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

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International Conference on Multiphase Flow (ICMF)
Rio de Janeiro, Brazil, 19-24 May 2019

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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.

Context: upscaling of information
Effect of void fraction profiles in bubbly flow

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Definition of “two-fluid” variables for CMFD:

- \( \phi_k^{-k} = \frac{\chi_k \Phi_k}{\chi_k} \) (weighted average by the phase indicator)
- Void fraction: \( \alpha_v = \chi_v \)
- Fluctuating velocities: \( u'_k = u_k - \bar{u}_k \)

Phase-averaged momentum equation:

\[
\frac{\partial \alpha_k \rho_k \bar{u}_k^k}{\partial t} + \nabla \cdot \left[ \alpha_k \rho_k \left( \bar{u}_k^k \bar{u}_k^k + R_{ij}^k \right) \right] = -\nabla \left( \alpha_k \bar{p}_k^k \right) + \alpha_k \rho_k \mathbf{g} + \nabla \cdot \left[ \alpha_k \bar{\tau}_k^k \right] - \left( p_k \mathbf{n}_k - \tau_k \cdot \mathbf{n}_k \right) \cdot \nabla \chi_k
\]

Constitutive equations on \( R_{ij}^k \) and \( M_k \) are required to close the system.

This presentation focuses on lateral motion induced by migration forces (\( M_k \) closure)

Momentum interfacial transfers are assessed by DNS:

\[
M_k = \frac{D(\alpha_k \rho_k \bar{u}_k^k)}{Dt} + \nabla \cdot (\alpha_k \rho_k R_{ij}^k) + \nabla(\alpha_k \bar{p}_k^k) - \alpha_k \rho_k g - \nabla \cdot [\alpha_k \bar{\tau}_k^k]
\]

They are in disequilibrium because of surface tension:

\[
M_l + M_v = \sigma \chi_v
\]

Beware, \(M_v\) is not the net force on the gas phase!

Classical interfacial momentum transfer is turned into a trajectory equation for the gas phase:

\[\alpha_v \rho_v \frac{d\bar{u}_v}{dt} = M_v^{\text{tot}}\]

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

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: \(\bar{p}_v' = \bar{p}_v = \bar{p}_l\)
- Lateral forces are made of lift, turbulent dispersion and wall lubrication forces only.
A deeper analysis of this trajectory equation for the gas phase (Newton’s second law):

\[
\alpha_v \rho_v \frac{d\mathbf{u}_v}{dt} = M^\text{tot}_v
\]

Buoyancy and part of the drag

\[
= \alpha_v (\rho_v - \langle \rho \rangle) g - \alpha_v \alpha_l (\rho_l - \rho_v) g - \alpha_v \left[ \rho_v \mathbf{u}'_v \mathbf{u}_v' - \rho_l \mathbf{u}'_l \mathbf{u}_l' \right] \nabla \alpha_v + M^{\text{TD}}
\]

Turbulent dispersion

\[
- \alpha_v \nabla \bar{p}^\text{m}_l
- \alpha_v \left[ \alpha_l \nabla \cdot \left( \rho_l \mathbf{u}'_l \mathbf{u}'_l \right) + \alpha_v \nabla \cdot \left( \rho_v \mathbf{u}'_v \mathbf{u}'_v \right) \right]
\]

Sub-part of Laminar and turbulent Lift

\[
M^L_\text{lam} + M^L_\text{turb} \propto (C_{\text{LL}} + C_{\text{TL}}) \rho_l \mathbf{u}_r \nabla \land (\mathbf{u}_l)
\]

\[
-\alpha_v \nabla \bar{p}^\text{SP}_l + M^L_{\text{VP}}
\]

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) \( \propto \mathbf{u}_r^2 \) NEW
- Turbulent (WIT) \( \propto \text{TKE} \)

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 \( \propto \rho_l \mathbf{u}_r \nabla \land (\mathbf{u}_l) \)

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…
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.

In the diagram:
- Averaging plane
- Periodic recirculation
- Flow direction

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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).

DNS of turbulent bubbly flows (1/4)
Set-up description & operating conditions

$Re_{\tau} = \frac{u_{\tau} h}{\nu_l}$

$Eo = \frac{\rho g d^2}{\sigma}$

$\alpha_v$ (%) 

$D_b/h$

$N_b$

Size

Resolution

Mesh size

Fluid

Gravity

$0.1/0.8$ (non-dimensional)

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DNS of turbulent bubbly flows (2/4)

Flow transition from wall to core peaking

Transition: wall/core peak

$g = 0.8$

$g = 0.1$

$E_o = 0.47$

$E_o = 3.6$

$Re_\tau = 180,$

$\alpha_v = 3\%,$

$D/h = 0.3,$

fluid...
Transition: wall/core peak

\[ Eo = 180, \]  
\[ R_e = 180, \]  
\[ \alpha_v = 3\%, \]  
\[ D/h = 0.3, \]  
\[ \text{fluid...} \]
DNS of turbulent bubbly flows – Results (3/4)

Void fraction profiles exhibit different behaviors

Wall-peaked, high void fraction

Intermediate peak (shifted), rather flat profile

Core peaked (negative lift?)

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Surprising contributions to the migration forces

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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 ($E_0$).
- 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.
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 resources allocated on COBALT super-computer at TGCC.
Thank you for your attention.

Questions?
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:
    \[
    \nabla \cdot \mathbf{u}_k = 0
    \]
    \[
    \frac{\partial \rho_k \mathbf{u}_k}{\partial t} + \nabla \cdot (\rho_k \mathbf{u}_k \mathbf{u}_k) = -\nabla p_k + \rho_k \mathbf{g} + \nabla \cdot \mathbf{\tau}_k \quad \text{with} \quad \mathbf{\tau}_k \equiv \mu_k (\nabla \mathbf{u}_k + \nabla^T \mathbf{u}_k)
    \]
  - Interfacial jump conditions:
    - Velocity continuity: \( u_1^n = u_2^n \) and \( u_1^t = u_2^t \)
    - Interfacial normal stress balance: \( \sum_k (p_k \mathbf{n}_k - \mathbf{\tau}_k \cdot \mathbf{n}_k) = -\sigma \kappa n \)

- **Extension to full space**
  - Multiply by phase indicator function \( \chi_k \): 1 in phase \( k \), 0 otherwise.
    \[
    \frac{\partial \chi_k \rho_k \mathbf{u}_k}{\partial t} + \nabla \cdot (\chi_k \rho_k \mathbf{u}_k \mathbf{u}_k) = -\nabla (\chi_k p_k) + \chi_k \rho_k \mathbf{g} + \nabla \cdot [\chi_k \mu_k (\nabla \mathbf{u}_k + \nabla^T \mathbf{u}_k)] - (p_k \mathbf{n}_k - \mathbf{\tau}_k \cdot \mathbf{n}_k) \cdot \nabla \chi_k
    \]
  - **One-fluid formulation**
    - Definition of “one-fluid” fields:
      \( \phi \equiv \sum_k \chi_k \phi_k \)
    - Adding up and using jump conditions:
      \[
      \frac{\partial \rho \mathbf{u}}{\partial t} + \nabla \cdot (\rho \mathbf{u} \mathbf{u}) = -\nabla p + \nabla \cdot [\mu (\nabla \mathbf{u} + \nabla^T \mathbf{u})] + \sigma \kappa n \delta^i
      \]
  - 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)

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Local instantaneous Navier-Stokes equations...

\[ \frac{\partial \rho_k u_k}{\partial t} + \nabla \cdot (\rho_k u_k u_k) = -\nabla p_k + \rho_k g + \nabla \cdot \tau_k \quad \text{with} \quad \tau_k \equiv \mu_k (\nabla u_k + \nabla^T u_k) \]

... and interfacial jump conditions:
- Velocity continuity: \( u_1^n = u_2^n \) and \( u_1^t = u_2^t \)
- Interfacial normal stress balance: \( \sum_k (p_k n_k - \tau_k \cdot n_k) = -\sigma \kappa n \)

... are solved by the “one-fluid” formulation valid at any point in the sense of distributions:

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

“one-fluid” fields: \( \phi \equiv \sum_k \chi_k \phi_k \) 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)