

Clustering in bubble swarm with DNS and Front-Tracking method

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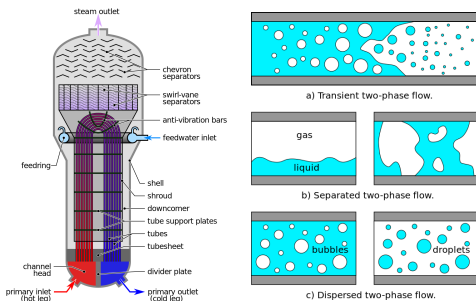
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Introduction

- General purpose: get a better understanding of **boiling flows**
- Development of **multiphase RANS modeling** for design and safety analysis
- Along experimental apparatus, use **DNS** to improve our understanding of physical mechanisms





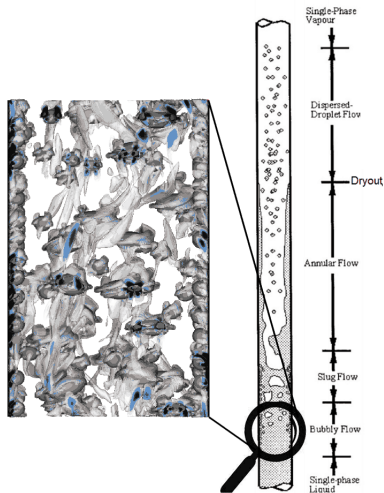
Industrial purposes and boiling flows

Boiling crisis

- Safety issue for press. water reactor
- Rode cladding integrity failure
- Decrease heat transfer at the wall: melting!

Boiling flows

- Many different flow regimes
- Concern about the transition between bubbly and slug flows
- Bubbles at the wall → heat transfer increase
- Importance of the void fraction prediction
- A lack of understanding of dynamical phenomena (dispersion forces, turbulent dispersion, bubble-induced turbulence)





Today's focus: clustering

- Why this concern?
- Numerous possible effects of clustering on modeling: local temperature, coalescence, momentum change and energy transfer mechanisms.
- Work of Bunner & Tryggvason (2002), Roghair *et al.* (2012)
- Many configurations to be considered (void fraction, viscosity effect, surface tension, etc.) **At high pressure, high void fraction flow stays bubbly.**
- Need to explore its behavior to correctly model the transition to more complex regimes (for instance Kuidjo *et al.* (2023))

Can we identify clustering effect in our simulations? Is there an influence of turbulence?



TRUST/TrioCFD & FieldZ

- TRUST/TrioCFD : **Open-source** C++ code for **DNS**, LES, RANS modeling of single and two-phase flows
- **Interface capturing method** using a mixed VOF/**Front-Tracking** method
- RK3 time scheme
- One-fluid formulation

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

with

- χ_k the phase indicator function (equals 1 in phase k , 0 otherwise)
 - velocity continuity
 - interfacial normal stress balance: $\Sigma_k (p_k \vec{n}_k - \vec{\tau}_k \cdot \vec{n}_k) = -\sigma_k \vec{n}$
- FieldZ: R. ZAMANSKY's spectral code, used for *a posteriori* spectral analysis in G. RAMIREZ's PhD



Turbulence forcing

- External random forcing proposed by Eswaran & Pope (1987)
- Used in two-phase flow by Chouippe & Uhlman (2015)
- **Two parameters**
 - T_L the characteristic time scale of the random process
 - an effective dissipation $\varepsilon^* = T_L \times \sigma$ with σ the random process variance
- Objective (G. RAMIREZ's PhD, not today's focus): how turbulence will affect the kinetic energy budget?
- Forcing on the 3 largest Fourier modes: **no direct coupling** with the bubble dynamics.



Bubbles and the swarm

Non-dimensional parameters

Geometrical parameters

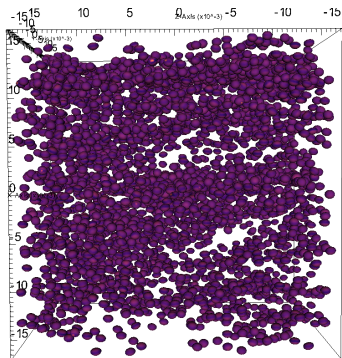
- Domain length: L
 - Bubble diameter: d_b
 - Cell size: Δ_x
- Mesh convergence: $\frac{d_b}{\Delta_x} \geq 20$
 - Non-overlapping: $\frac{L}{d_b} \geq 30$
 - Simulation cost: $N^3 = \left(\frac{L}{\Delta_x}\right)^3 \approx 600^3 \sim 10^8$

Physical parameters

- Liquid phase: $\rho_l; \mu_l$
 - Vapor phase: $\rho_v; \mu_v$
 - Void fraction: α
 - Surface tension: σ
 - Gravity: g
- Ratio liquid vapor: $\frac{\rho_l}{\rho_v} = 13; \frac{\mu_l}{\mu_v} = 1$
 - Deformation: $Bo = \frac{\Delta\rho g d_b^2}{\sigma} = 0.6$
 - Wake Instability: $Ar = \frac{d_b \sqrt{\frac{\Delta\rho}{\rho_l} g d_b}}{\nu} = 300$
 - Void fraction: $\alpha = 3\%$; 6% ($N_b = 1825$ and $N_b = 3650$, resp.)
 - Bubble Reynolds number: $Re_b = 319$



Results



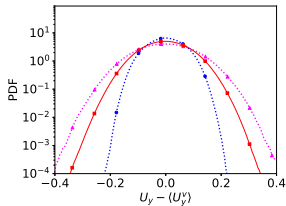
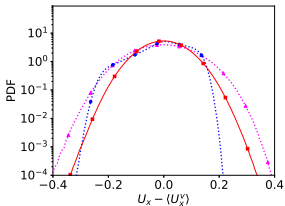
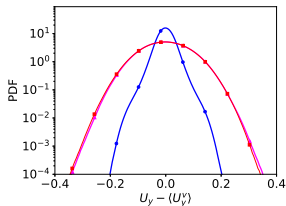
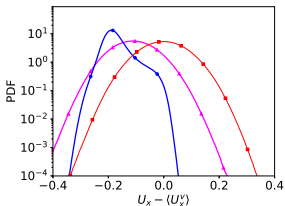
Swarm of 3650 bubbles ($\alpha = 6\%$)

- 1 **PDFs** of liquid and vapor horizontal and vertical **velocities**
- 2 **Kinetic energy spectra** of BIA, THI and the coupled THI-BIA computations
- 3 **PDFs of the Voronoï volumes** for a 3 % and 6 % computations (with a few words on modelling it)
- 4 **Radial distribution functions**, compared with a random distribution



PDFs

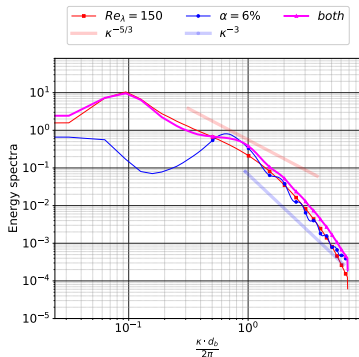
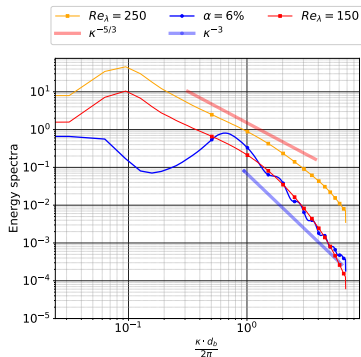
- **BIA** = bubbles-only, **THI** = single-phase forcing only, **THI+BIA** = coupled simulation of bubbles+forcing
- Top = liquid, bottom = vapor. Left = axial, right = transverse





Spectra

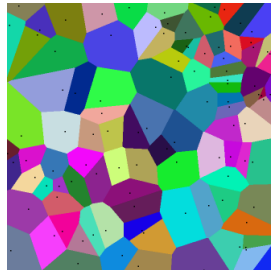
- Forcing adjusted not to wipe BIA energy
- **Magenta curve**: THI + BIA kinetic energy spectra





Voronoi method

- Voronoi volumes equivalent to concentration field
- **Small volumes means high concentration**
- 3D tessellation using SciPy



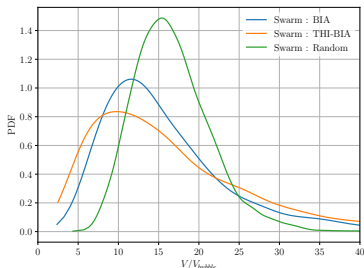
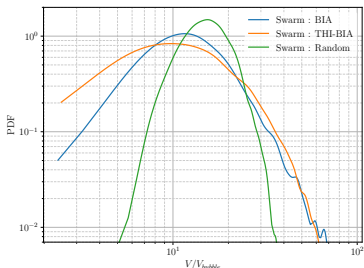
2D Voronoi tessellation, from Wikipedia

- R. MONCHAUX et al. "Analyzing Preferential Concentration and Clustering of Inertial Particles in Turbulence". *International Journal of Multiphase Flow* 40 (2012), p. 1-18
- Y. TAGAWA et al. "Three-Dimensional Lagrangian Voronoi Analysis for Clustering of Particles and Bubbles in Turbulence". *Journal of Fluid Mechanics* 693 (2012), p. 201-215
- Y. LIU et al. "Life and Death of Inertial Particle Clusters in Turbulence". *Journal of Fluid Mechanics* 902 (2020)



Voronoi tessellation, $\alpha = 6\%$

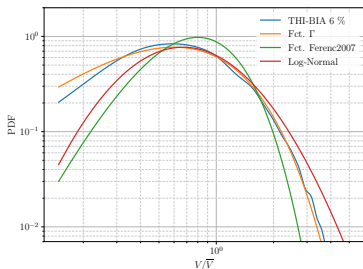
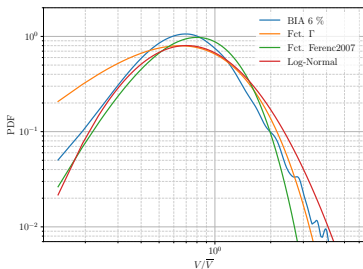
- Lots of work with particles or very small bubbles
- **Objective:** identify a parameter that characterizes the cluster
- Turbulence tends to spread the distribution: more small volumes
- Random = random distribution at startup with exclusion zone





Voronoi tessellation, $\alpha = 6\%$

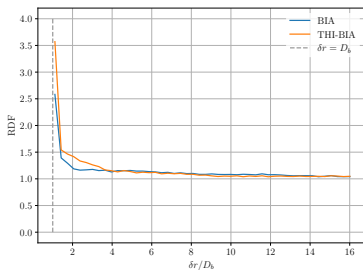
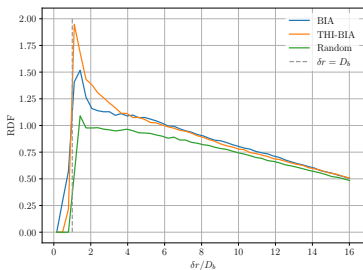
- Can we model the distribution?
- Literature suggests BIA is close to a log-normal distribution
- Literature suggests THI+BIA should be closer to a Γ function $f(V, std(V))$
- Ferenc2007: $f(V) = \frac{3125}{24} V^4 \exp(-5V)$





Radial distribution function, $\alpha = 6\%$

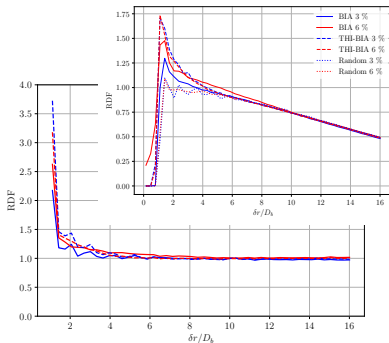
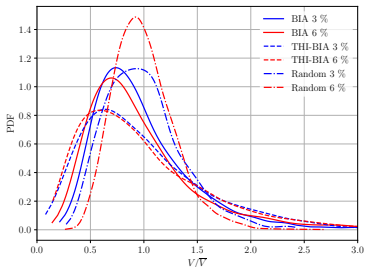
- Right: divided by the random distribution
- In coherence with Voronoï measure, bubble concentration at small radius
- RDF = 1, uniform concentration. **RDF > 1, excess concentration**





Comparison between $\alpha = 3\%$ and $\alpha = 6\%$

- Voronoï pdfs, abscissa normalized by mean Voronoï volume to superimpose curves
- Turbulence removes differences between $\alpha = 3\%$ and $\alpha = 6\%$





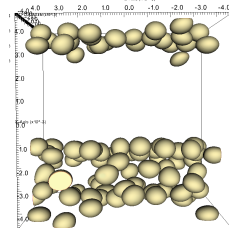
Finale

Conclusion

- Preliminary results!
- Effect of turbulence forcing on concentration:
 - larger vapor velocity fluctuations **and** higher probability of concentration
 - Same concentration on both $\alpha = 3\%$ and $\alpha = 6\%$
- Not shown: no horizontal packing as in Roghair or Brenner papers **for large swarm**, but packing for smaller swarms?

Ongoing

- Plot angular distribution
- Larger void fractions?
- Small domain effect?
- Study bubbles trajectories





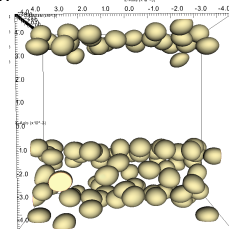
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Questions? alan.burlot@cea.fr