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DE LA RECHERCHE À L'INDUSTRIE

cea

5th International Conference on Turbulence and Interactions

Towards an innovative $R_{ij} - \epsilon$ model for turbulence in bubbly flows from DNS simulations



A. du Cluzeau ¹ G. Bois ¹ A. Toutant ² J-M. Martinez ²

¹ : DEN-Service de thermo-hydraulique et de mécanique des fluides (STMF), CEA, Université Paris-Saclay, F-91191 Gif-sur-Yvette

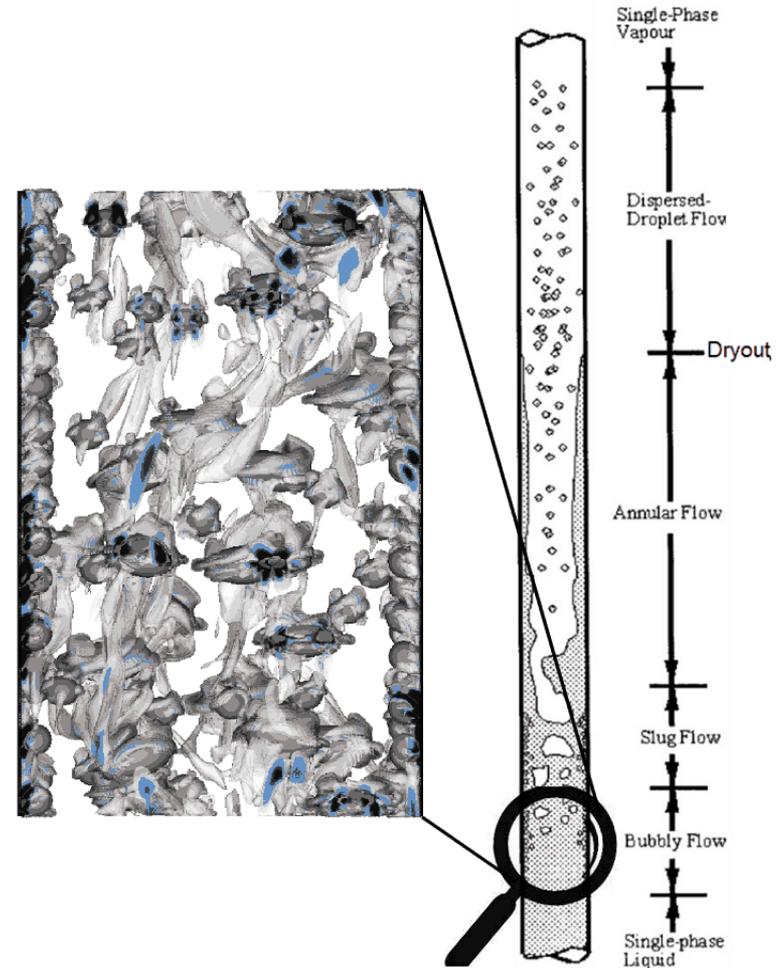
² : PROMES-CNRS (UPR 8521) Université de Perpignan Via Domitia |

Safety issue for PWR : the boiling crisis

- Pressurized water reactor : a very large system
- Critical heat flux : a very local phenomenon
- **Solution : the upscaling strategy**

Lack of predictive model in two phase flows

- A lot of different regimes
- The importance of the transition between boiling and slug flows
- Bubbles at the wall → decrease of heat transfer
- Importance of the void fraction prediction
- **Focus on dynamical aspects in bubbly flows**



Towards a numerical reactor

- Need for powerful simulations



DNS

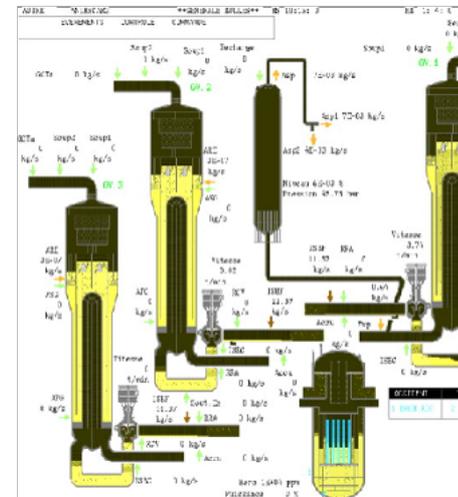



M-CFD



CATHARE
System

- How can complex two-phase flows be solved in a system code ?



Towards a numerical reactor

- Need for powerful simulations



DNS

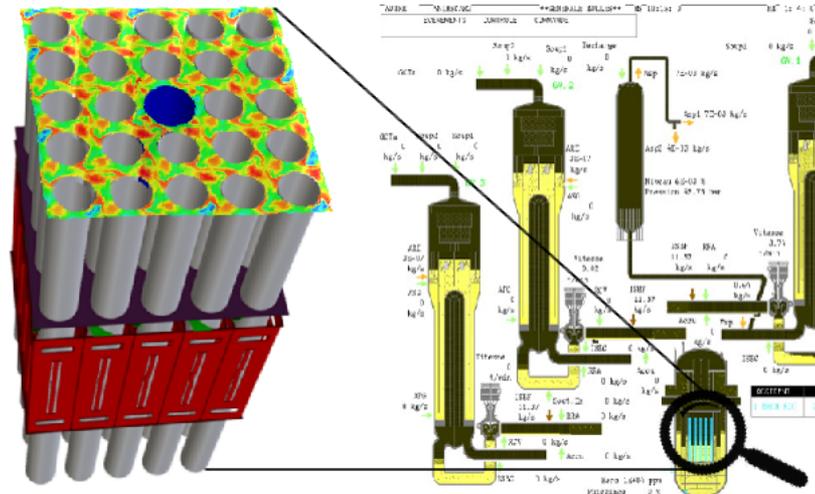



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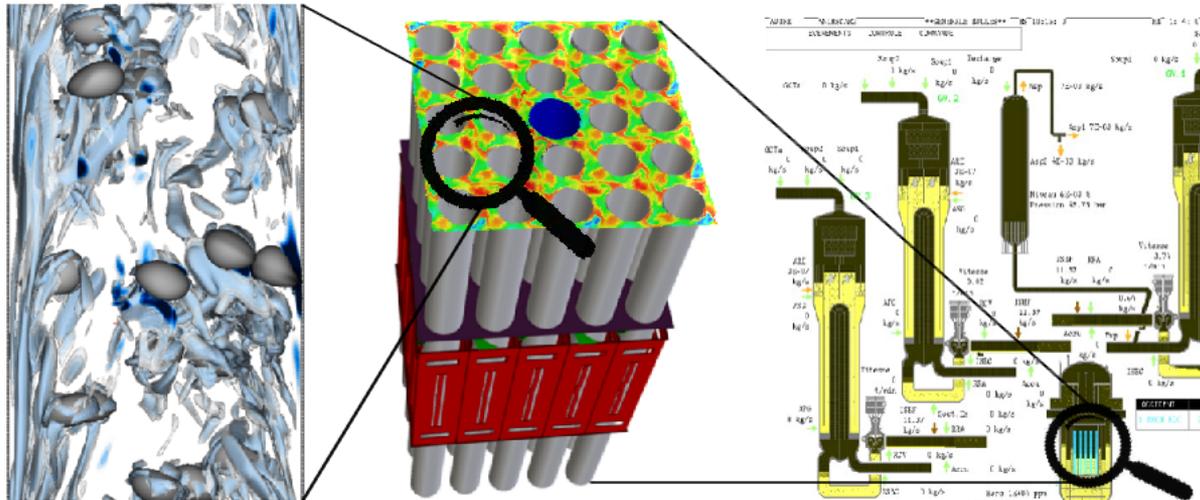


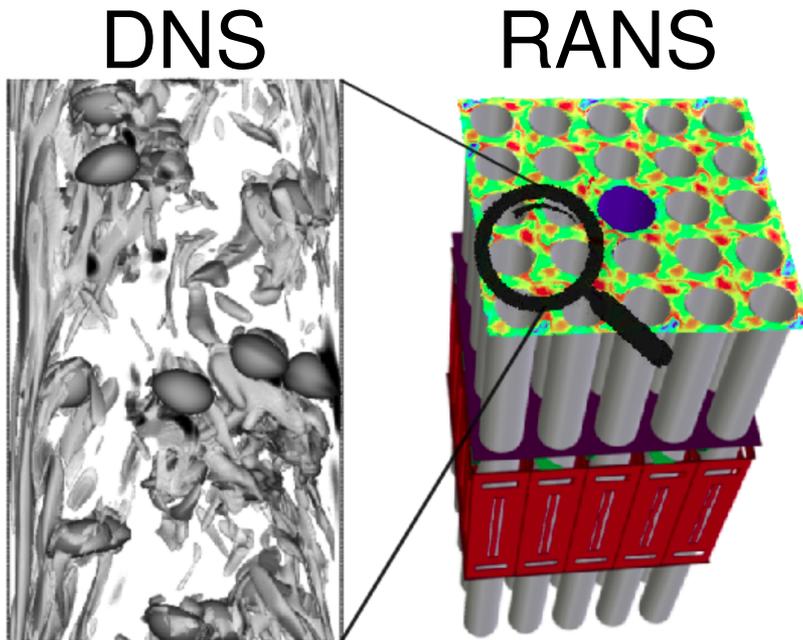
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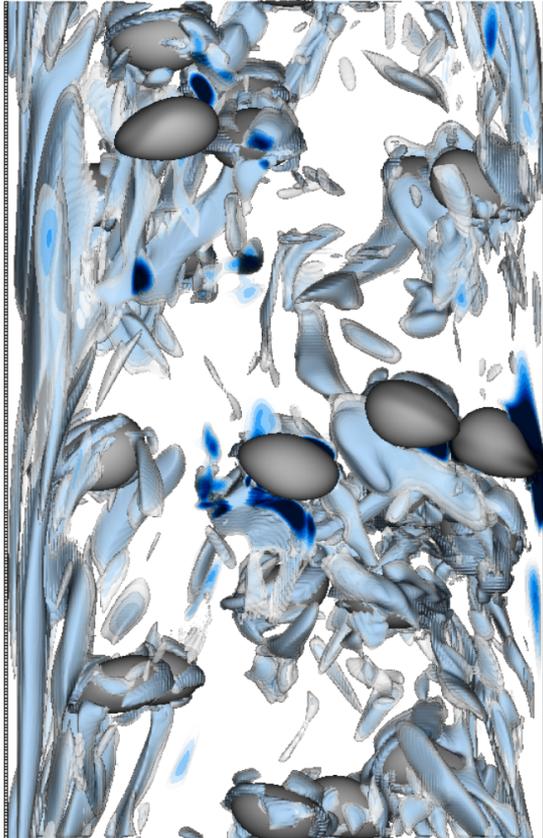
RANS closures limitations

- Empirical correlations built on coupled mechanism simultaneously
 - Interfacial forces :
 - Drag force
 - Lift force
 - Added-mass force
 - Dispersion forces
- Point-size particle approach
 - No surface tension effects
 - One pressure closure
- Theoretical modelling based on questionable parallel with single phase flows

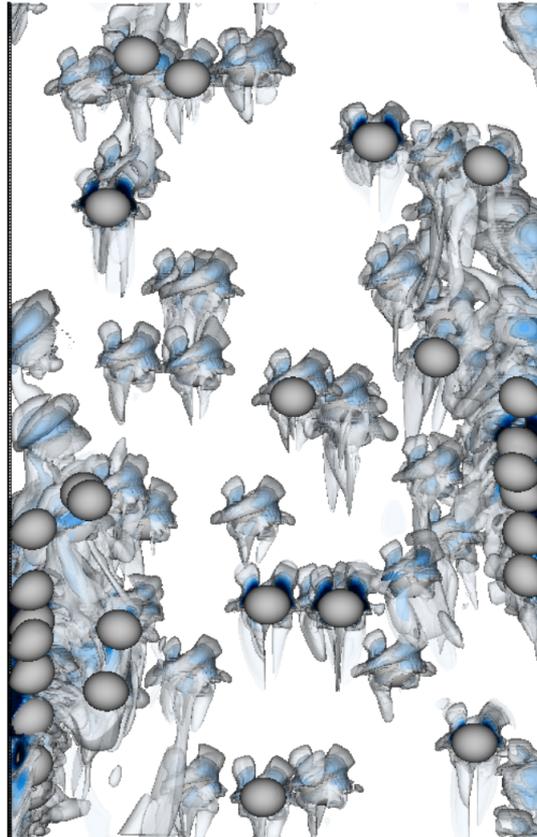
→ Turbulence closure

- Single-phase turbulence
- Wake structure
- Wake interactions and instabilities

SPT



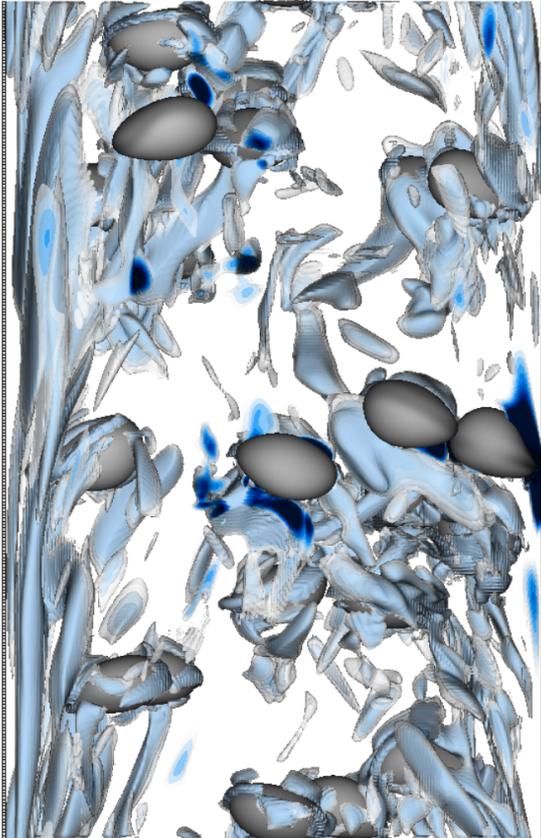
WIF+WIT



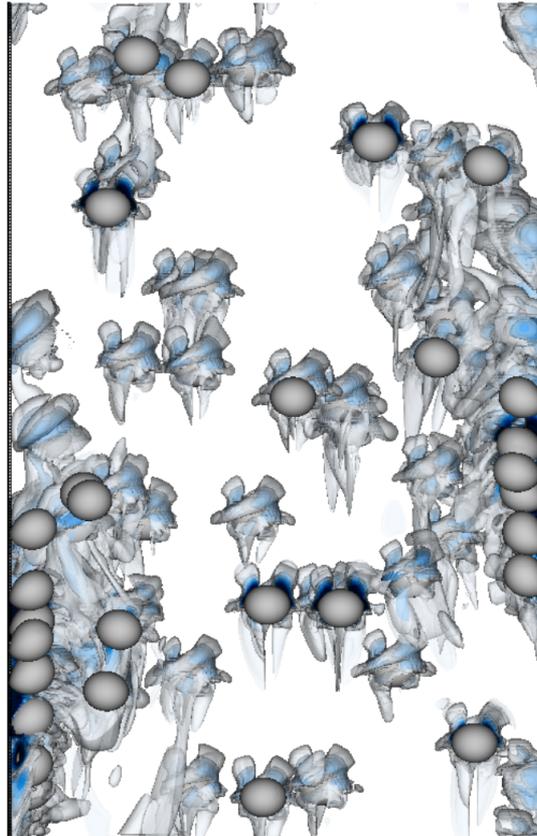
Flow led by the upward pressure gradient

- Classical turbulence with elongated streaks
- Single Phase Turbulence (SPT) due to shear stresses at the wall
- Sufficient existing model

SPT



WIF+WIT



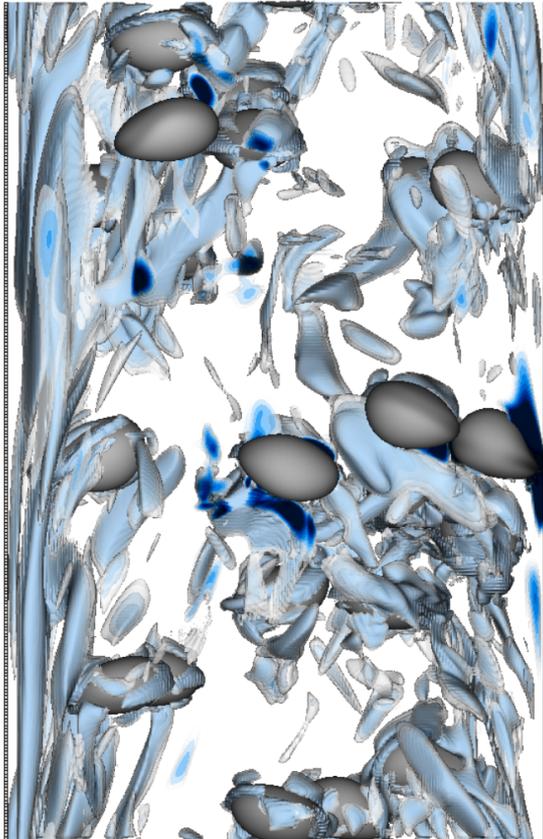
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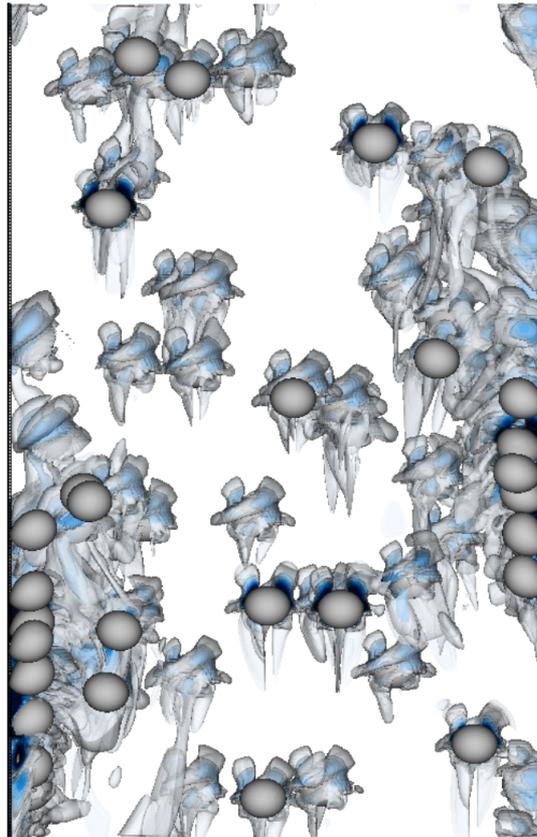
Flow led by bubbles buoyancy (WIF+WIT)

- Potential flow and averaged Wake Induced Fluctuations (WIF)
- Wake Induced Turbulence due to interactions and instabilities of wakes (WIT)
- Unsatisfactory models

SPT



WIF+WIT



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Modelling conclusion : Bubble turbulence cannot be modelled as a kinetic energy source term

Introduction

Direct Numerical Simulations

- Governing equations

- Limitation of DNS

- Numerical setup

Results and modelling on swarm calculations

Local instantaneous description

- Navier-Stokes equations :

$$\frac{D\rho_k \mathbf{u}_k}{Dt} = -\nabla P_k + \rho_k \mathbf{g} + \underbrace{\nabla \cdot [\mu_k (\nabla \mathbf{u}_k + \nabla^T \mathbf{u}_k)]}_{\tau_k}$$

- Interfacial jump conditions :

$$\mathbf{u}_l^i = \mathbf{u}_v^i, \quad \sum_k (\rho_k \mathbf{n}_k - \tau_k \cdot \mathbf{n}_k) = \sigma \kappa \mathbf{n}_k$$

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Extension to full space

- Multiply by phase indicator function :

$\chi_k = 1$ in phase k , 0 otherwise.

$$\begin{aligned} \frac{D\chi_k \rho_k \mathbf{u}_k}{Dt} = & -\nabla (\chi_k P_k) + \chi_k \rho_k \mathbf{g} + \nabla \cdot (\chi_k \tau_k) \\ & - (\rho_k \mathbf{n}_k - \tau_k \cdot \mathbf{n}_k) \cdot \nabla \chi_k \end{aligned}$$

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One-fluid formulation

- 'one-fluid' variables : $\phi = \sum_k \chi_k \phi_k$

$$\frac{D\rho \mathbf{u}}{Dt} = -\nabla P + \rho \mathbf{g} + \nabla \cdot [\mu (\nabla \mathbf{u} + \nabla^T \mathbf{u})] + \sigma \kappa \mathbf{n} \delta^i$$

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Definition of averaging operators

- Statistical average = temporal average :

$$\overline{\phi(x, y, z)}^{TX} = \frac{1}{\Delta t} \int_{t-\Delta t/2}^{t+\Delta t/2} \phi(x, y, z, \tau) d\tau$$

- Phase average :

$$\overline{\phi}^k = \frac{\overline{\chi_k \phi_k}^{TX}}{\overline{\chi_k}^{TX}}$$

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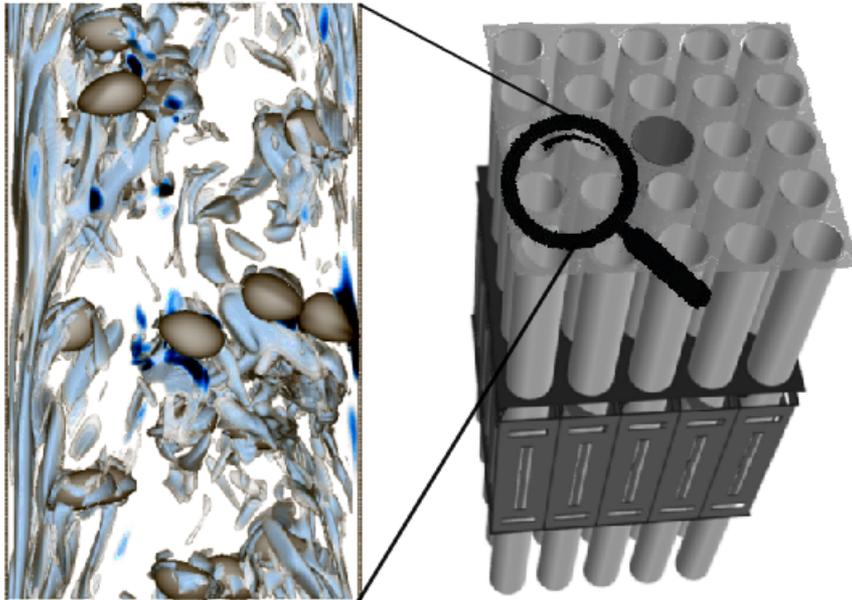
Two-fluid averaged formulation

- Note $\alpha_k = \overline{\chi_k}^{TX}$

$$\begin{aligned} \frac{D\alpha_k \rho_k \overline{\mathbf{u}_k}^k}{Dt} &= -\nabla (\alpha_k \overline{P_k}^k) + \alpha_k \rho_k \mathbf{g} + \nabla \cdot (\alpha_k \overline{\boldsymbol{\tau}_k}^k) \\ &+ \nabla \cdot (\alpha_k \overline{\boldsymbol{\tau}_k}^k) - \underbrace{(\rho_k \mathbf{n}_k - \boldsymbol{\tau}_k \cdot \mathbf{n}_k) \cdot \nabla \chi_k}_{\mathbf{M}_k}^{TX} \end{aligned}$$

- \mathbf{M}_k is the interfacial force exerted on phase k

$$\mathbf{M}_I + \mathbf{M}_V = \overline{\sigma \kappa \mathbf{n} \delta^i}^{TX}$$



Framework hypotheses

- incompressible
- isothermal

Limitation of DNS

- Low void fraction → to avoid coalescence (No contact line models)
- Limited Reynolds number → moderate resolution of the mesh
 - Unreachable industrial conditions for bubble columns
 - Reachable industrial conditions for bubble swarms
- Models extracted from the DNS need a posteriori validation on experiments in reactor conditions

Physical setup

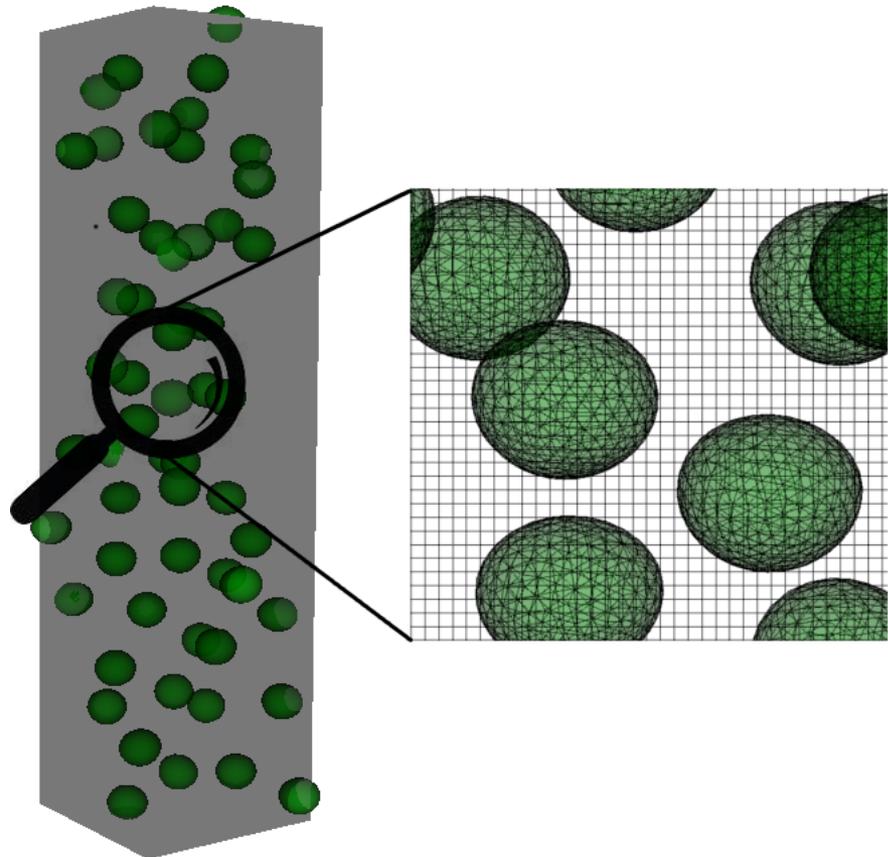
- Bubble swarm in a flow initially at rest
- Fixed bubble simulation → Spring force
- periodicity in x,y,z
- Different predefined population of bubbles
- Computation in typical reactor condition based on DEBORA experiments (freon 24 bar)
- $Re_b = 1176$ and $Eo = 0.59$

A Front-Tracking algorithm

- One-fluid equations are solved on an Eulerian / Cartesian mesh
- Interfaces are tracked on a Lagrangian mesh
- Validated by comparison with works of J.Lu and G.Tryggvason

HPC calculations

- → ≈ 80 millions of cells
- → $\approx 1.000.000$ h CPU a case



Introduction

Direct Numerical Simulations

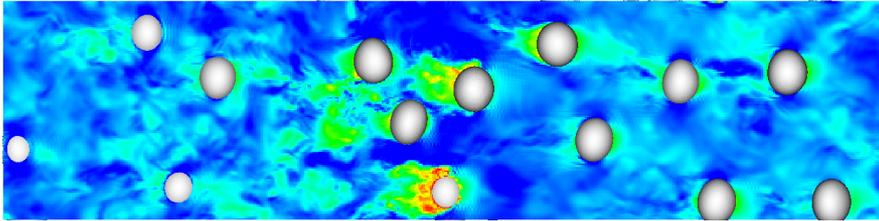
Results and modelling on swarm calculations

Turbulent and non turbulent fluctuations

Spectral analysis

New turbulence modelling

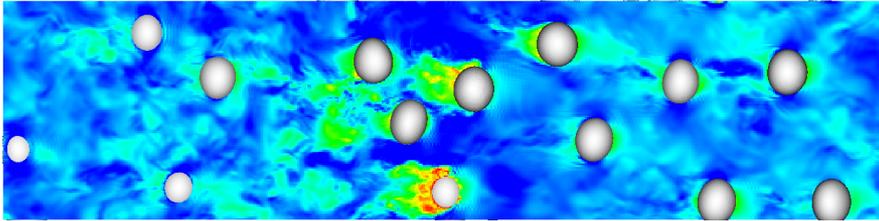
Instantaneous velocity field from DNS with
fixed bubbles *SPT*



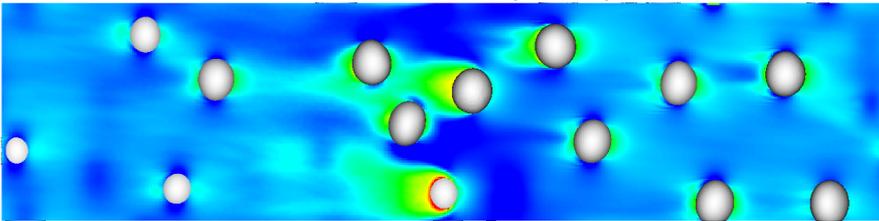
Following F. Risso et al.

- Frame of reference of bubbles
 - Fixed bubble simulations
 - Spring force
- Total fluctuations

Instantaneous velocity field from DNS with fixed bubbles *SPT*



Temporal average → Wake-induced fluctuations (WIF)



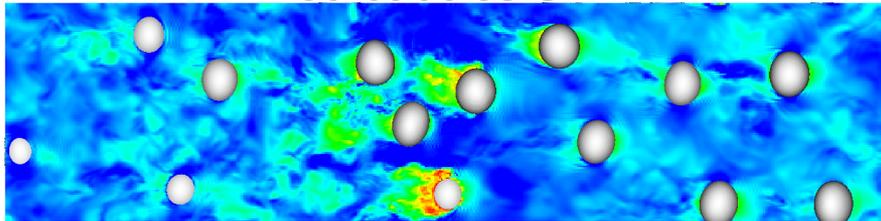
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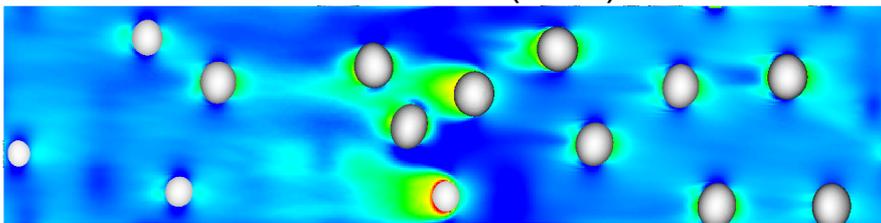
Wake Induced Fluctuations (WIF)

- Temporal average → spatial fluctuations
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- Due to potential flow around bubbles
- It is not turbulence !

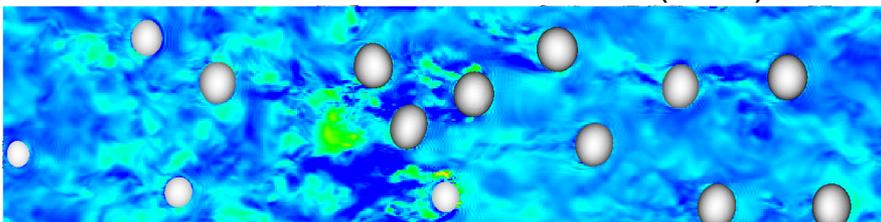
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Wake-induced Turbulence (WIT)



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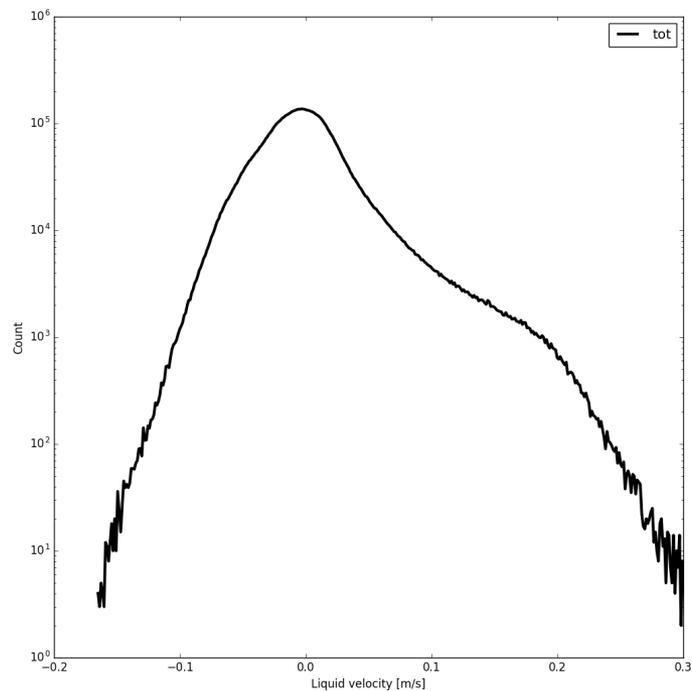
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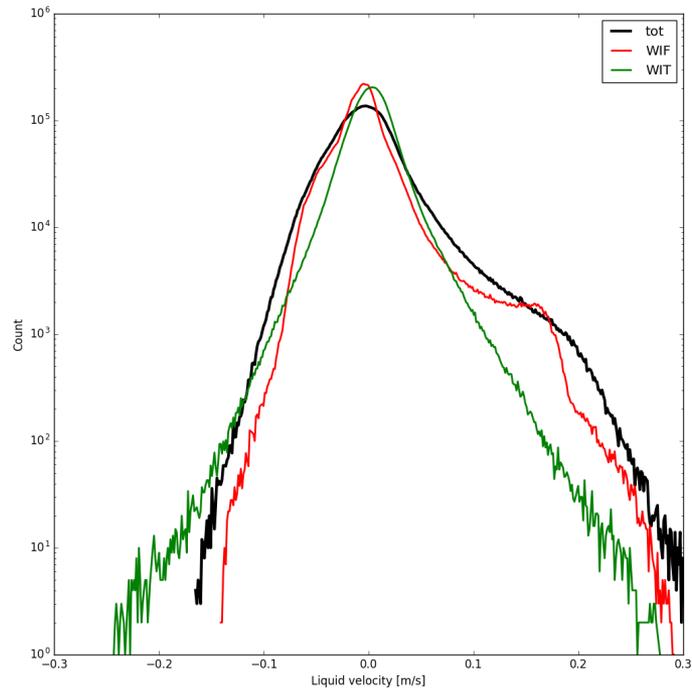
Wake Induced Turbulence (WIT)

- Temporal fluctuations
- Interactions and instabilities of wakes
- Is WIT similar to classical turbulence ?

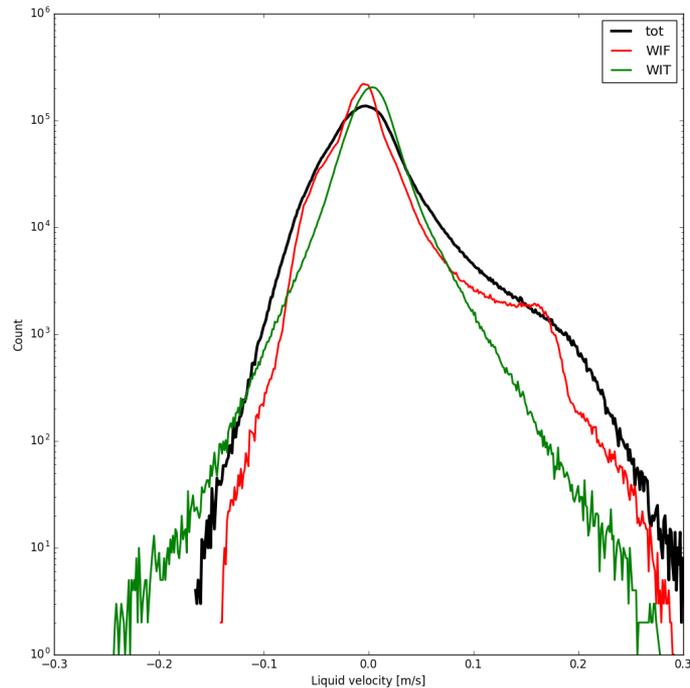
Modelling conclusion : WIF and WIT have to be modelled separately



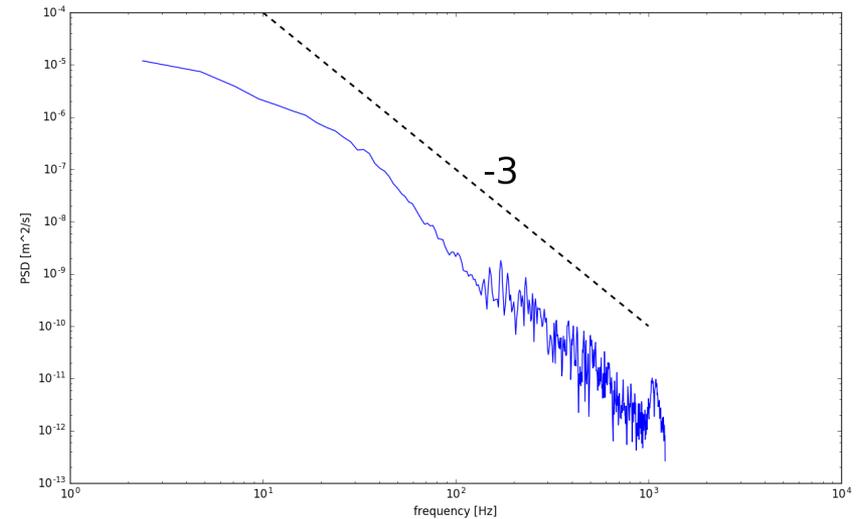
PDF of velocity fluctuations
(On \approx 8 million points)



PDF of velocity fluctuations
(On ≈ 8 million points)



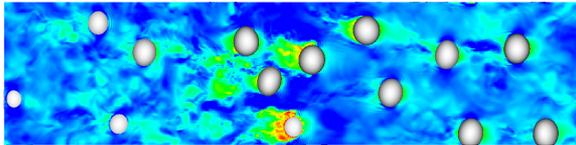
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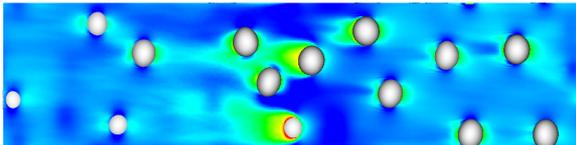
Mean temporal spectrum
(on ≈ 120 probes)

Modelling conclusion : WIT needs its own transport equation because its statistical signature is different than SPT

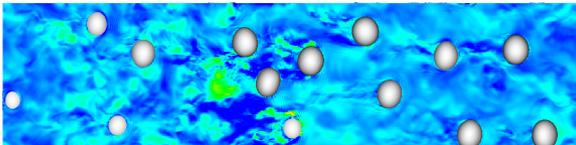
Splitting of the fluctuations



=



+



An innovative splitting of the R_{ij} transport equation

$$\frac{DR_{ij}}{Dt} = -\mathbf{P}_{ij} + \mathbf{D}_{ij} + \phi_{ij} + \epsilon_{ij}$$

=

$$\frac{DR_{ij}^{WIF}}{Dt} = -\mathbf{P}_{ij}^X + \mathbf{D}_{ij}^X + \phi_{ij}^X + \epsilon_{ij}^X$$

+

$$\frac{DR_{ij}^{WIT}}{Dt} = -\mathbf{P}_{ij}^T + \mathbf{D}_{ij}^T + \phi_{ij}^T + \epsilon_{ij}^T$$

Exemple with the dissipation tensor

$$\epsilon_{11} = -2 \frac{\mu_l}{\rho_l} \overline{\chi_l \frac{\partial u_l}{\partial x_b} \chi_l \frac{\partial u_l}{\partial x_b}}^{TX} \quad (100\%)$$

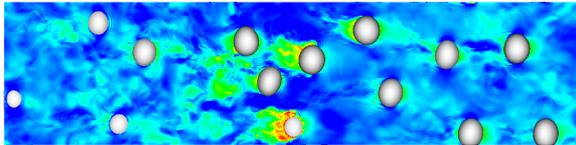
=

$$\epsilon_{11}^X = -2 \frac{\mu_l}{\rho_l} \overline{\chi_l \frac{\partial u_l}{\partial x_b} \chi_l \frac{\partial u_l}{\partial x_b}}^{TX} \quad (23\%)$$

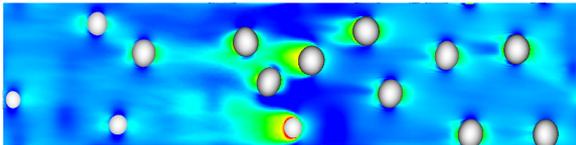
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$$\epsilon_{11}^T = -2 \frac{\mu_l}{\rho_l} \overline{\chi_l \frac{\partial u_l'}{\partial x_b} \chi_l \frac{\partial u_l'}{\partial x_b}}^{TX} \quad (77\%)$$

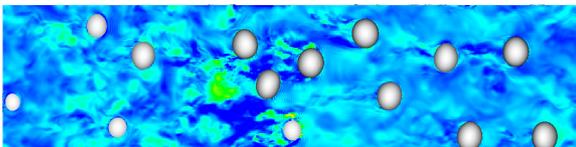
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With DNS → post-treatment of all the statistical correlations in order to find scaling laws for the interfacial production, the dissipation etc...

Modelling conclusion :

- 1 - BIF cannot be modelled as a kinetic energy source term
- 2 - WIF and WIT have to be modelled separately
- 3 - WIT needs its own transport equation because its statistical signature is different than SPT

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Formal summary

$$R_{ij} = R_{ij}^{SPT} + R_{ij}^{WIT} + R_{ij}^{WIF}$$

$$\frac{DR_{ij}^{SPT}}{Dt} = \text{single-phase transport equation}$$

$$\frac{DR_{ij}^{WIT}}{Dt} = -P_{ij}^{WIT} + D_{ij}^{WIT} + \phi_{ij}^{WIT} + \epsilon_{ij}^{WIT}$$

$$R_{ij}^{WIF} = \text{algebraic closure}$$

- Sufficient existing models for R_{ij}^{SPT}

Modelling conclusion :

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Formal summary

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$$\mathbf{R}_{ij}^{\text{WIF}} = \text{algebraic closure}$$

- Sufficient existing models for $\mathbf{R}_{ij}^{\text{SPT}}$

On going work

- Computation of bubble swarms at different void fraction and bubble Reynolds number
- Model for $\mathbf{R}_{ij}^{\text{WIF}}$ based on previous works (F.Risso and al.) on averaged wake and potential flow solution around bubbles
- Post-treatment of all the statistical correlations of the $\mathbf{R}_{ij}^{\text{WIT}}$ transport equation in order to find scaling laws for $\mathbf{P}_{ij}^{\text{WIT}}$, ϕ_{ij}^{WIT} and $\epsilon_{ij}^{\text{WIT}}$

Up-scaling process from DNS database

- Answer to complex industrial applications (PWR core evolution)
 - RANS Euler calculations need predictive model
 - DNS used as numerical experiments
- DNS of channel bubbly flows (not presented here)
 - Lots of data available for processing
 - Already used to model interfacial forces
- DNS of swarms with fixed bubbles for the study of bubble-induced turbulence
 - (prospect) Characterise the impact of fixed bubbles
 - (prospect) Comparison with calculation of free bubbles
 - (prospect) Parametric analysis with different Reynolds number and different void fraction

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Turbulence modelling

- Bubble-induced turbulence is different than single-phase turbulence
 - Bubble-induced turbulence has a part of turbulent fluctuation (WIT) and a part of non turbulent fluctuations (WIF)
 - WIF is related to the averaged wake and to the potential flow around bubble
 - WIT is related to wakes interactions and instabilities
- Those three fluctuations have to be modelled separately
 - SPT : classical transport equation
 - (prospect) WIT : new transport equation modelling
 - (prospect) WIF : algebraic closure

Thank you for your attention !

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