DE LA RECHERCHE À L'INDUSTRIE

# On the effect of buoyancy on lateral migration of bubbles in turbulent flows: insights from Direct Numerical Simulations

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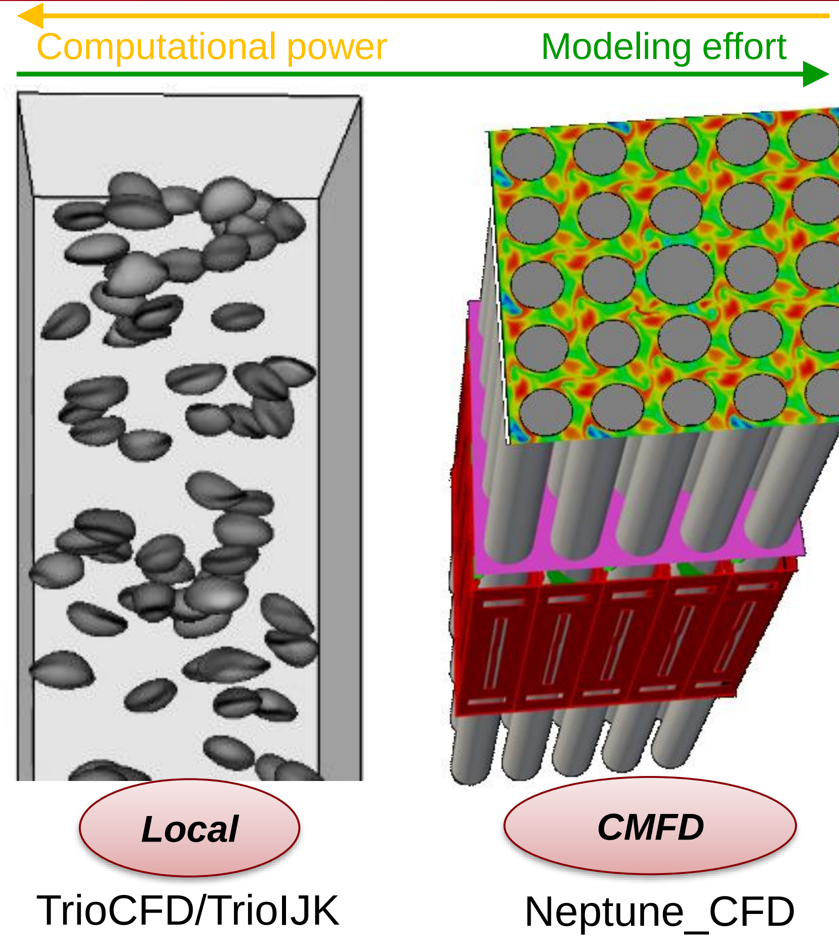
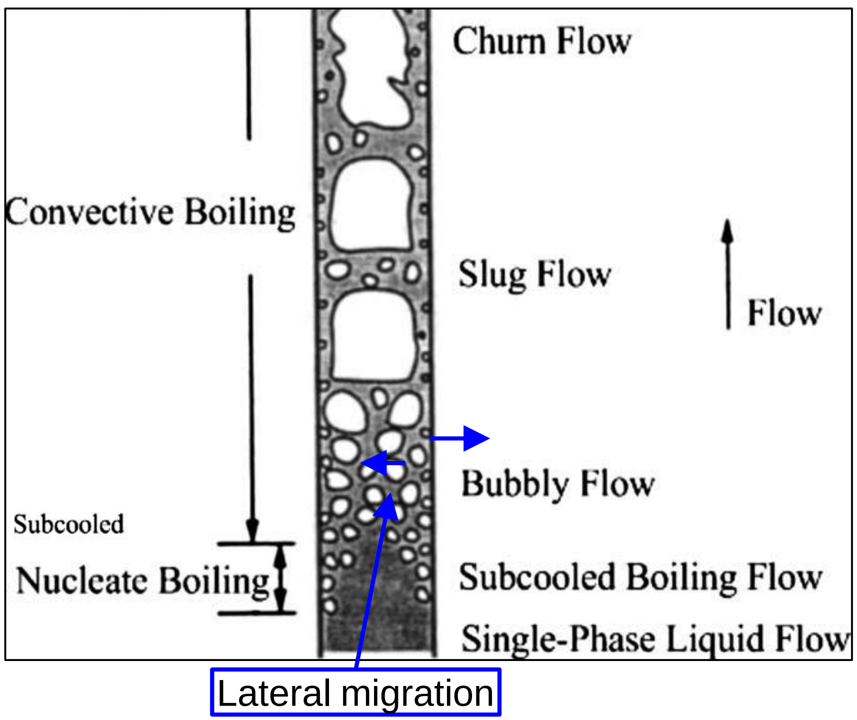
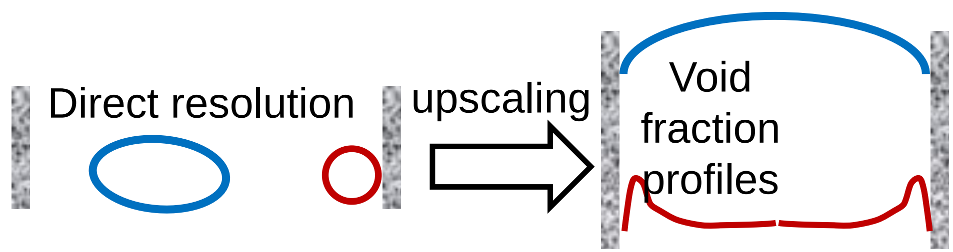
# Context: upscaling of information

## Effect of void fraction profiles in bubbly flow

- Broad application: Critical Heat Flux prediction in PWR conditions (high T&P);
- Focus on the effects of void accumulation at the wall / core due to lateral migration of bubbles;
- Separate effects analysis: adiabatic conditions;
- Up-scaling DNS understanding into CMFD models.



# Governing equations (exact, averaged)

## Two-fluid model used in CMFD codes

ICMF 2019

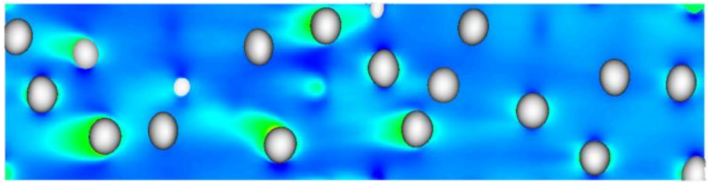
- Definition of "two-fluid" variables for CMFD:
  - $\overline{\phi_k}^k \triangleq \frac{\overline{\chi_k \phi_k}}{\overline{\chi_k}}$ (weighted average by the phase indicator)
  - Void fraction: $\alpha_v = \overline{\chi_v}$
  - Fluctuating velocities: $\boldsymbol{u}'_k = \boldsymbol{u}_k - \overline{\boldsymbol{u}}_k^k$
- Phase-averaged momentum equation:

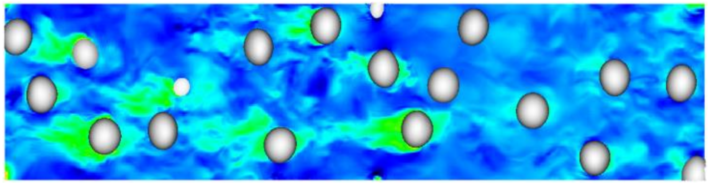
$$\frac{\partial \alpha_k \rho_k \overline{\boldsymbol{u}}_k^k}{\partial t} + \nabla \cdot \left[\alpha_k \rho_k \left(\overline{\boldsymbol{u}}_k^k \overline{\boldsymbol{u}}_k^k + \boldsymbol{R}_{ij}^k\right)\right] = -\nabla\left(\alpha_k \bar{p}_k^k\right) + \alpha_k \rho_k \boldsymbol{g} + \nabla \cdot \left[\alpha_k \overline{\boldsymbol{\tau}}_k^k\right] - \overline{\left(p_k \boldsymbol{n}_k - \boldsymbol{\tau}_k \cdot \boldsymbol{n}_k\right) \cdot \nabla \chi_k}$$

Momentum interfacial transfer defined from local fields: $\boldsymbol{M}_k = \boldsymbol{M}_k(\chi, u, p)$

Correlation between fluctuations, Reynolds stresses : $\boldsymbol{R}_{ij}^k = \overline{u'_i u'_j}^k$

- Constitutive equations on $\boldsymbol{R}_{ij}^k$ and $\boldsymbol{M}_k$ are required to close the system.
- This presentation focuses on lateral motion induced by migration forces ($\boldsymbol{M}_k$ closure)
- See abstract 168047. Talk at 11:30am on Thursday for a focus on turbulence modelling.
  *Modeling of Bubble-Induced Fluctuations in turbulent bubbly up-flow from Direct Numerical Simulations*,
  A. du Cluzeau, G. Bois, A. Toutant & A. Burlot.



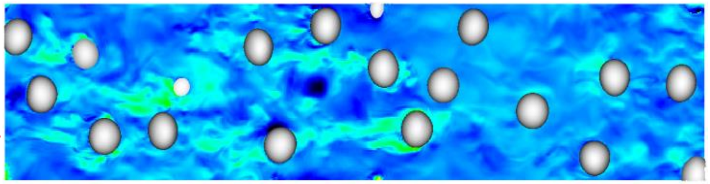


Instantaneous velocity → Reynolds stresses

$$\overline{\boldsymbol{u}'_l \boldsymbol{u}'_l}^l = \overline{\boldsymbol{u}'_l \boldsymbol{u}'_l}^l\Big|_{\text{lam}} + \overline{\boldsymbol{u}'_l \boldsymbol{u}'_l}^l\Big|_{\text{turb}}$$

Space fluctuations of the velocity (WIF)

Time fluctuations of the velocity (WIT)



# CMFD equations: modelling

## Two-fluid One-pressure model: hypotheses

- Momentum interfacial transfers are assessed by DNS:

$$\boldsymbol{M}_k = \frac{D\left(\alpha_k\rho_k\overline{\boldsymbol{u}}_k^k\right)}{Dt} + \nabla\cdot\left(\alpha_k\rho_k\boldsymbol{R}_{ij}^k\right) + \nabla\left(\alpha_k\bar{p}_k^k\right) - \alpha_k\rho_k\boldsymbol{g} - \nabla\cdot\left[\alpha_k\bar{\boldsymbol{\tau}}_k^k\right]$$

- They are in disequilibrium because of surface tension:

$$\boldsymbol{M}_l + \boldsymbol{M}_v = \cancel{\overline{\sigma\kappa\nabla\chi_v}}$$

- Beware, $\boldsymbol{M}_v$ is not the net force on the gas phase!
- Classical interfacial momentum transfer is turned into a trajectory equation for the gas phase:

Net force on the gas phase

$$\alpha_v\rho_v\frac{d\overline{\boldsymbol{u}}_v^v}{dt} = \mathbf{M}_{\mathrm{v}}^{\mathrm{tot}}$$

$$= \alpha_v(\rho_v - \langle\rho\rangle)\mathbf{g} - \alpha_v\alpha_l(\rho_l - \rho_v)\mathbf{g} - \alpha_v\left[\rho_v\cancel{\overline{\boldsymbol{u}_v'\boldsymbol{u}_v'}^v} - \rho_l\overline{\boldsymbol{u}_l'\boldsymbol{u}_l'}^l\right]\cdot\nabla\alpha_v + \alpha_v\cancel{\overline{\sigma\kappa\nabla\chi_v}} - \alpha_v\nabla\left[\cancel{\left(\bar{p}_v^v - \bar{p}_l^i\right)}\alpha_v\right]$$
$$- \alpha_v\nabla\overline{p_l^n}^l - \alpha_v\left[\alpha_l\nabla\cdot\left(\rho_l\overline{\boldsymbol{u}_l'\boldsymbol{u}_l'}^l\right) + \alpha_v\nabla\cdot\cancel{\left(\rho_v\overline{\boldsymbol{u}_v'\boldsymbol{u}_v'}^v\right)}\right]$$

Classically neglected in the standard two-fluid one-pressure model

  - Negligible in our conditions (from DNS and for readability): added-mass force, viscous terms

- Physical assumptions (classical two-fluid one-pressure modeling):
  - Fluctuations are neglected in the vapor phase;
  - Differences between pressures are neglected: $\bar{p}_v^v = \bar{p}_v^i = \bar{p}_l^l$
  - Lateral forces are made of lift, turbulent dispersion and wall lubrication forces only.

# Governing equations

## Reformulation and physical interpretation

- A deeper analysis of this trajectory equation for the gas phase (Newton's second law):

$$\alpha_v\rho_v\frac{d\overline{\boldsymbol{u}}_v^v}{dt} = \mathbf{M}_\mathrm{v}^\mathrm{tot}$$

Buoyancy and part of the drag

$\mathbf{M}^\mathrm{TD}$ Turbulent dispersion

$\mathbf{M}^\mathrm{LD}$ Laminar dispersion

$$= \alpha_v(\rho_v - \langle\rho\rangle)\mathbf{g} - \alpha_v\alpha_l(\rho_l-\rho_v)\mathbf{g} - \alpha_v\left[\rho_v\overline{\boldsymbol{u}_v'\boldsymbol{u}_v'}^v - \rho_l\overline{\boldsymbol{u}_l'\boldsymbol{u}_l'}^l\right]\cdot\nabla\alpha_v + \alpha_v\overline{\sigma\kappa\nabla\chi_v} - \alpha_v\nabla\left[(\bar{p}_v^v - \bar{p}_l^l)\alpha_v\right]$$

$$-\alpha_v\nabla\overline{p_l^n}^l - \alpha_v\left[\alpha_l\nabla\cdot\left(\rho_l\overline{\boldsymbol{u}_l'\boldsymbol{u}_l'}^l\right) + \alpha_v\nabla\cdot\left(\rho_v\overline{\boldsymbol{u}_v'\boldsymbol{u}_v'}^v\right)\right]$$

Sub-part of Laminar and turbulent Lift

$$\mathrm{M}_\Re^L\Big|_\mathrm{lam} + \mathrm{M}_\Re^L\Big|_\mathrm{turb} \propto (C_{LL}+C_{TL})\rho_l\boldsymbol{u}_r\nabla\wedge(\boldsymbol{u}_l)$$

$$\mathbf{M}_\Re^\mathbf{L}|_\mathrm{lam} + \mathbf{M}_\Re^\mathbf{L}|_\mathrm{turb}$$

$$-\alpha_v\nabla\overline{p_l^{SP}} + \mathbf{M}_{\nabla\mathbf{P}}^\mathbf{L}$$

Complex combination of single-phase pressure gradient and lift force due to pressure (induced by surface tension, NEW)

NEW, classically neglected

Two-phases Reynolds stresses:
- Laminar (WIF) $\propto \boldsymbol{u}_r^2$ NEW
- Turbulent (WIT) $\propto$ TKE

The turbulent part (NEW) can cause core-peaking ($C_{TL} < 0$)
It cannot be assessed on isolated bubbles (like Tomyiama's)
Turbulent lift is still $\propto \rho_l\boldsymbol{u}_r\nabla\wedge(\boldsymbol{u}_l)$

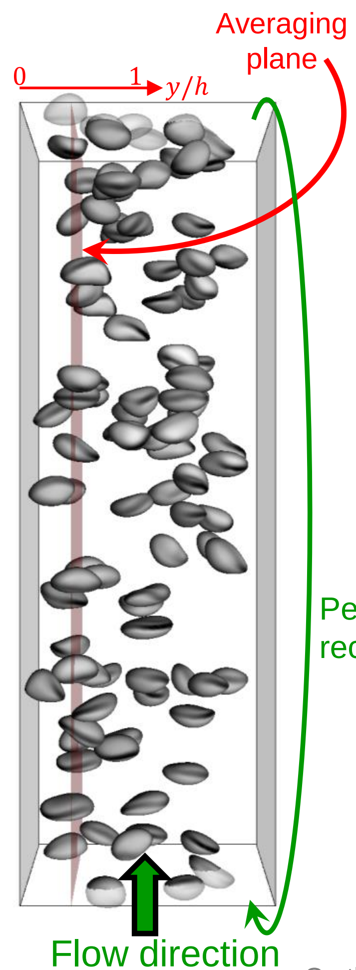
  - Viscous terms and added mass are neglected

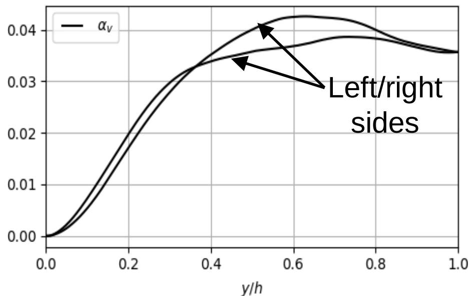
- We derived an exact relation with the definition of forces from local variables!
- Classical closures pile up assumptions and lack physical understanding of collective effects;
- We propose to generate and leverage DNS data to evaluate this equilibrium equation…

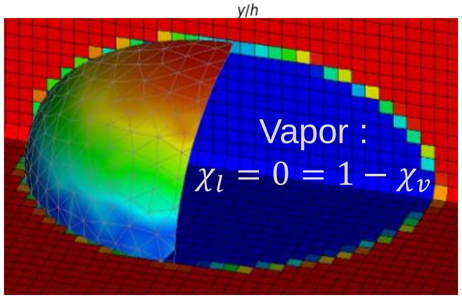
# Upscaling of DNS information

## Objective: DNS-informed lateral migration

- Interfacial transfers and turbulence in bubbly flows;
  - DNS of a bubbly turbulent channel flow with a Front-Tracking algorithm (TrioCFD/TrioIJK);
  - « Numerical experiments »: separated effects unit-tests (adiabatic, no contact line or coalescence);
  - Mean profiles and higher-order statistics are computed.



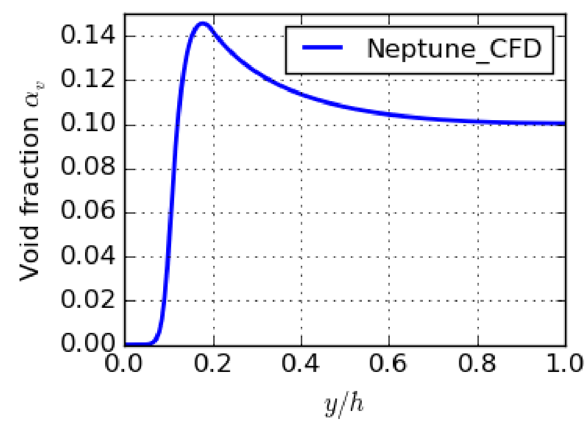



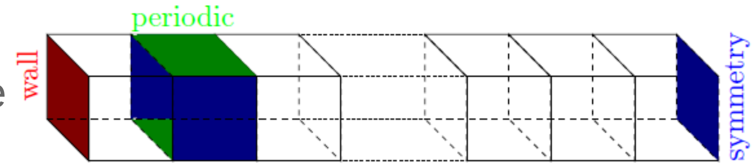




Upscaling

Local scale
DNS

Averaged scale
2-phase RANS
CFD



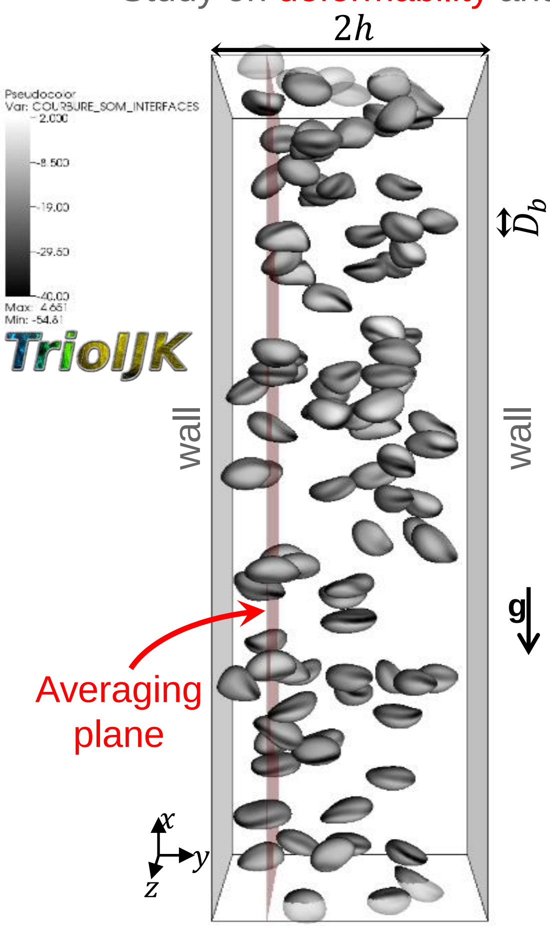



# DNS of turbulent bubbly flows (1/4)

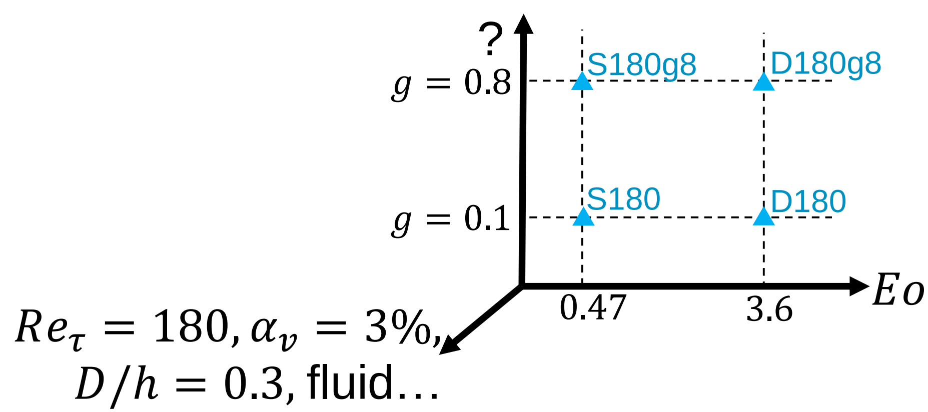
## Set-up description & operating conditions



- Lu & Tryggvason (Physics of Fluids, 20, 2008).
  ⇒ Code benchmark for validation;
  ⇒ Additional statistical analysis.
- Extended to higher Reynolds numbers;
  - Study on deformability and gravity (relative velocity).

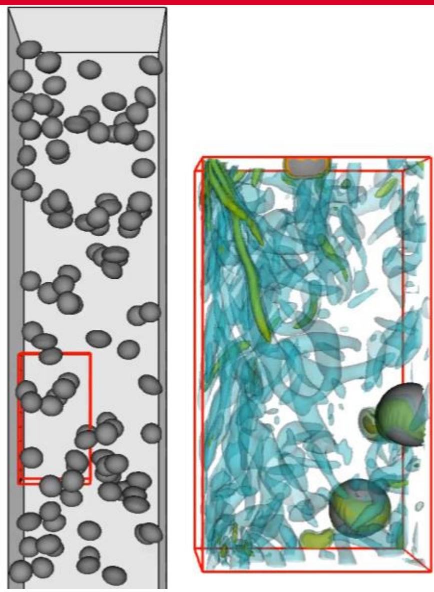


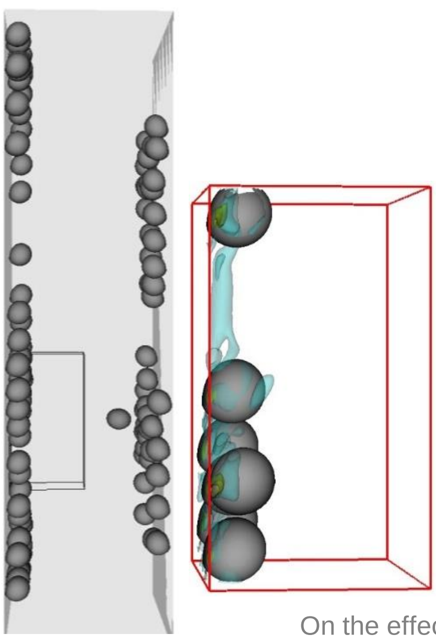

| | S | D |
|---|---|---|
| $Re_\tau = u_\tau h/\nu_l$ | 180 | |
| $Eo = \rho g d^2/\sigma$ | 0.47 | 3.6/3.74 |
| $\alpha_v$ (%) | 3 | |
| $D_b/h$ | 0.3 | |
| $N_b$ | 80 | |
| Size | $\pi h \times 2h \times \pi h/2$ | |
| Resolution | $384 \times 1152 \times 192 \approx 85$M^ons^ | |
| Mesh size | 0.3 to 3 $h/Re_\tau$ | |
| Fluid | Fictitious | |
| Gravity | 0.1/0.8 (non-dimensional) | |

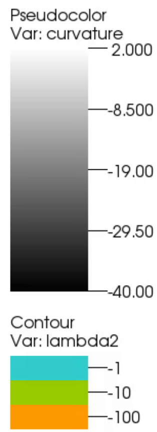


# DNS of turbulent bubbly flows (2/4)

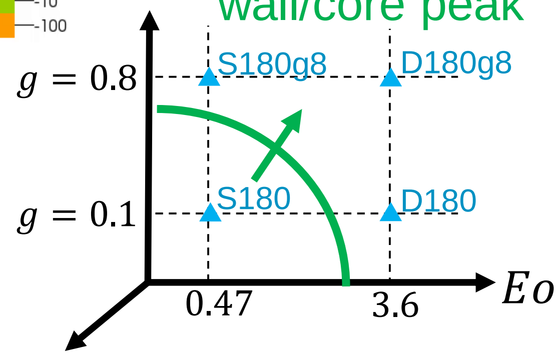
## Flow transition from wall to core peaking



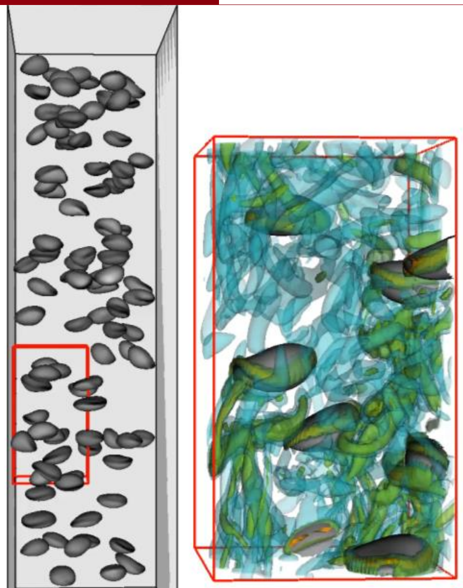


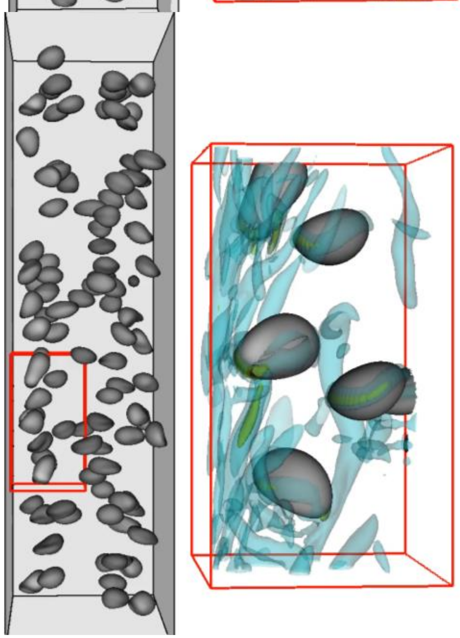



Transition:
wall/core peak



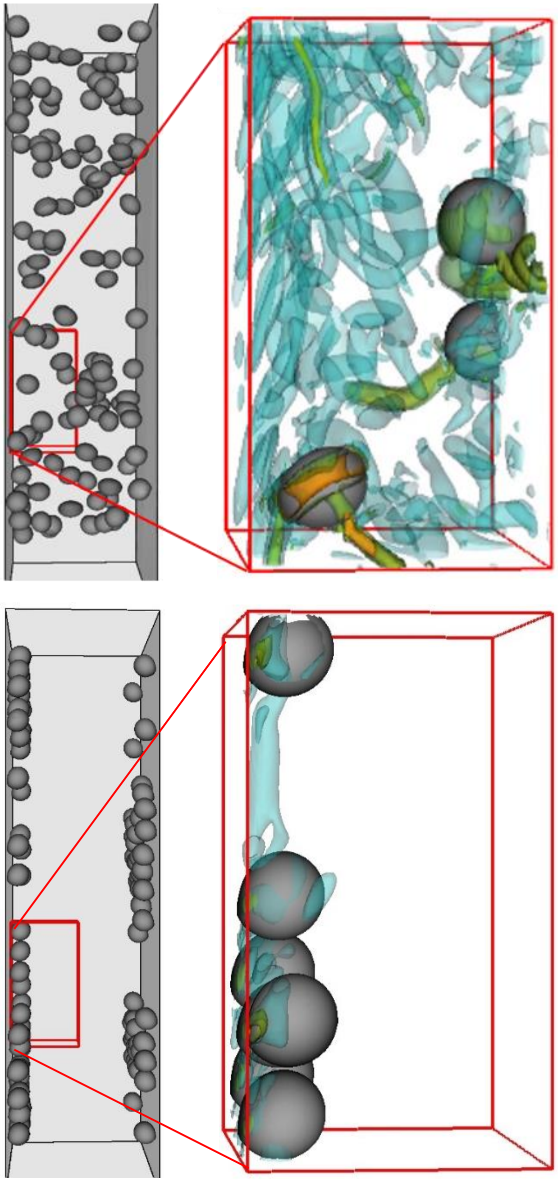

$Re_\tau = 180,$
$\alpha_v = 3\%,$
$D/h = 0.3,$
fluid…

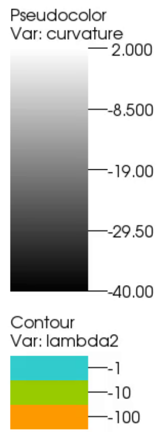




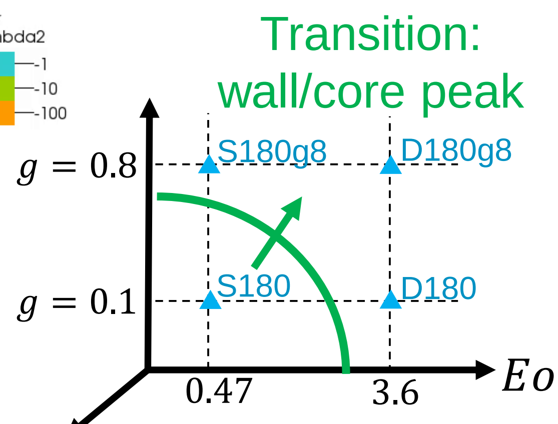
# DNS of turbulent bubbly flows (2/4)

## Flow transition from wall to core peaking

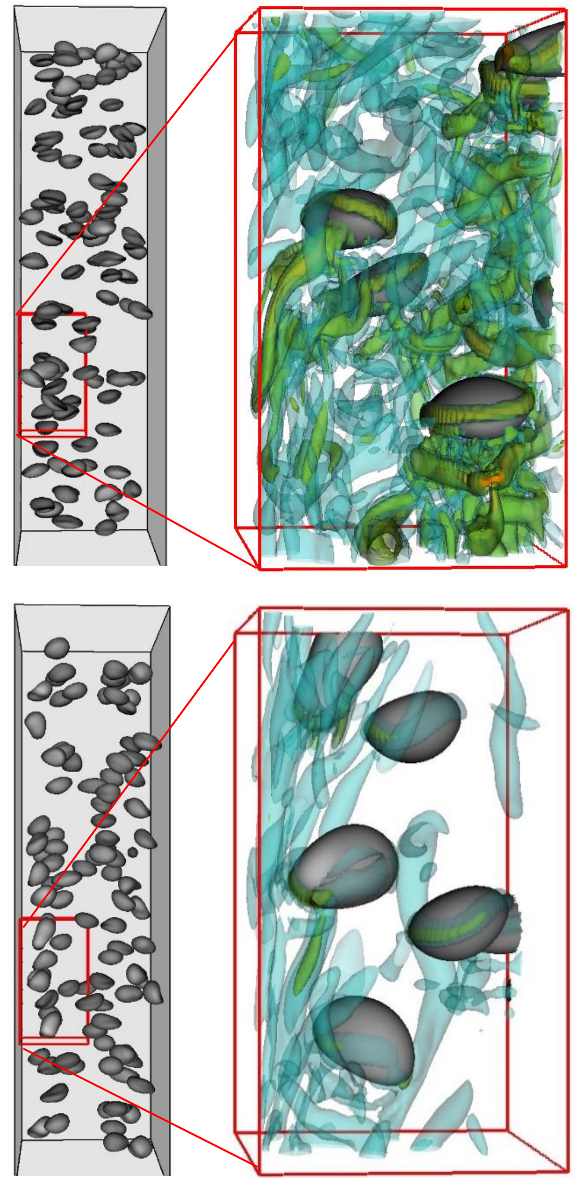





TrioIJK

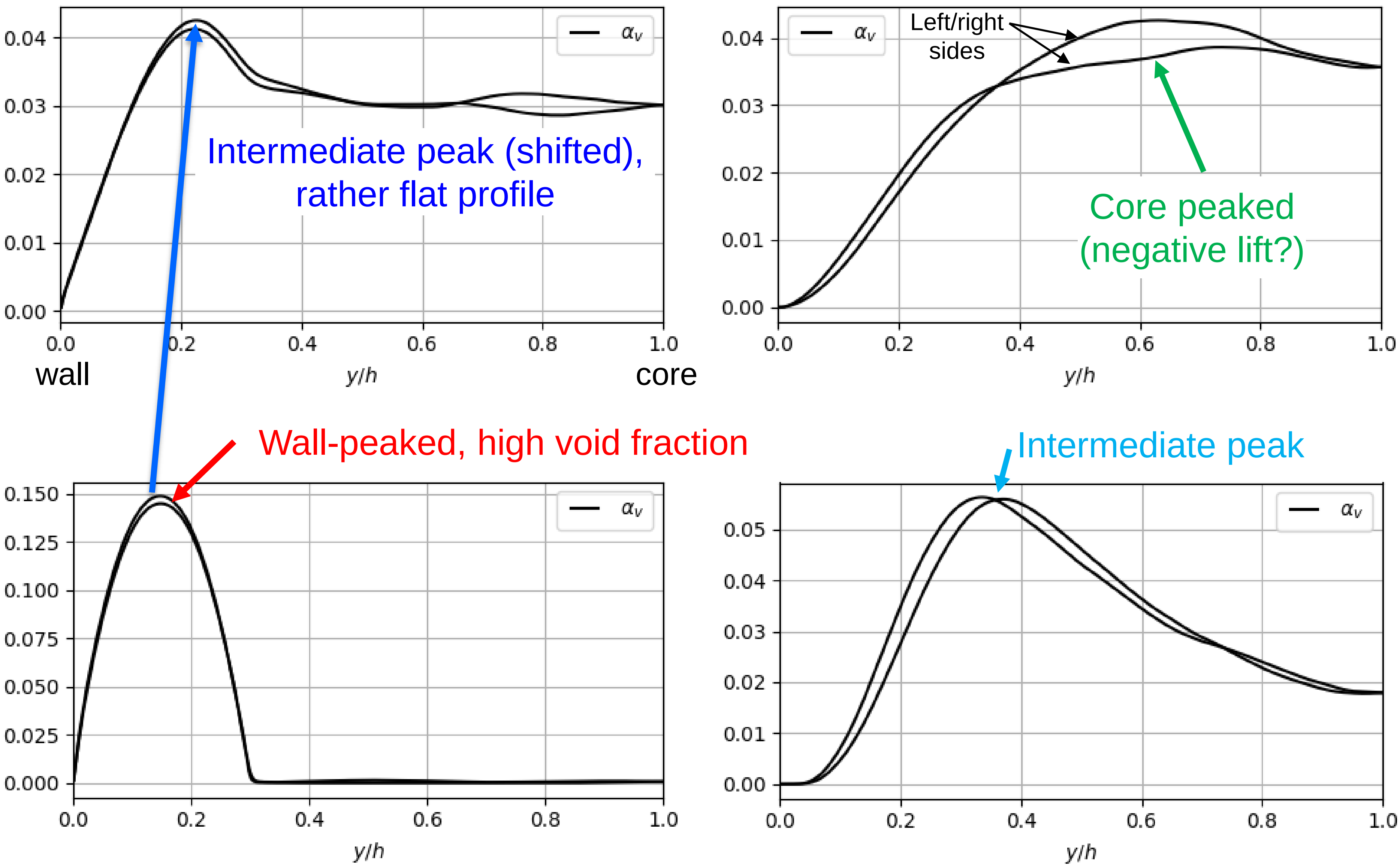



$Re_\tau = 180,$
$\alpha_v = 3\%,$
$D/h = 0.3,$
fluid…



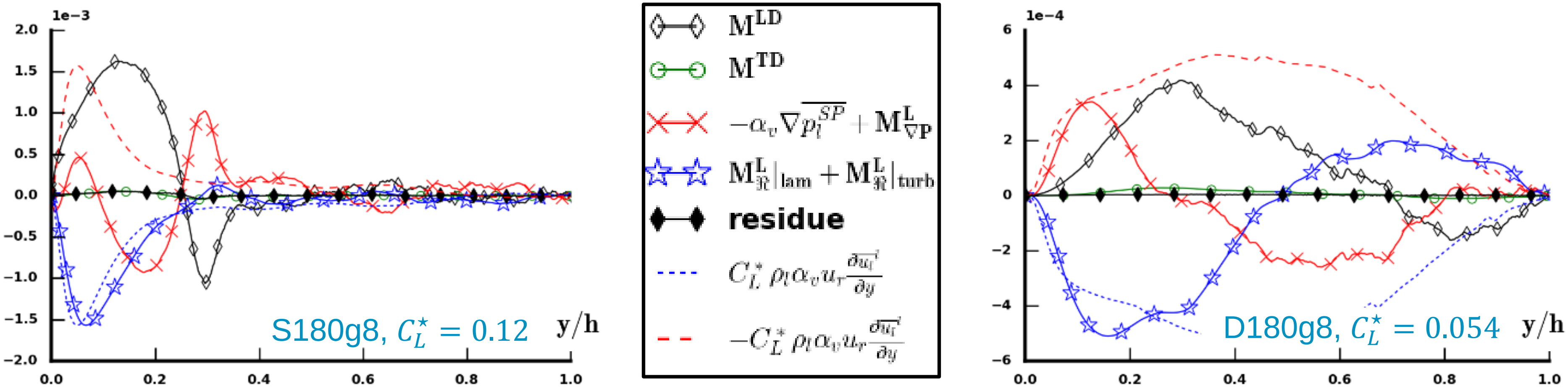
# DNS of turbulent bubbly flows – Results (3/4)

## Void fraction profiles exhibit different behaviors



# DNS of turbulent bubbly flows – Results (4/4)

## Surprising contributions to the migration forces



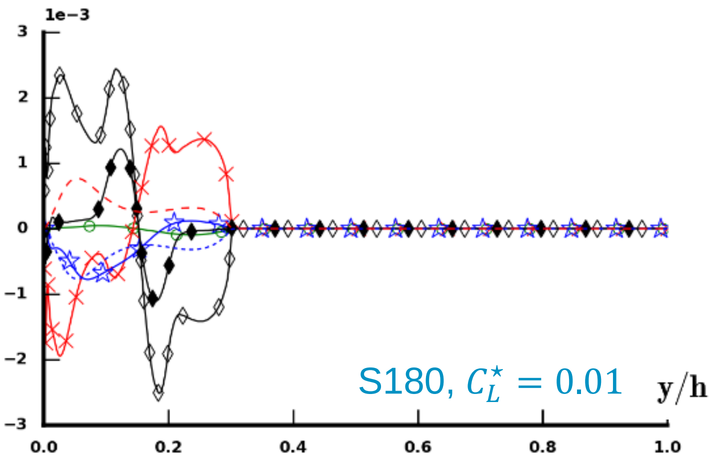

$$\mathbf{M}_v^{tot} = -\alpha_v \left[\rho_v \overline{\boldsymbol{u}'_v \boldsymbol{u}'_v}^v - \rho_l \overline{\boldsymbol{u}'_l \boldsymbol{u}'_l}^l\right] \cdot \nabla \alpha_v + \alpha_v \overline{\sigma \kappa \nabla \chi_v} - \alpha_v \nabla\left[\left(\bar{p}_v^v - \bar{p}_l^l\right)\alpha_v\right] - \alpha_v \nabla \overline{p_l^n}^l - \alpha_v \left[\alpha_l \nabla \cdot \left(\rho_l \overline{\boldsymbol{u}'_l \boldsymbol{u}'_l}^l\right) + \alpha_v \nabla \cdot \left(\rho_v \overline{\boldsymbol{u}'_v \boldsymbol{u}'_v}^v\right)\right]$$

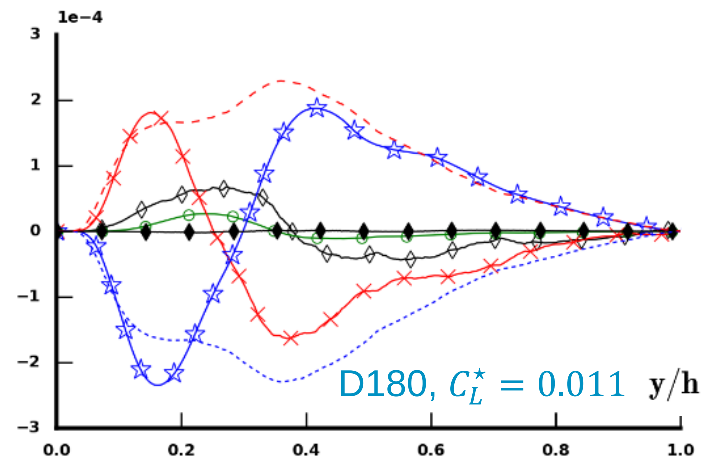
Turbulent dispersion

Laminar dispersion

Laminar and turbulent lift

Single-phase pressure gradient and lift force (induced by surface tension)



# Conclusion & Prospects

- Core, wall and intermediate peaking are depicted from DNS (through variations of $\sigma$ and $g$)
  - Wall-to-core peak transition cannot be reduced to the inversion of the lift coefficient due to the bubble deformability ($Eo$).
  - Other classical hypotheses are in failure (surface tension effect, laminar Reynolds stresses…)

- Dominant role of the closure relations (interfacial forces and turbulence) on the flow dynamics

⇒ In-depths revision of hypotheses and closures.

  - Bubble-induced turbulence level plays a key role in the transition and must be predicted accurately

*see Session XIV – Thursday 11:30am – #168047 – A. Burlot*

*Reynolds stresses splitted into classical & bubble-induced turbulence, wake induced fluctuations;*

  - Interfacial momentum transfer:
    - The new formulation of the trajectory equation is an alternative to the classical particle approach;
    - New forces are essential in the equilibrium (related to surface tension, pressure difference and laminar Reynolds stresses (WIF) effects).

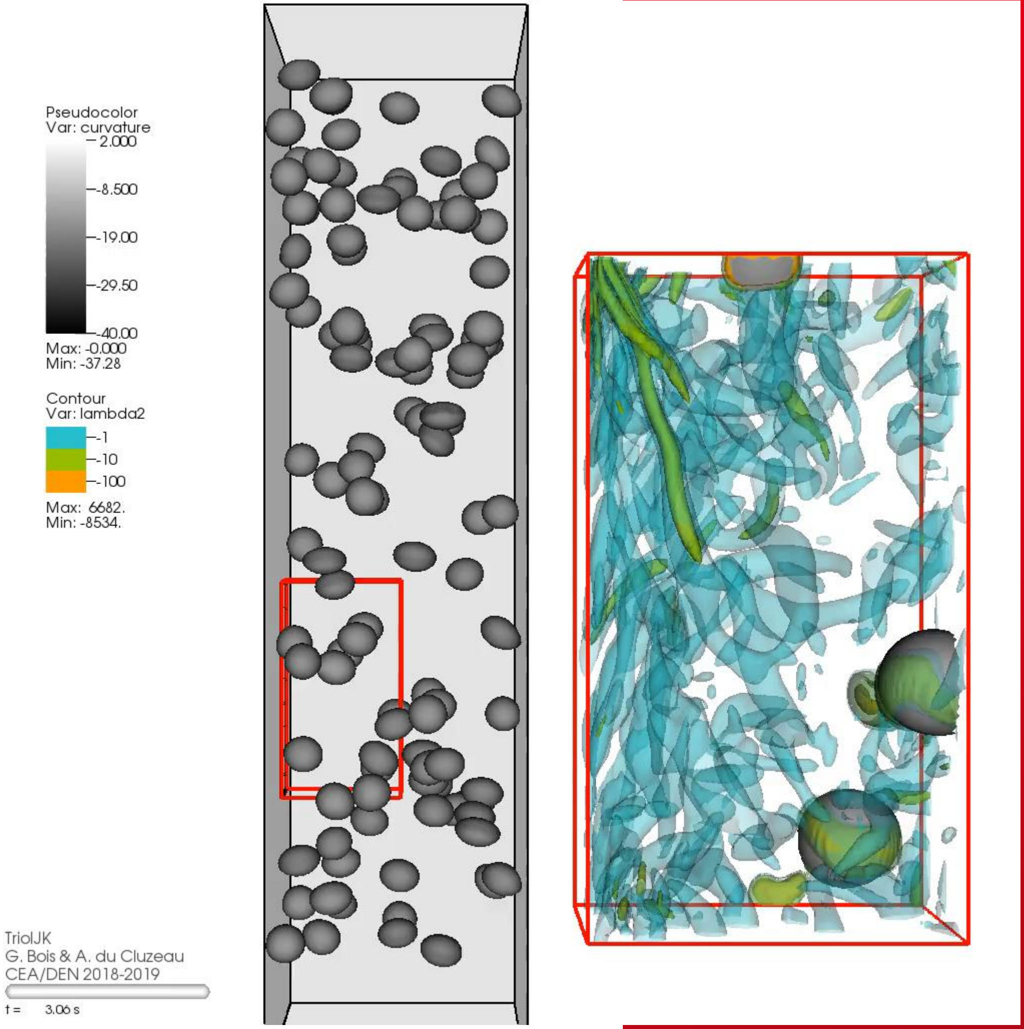
- The database in construction is:
  - Validated against other numerical work (further experimental validation is of interest);
  - Very rich: a lot of statistical information to build all kinds of models;
  - Well-designed for step-by-step analysis: DNS allows One At a Time (OAT) variations.

- Further analysis and model development are under way.
  - To derive and assess models for averaged to 2-phase RANS CFD calculations;
  - Extend the analysis to a broader parametric study and to bubble swarms.

# Acknowledgments


- This work was granted access to the HPC resources of CINES under the allocations x20162b7712, A0022b7712 and A0042b7712 made by GENCI.

- Acknowledgment to CEA/DEN for the HPC ressources allocated on COBALT super-computer at TGCC.




Thank you for your attention.

Questions?

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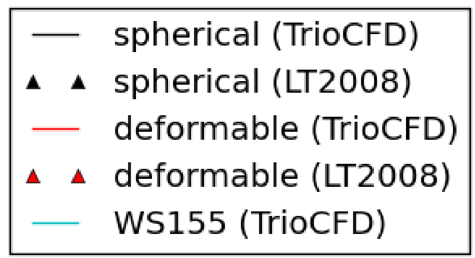
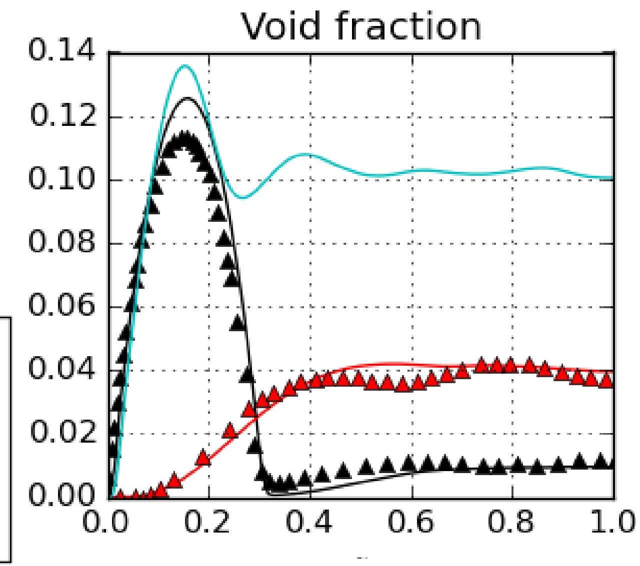
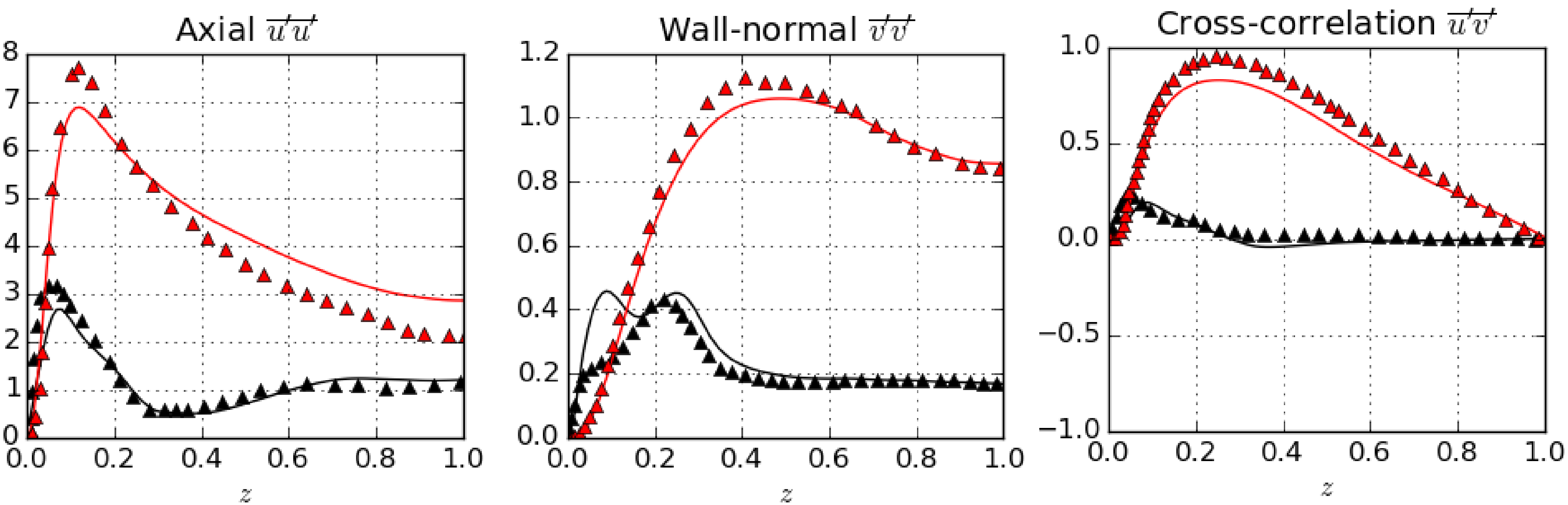
# DNS of turbulent bubbly flows

## Validation

- Very good agreements;
- Small discrepancies can reasonably be attributed to:
  - Higher statistical convergence of our results (longer time);
  - Small differences in lagrangian mesh management;
  - Discontinuous properties and sharp interfacial force treatment;
  - Uniform vs. non-uniform eulerian mesh.



# Governing equations

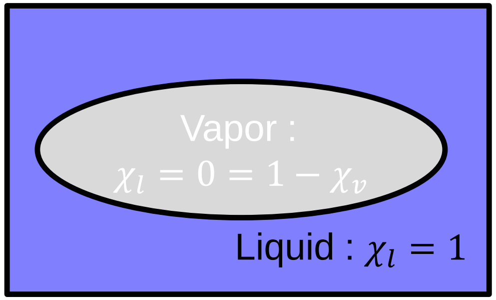
## One-fluid formulation (local instantaneous description)

- **Local instantaneous description (continuum fluid mechanics)**
  - Navier-Stokes equations:

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

$$\frac{\partial \rho_k \boldsymbol{u}_k}{\partial t} + \nabla \cdot (\rho_k \boldsymbol{u}_k \boldsymbol{u}_k) = -\nabla p_k + \rho_k \boldsymbol{g} + \nabla \cdot \boldsymbol{\tau}_k \text{ with } \boldsymbol{\tau}_k \mathrel{\widehat{=}} \mu_k(\nabla \boldsymbol{u}_k + \nabla^T \boldsymbol{u}_k)$$

  - Interfacial jump conditions:
    - Velocity continuity: $u_1^n = u_2^n$ and $u_1^t = u_2^t$
    - Interfacial normal stress balance: $\sum_k (p_k \boldsymbol{n}_k - \boldsymbol{\tau}_k \cdot \boldsymbol{n}_k) = -\sigma\kappa\boldsymbol{n}$




- **Extension to full space**
  - Multiply by phase indicator function $\chi_k$: 1 in phase k, 0 otherwise.

$$\frac{\partial \chi_k \rho_k \boldsymbol{u}_k}{\partial t} + \nabla \cdot (\chi_k \rho_k \boldsymbol{u}_k \boldsymbol{u}_k) = -\nabla(\chi_k p_k) + \chi_k \rho_k \boldsymbol{g} + \nabla \cdot [\chi_k \mu_k (\nabla \boldsymbol{u}_k + \nabla^T \boldsymbol{u}_k)] - (p_k \boldsymbol{n}_k - \boldsymbol{\tau}_k \cdot \boldsymbol{n}_k) \cdot \nabla \chi_k$$

- **One-fluid formulation**
  - Definition of "one-fluid" fields: $\phi \mathrel{\widehat{=}} \sum_k \chi_k \phi_k$
  - Adding up and using jump conditions:

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

$$\frac{\partial \rho \boldsymbol{u}}{\partial t} + \nabla \cdot (\rho \boldsymbol{u}\boldsymbol{u}) = -\nabla p + \nabla \cdot [\mu(\nabla \boldsymbol{u} + \nabla^T \boldsymbol{u})] + \sigma\kappa\boldsymbol{n}\,\delta^i$$

  - Combined "one-fluid" formulation valid at any point in the sense of distributions
  - Phase-indicator function $\chi_k$ is advected by the local velocity field (mixed VOF/FT algorithm)

# DNS of turbulent bubbly flows

## One-fluid formulation and Front-Tracking



- Local instantaneous Navier-Stokes equations…

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

$$\frac{\partial \rho_k \boldsymbol{u}_k}{\partial t} + \nabla \cdot (\rho_k \boldsymbol{u}_k \boldsymbol{u}_k) = -\nabla p_k + \rho_k \boldsymbol{g} + \nabla \cdot \boldsymbol{\tau}_k \text{ with } \boldsymbol{\tau}_k \widehat{=} \mu_k (\nabla \boldsymbol{u}_k + \nabla^T \boldsymbol{u}_k)$$

- … and interfacial jump conditions:
  - Velocity continuity: $u_1^n = u_2^n$ and $u_1^t = u_2^t$
  - Interfacial normal stress balance: $\sum_k (p_k \boldsymbol{n}_k - \boldsymbol{\tau}_k \cdot \boldsymbol{n}_k) = -\sigma \kappa \boldsymbol{n}$
- … are solved by the "one-fluid" formulation valid at any point in the sense of distributions:

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

$$\frac{\partial \rho \boldsymbol{u}}{\partial t} + \nabla \cdot (\rho \boldsymbol{u}\boldsymbol{u}) = -\nabla p + \nabla \cdot [\mu(\nabla \boldsymbol{u} + \nabla^T \boldsymbol{u})] + \sigma \kappa \boldsymbol{n}\, \delta^i$$

- "one-fluid" fields: $\phi \widehat{=} \sum_k \chi_k \phi_k$ with $\chi_k$ the phase indicator function.

- The phase-indicator function $\chi_k$ is advected by the velocity field (mixed VOF/FT algorithm)
  - Interfaces are explicitly tracked;
  - All scales are resolved in each phase

Normal, curvature

Phase indicator, velocity, pressure (MAC arrangement)