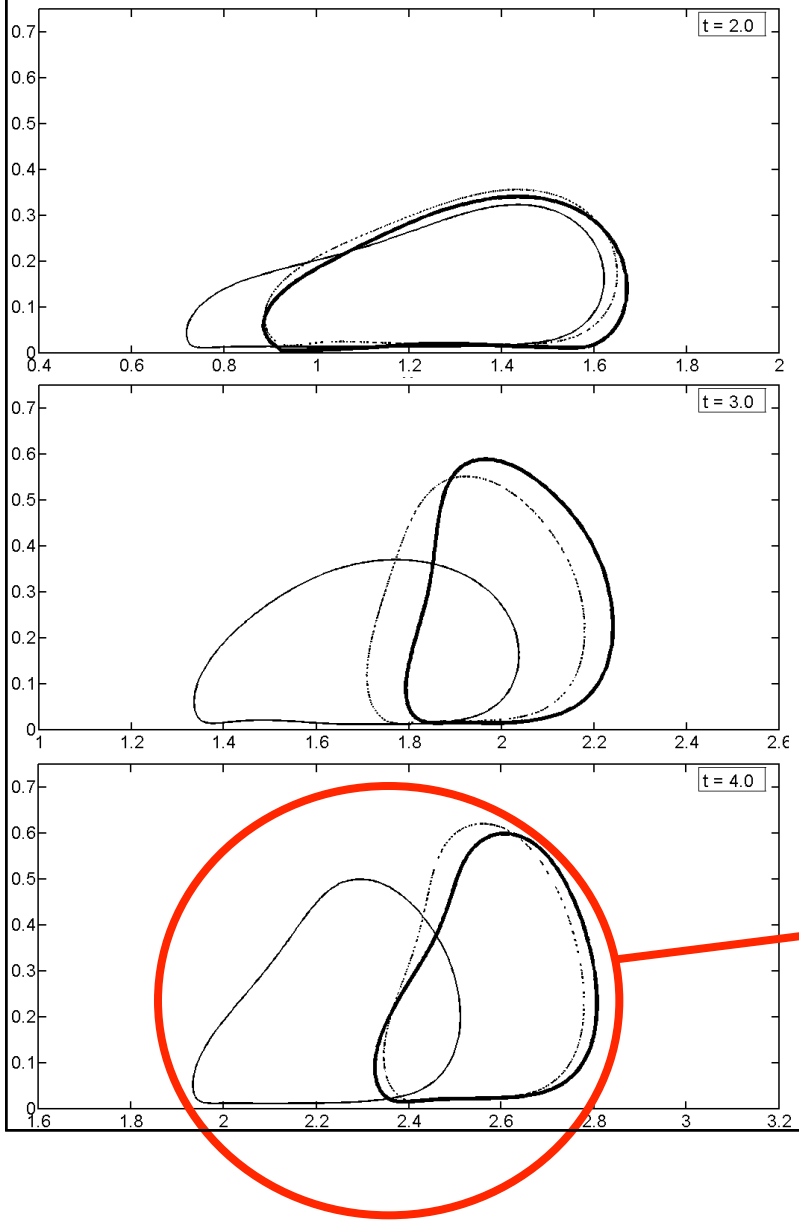
2. For film wall-points, given h and U_f, find the wall-shear and set the ghost velocities. For points outside the film, use the no-slip boundary condition.

3. Solve the Navier-Stokes equations for the velocity and pressure at the next time step, using the ghost velocities set above.

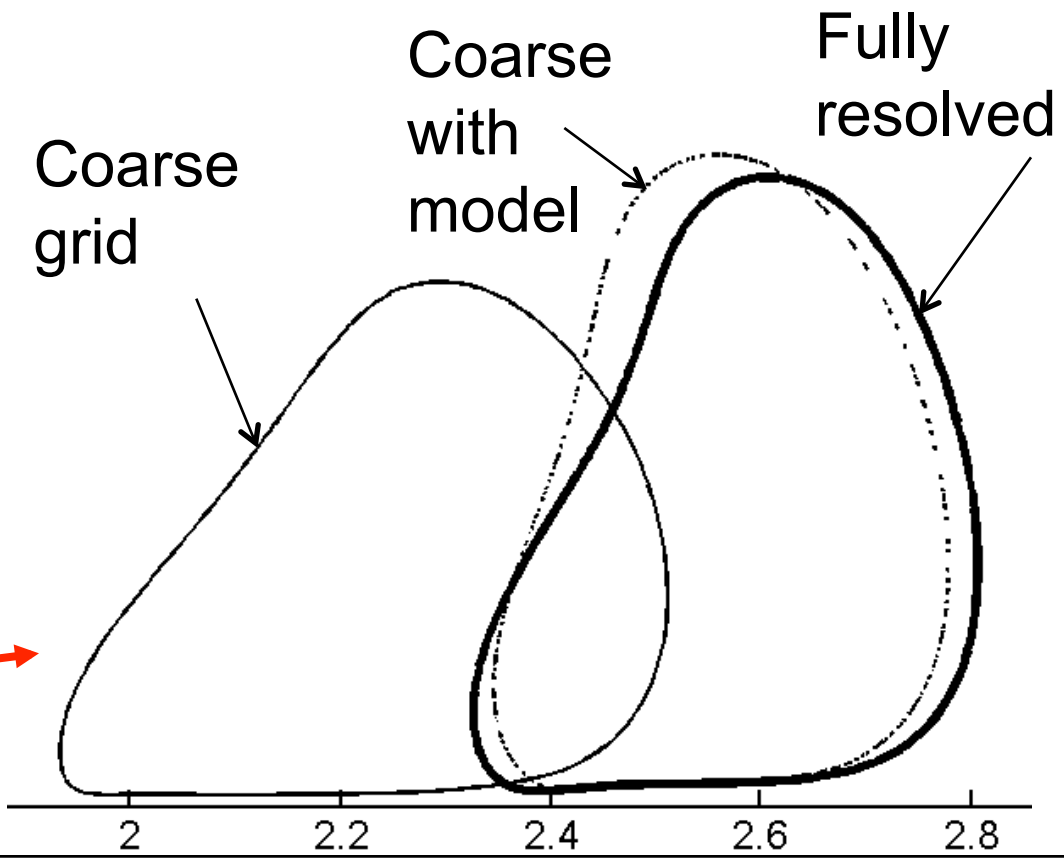
4. Integrate the thin film equations, using the pressure at the wall as computed by solving the Navier-Stokes equations (step 3).

5. Go back to (1)

DNS of Multiphase Flows
DNS with multi-scale models



Drop motion on a sloping wall.
Impact of fully resolving the film between the drop and the wall



DNS of Multiphase Flows

Mass transfer for bubble swarms

Computations of chemical reactions in bubble wakes

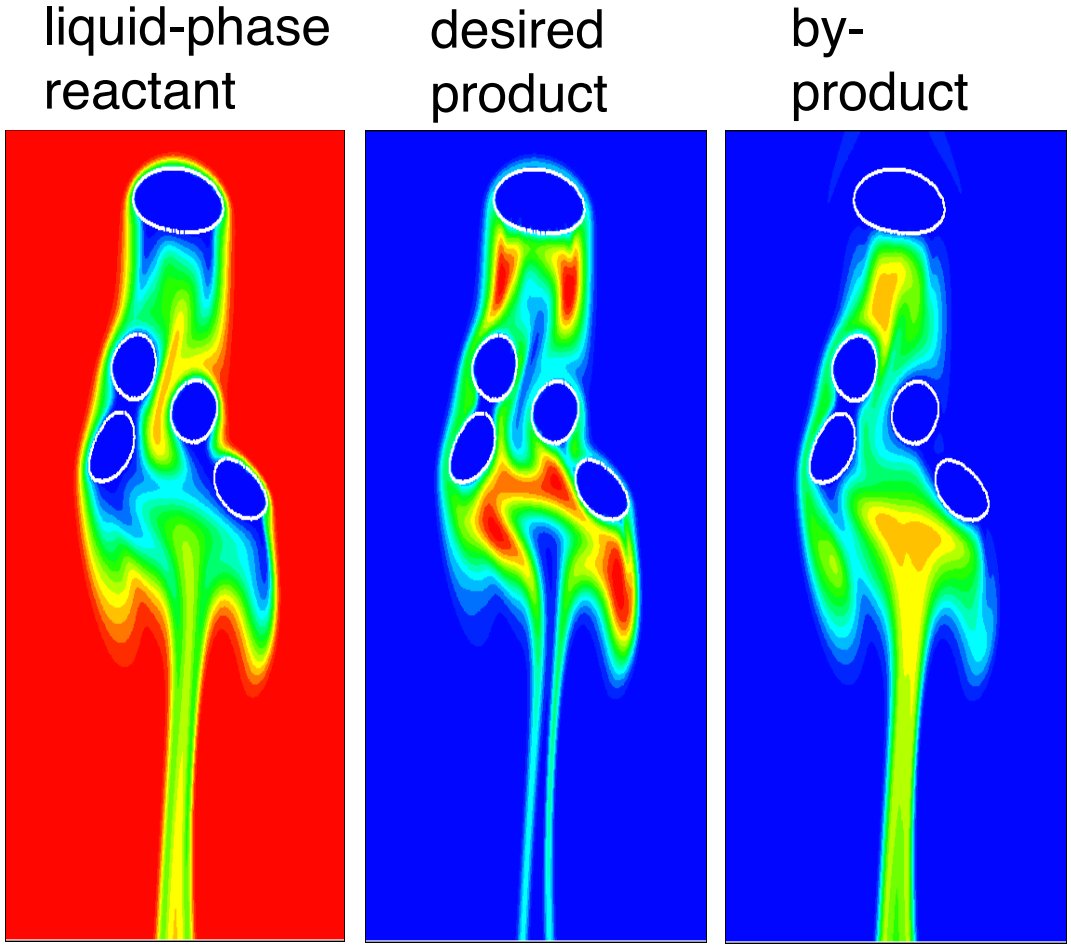
$$A + B \rightarrow R$$

$$A + R \rightarrow S$$

A-liquid reactant,
B-gaseous reactant,
R-desired product,
S-impurity.

Re=20, based on the large bubble;
bubble diameter ratio – 1:1.4;
Sc=300,
Da_1=0.25 and Da_2=0.025

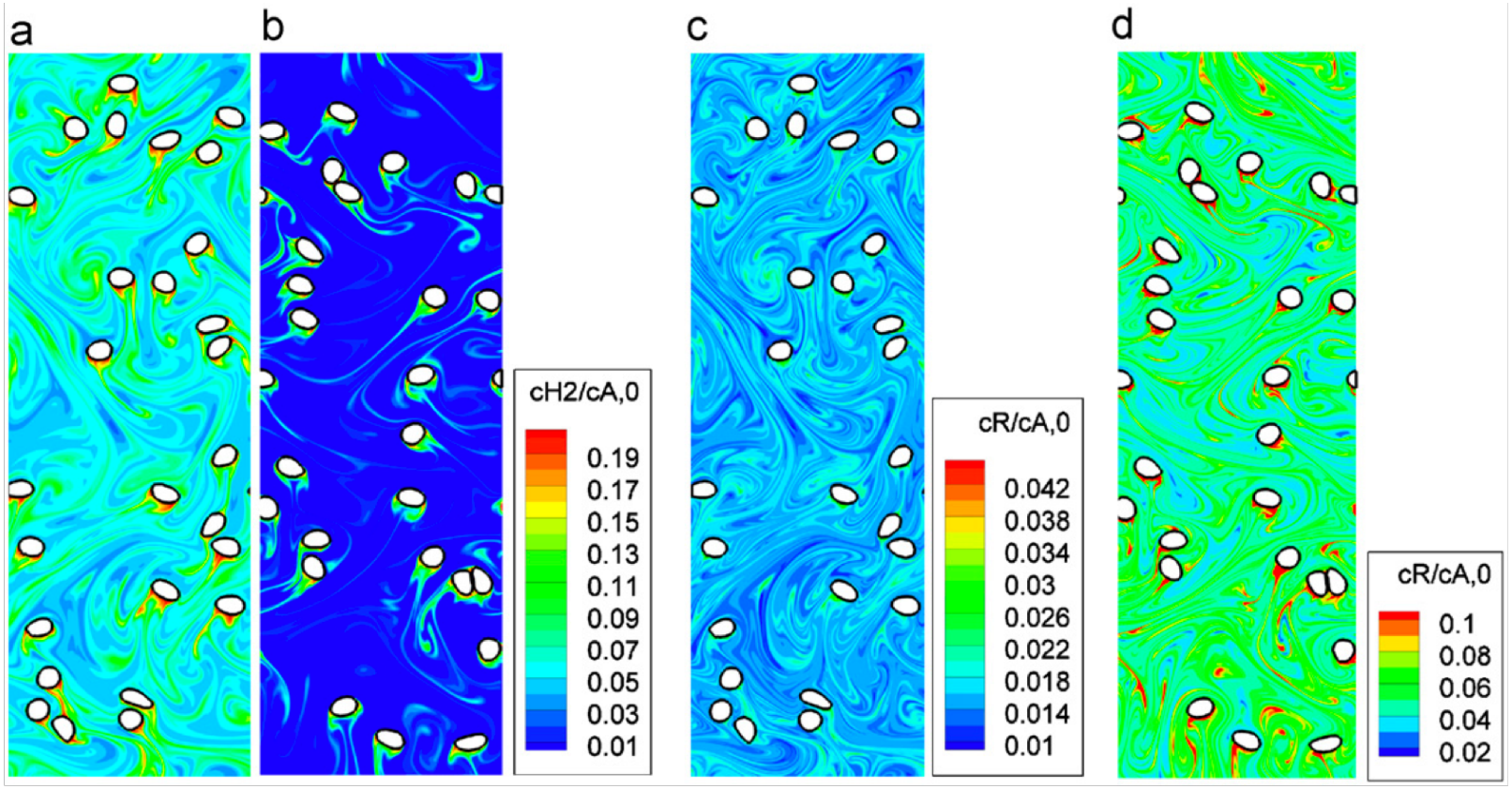
Dimensionless reaction rates:
$r_1 = Da_1 \cdot c_A \cdot c_B$
$r_2 = Da_2 \cdot c_A \cdot c_R$.



A. Koynov, G. Tryggvason, and J. G. Khinast. “Mass Transfer and Chemical Reactions in Bubble Swarms with Dynamic Interfaces.” *AIChE Journal* 10 (2005), 2786-2800.

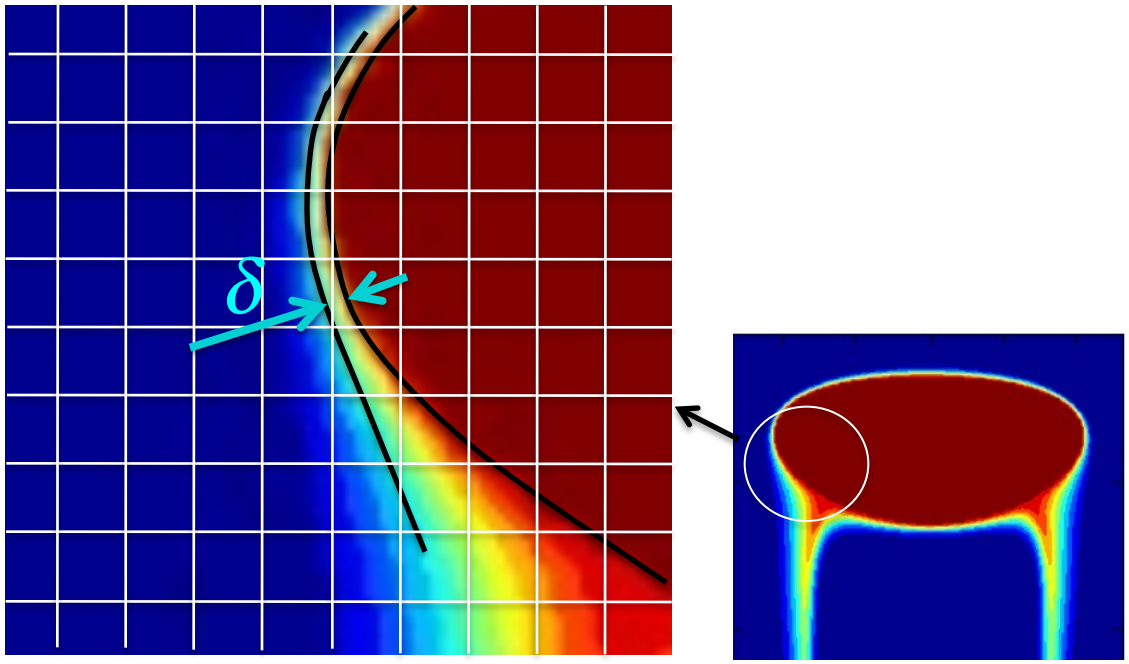
A. Koynov, G. Tryggvason, M. Schlüter, J. G. Khinast. “Mass Transfer and Chemical Reactions in Reactive Deformable Bubble Swarms.” Appl. Phys. Lett. 88, 134102 (2006)

DNS of Multiphase Flows
DNS with multi-scale models



Results from simulations of the of the catalytic hydrogenation of nitroarenes. The hydrogen (frames a and b) and hydroxylamine (frames c and d) concentration profiles are shown for one time for two simulations. In frames a and c the reaction rates are relatively slow, compared with the mass transfer, but in frames b and d the reaction is relatively fast. From Radl et al.

DNS of Multiphase Flows
Mass diffusion in liquids



Approximate

$$M_0 = \int_0^\infty f\, dn$$

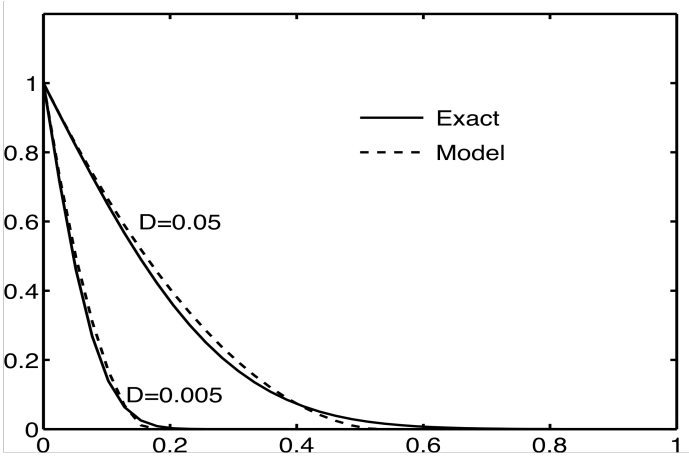
$$M_1 = \int_0^\infty n\, f\, dn$$

$$\frac{dM_0}{dt} = -2\sigma M_0 + 4D\left.\frac{\partial f}{\partial n}\right|_0$$

$$\frac{dM_1}{dt} = -3\sigma M_1 + 4Df_0$$

In the mass boundary layer

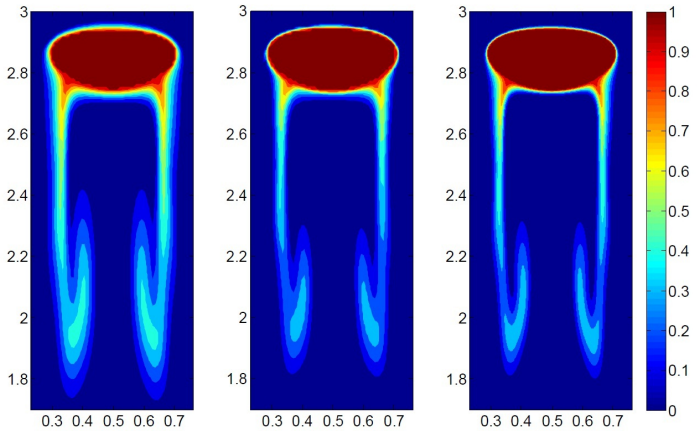
$$\frac{\partial f}{\partial t} = \sigma n \frac{\partial f}{\partial n} + D\frac{\partial^2 f}{\partial n^2}$$

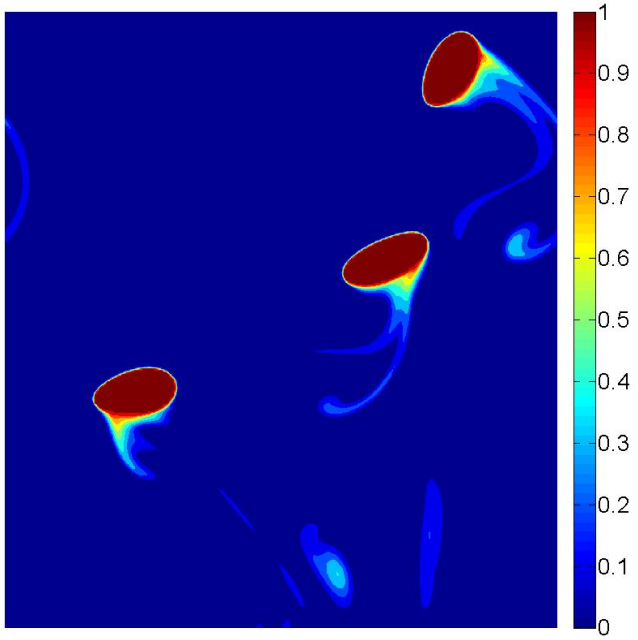


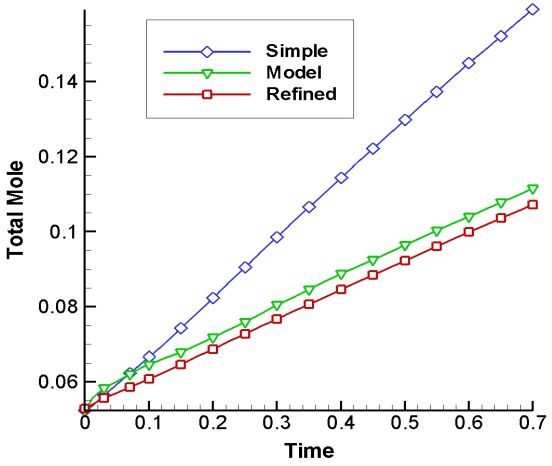
Dissertation work of B. Aboulhasanzadeh

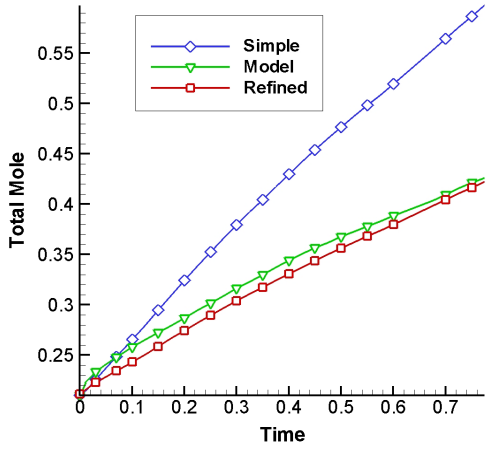
DNS of Multiphase Flows
Mass diffusion in liquids

Low resolution; Fully resolved;
Low resolution with model



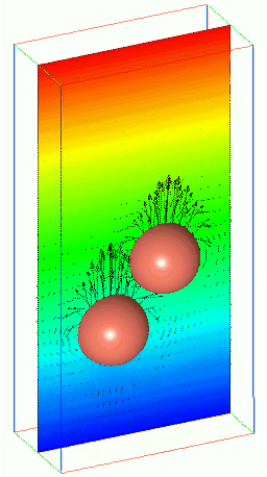




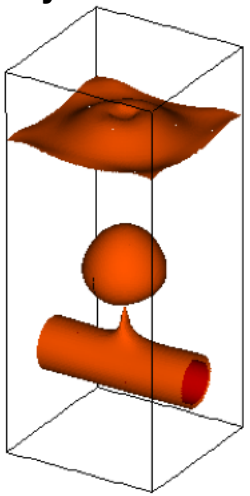


DNS of Multiphase Flows
And Many More!

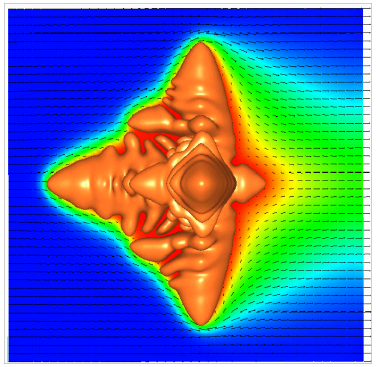
Thermo-capillary migration

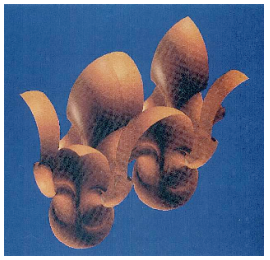


Film boiling from a hot cylinder

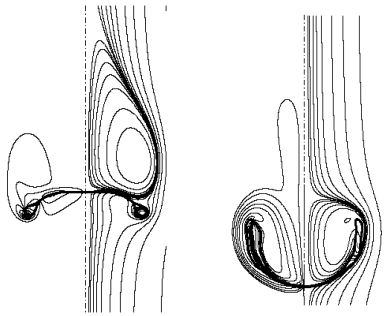


Effect of flow on dendritic solidification

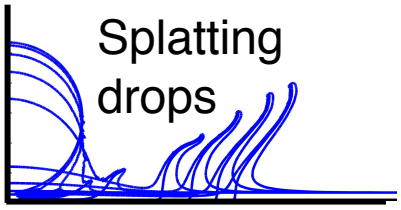


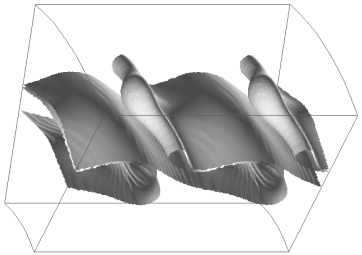


Rayleigh-Taylor

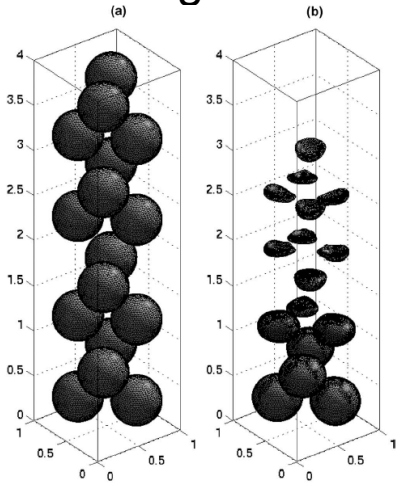


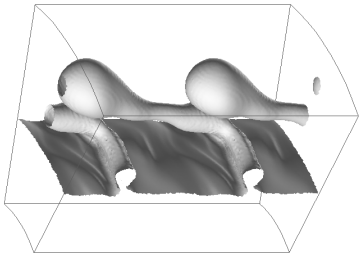
Drop breakup

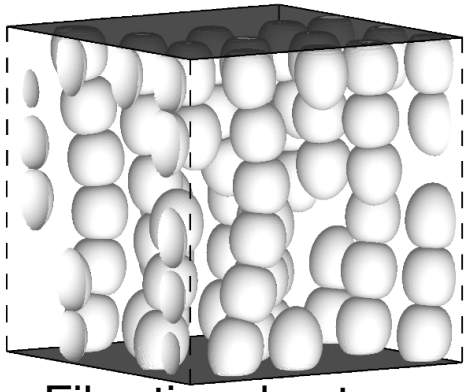




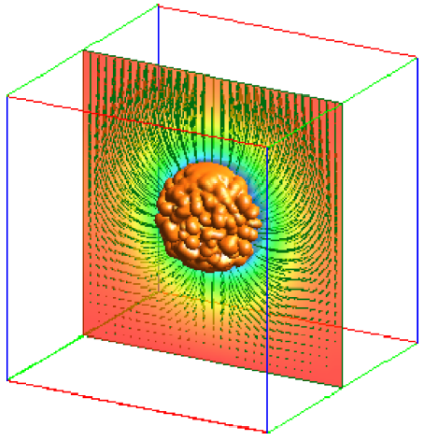
Cavitating bubbles



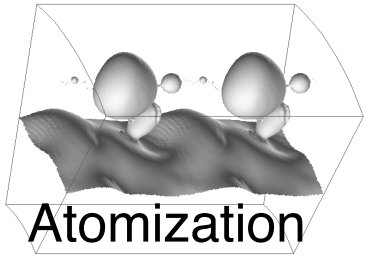




Fibration due to electric fields



Explosive Boiling



Atomization

Summary

The front tracking method described here has the right combination of simplicity and accuracy to allow simulation of fairly complex multiphase flow problems.

The control over topology changes provides the user with the ability to either include or exclude such changes.

Generally, explicit tracking provides more accurate results for the same resolution than marker function methods, but at the cost of slightly more complexity.

The presence of separate computational elements to track the front allows for many extensions and improvements

DNS of Multiphase Flows
What Now?

We now have the ability to conduct DNS of disperse multiphase flows for a fairly large range of situations. These simulations have been shown to yield insight of the same type obtained from DNS of single phase turbulent flows

Modeling of multiphase flows is far behind single phase flows and the development of more advanced models that can incorporate the new insight and data is perhaps the most urgent task in computational studies of multiphase flows

Numerical challenges still remain, but those are of critical importance primarily for flows that are more complex than those discussed here (churn-turbulent, phase change, etc.)

One of the biggest obstacle for more rapid increase in the use of DNS is the high “entry barrier” for new investigators. Many “things” to learn!