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

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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 $\rightarrow$ 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

TRUST  \implies  NuPTUNE  \implies  CATHARE System

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

- Need for powerful simulations

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

- Need for powerful simulations

$$\textbf{TRUST} \quad \Rightarrow \quad \textbf{NuPTUNE} \quad \Rightarrow \quad \text{CATHARE System}$$

- How can complex two-phase flows be solved in a system code?
Failures and needs of the averaged scale (RANS)

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
Two different kinds of turbulence

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
Two different kinds of turbulence

**SPT**
- Flow led by the upward pressure gradient
- Sufficient existing model

**WIF+WIT**
- Classical turbulence with elongated streaks
- Single Phase Turbulence (SPT) due to shear stresses at the wall
- 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
Two different kinds of turbulence

**SPT**

Flow led by the upward pressure gradient
- Classical turbulence with elongated streaks
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**WIF+WIT**

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

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

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Introduction

Direct Numerical Simulations
- Governing equations
- Limitation of DNS
- Numerical setup

Results and modelling on swarm calculations
Local instantaneous description

Navier-Stokes equations:

\[
\frac{D \rho_k u_k}{Dt} = - \nabla P_k + \rho_k g + \nabla \cdot \left[ \mu_k \left( \nabla u_k + \nabla^T u_k \right) \right]
\]

Interfacial jump conditions:

\[
u_i^l = u_i^v, \quad \sum_k \left( \rho_k n_k - \tau_k \cdot n_k \right) = \sigma \kappa n_k
\]
Local scale (DNS) / Averaged scale (RANS)

Local instantaneous description

- Navier-Stokes equations:

$$\frac{D \rho_k u_k}{Dt} = - \nabla P_k + \rho_k g + \nabla \cdot \left[ \mu_k (\nabla u_k + \nabla^T u_k) \right]$$

- Interfacial jump conditions:

$$u_i^l = u_i^v, \quad \sum_k (\rho_k n_k - \tau_k \cdot n_k) = \sigma_k n_k$$

Extension to full space

- Multiply by phase indicator function:

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

$$\frac{D \chi_k \rho_k u_k}{Dt} = - \nabla (\chi_k P_k) + \chi_k \rho_k g + \nabla \cdot (\chi_k \tau_k)$$

$$- (\rho_k n_k - \tau_k \cdot n_k) \cdot \nabla \chi_k$$

M_k is the interfacial force exerted on phase k.
Local scale (DNS) / Averaged scale (RANS)

Local instantaneous description

- Navier-Stokes equations:
  \[
  \frac{D \rho_k u_k}{Dt} = - \nabla P_k + \rho_k g + \nabla \cdot \left[ \mu_k \left( \nabla u_k + \nabla^T u_k \right) \right] + \frac{\tau_k}{\rho_k} \nabla \chi_k
  \]

- Interfacial jump conditions:
  \[
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  \[
  \frac{D \chi_k \rho_k u_k}{Dt} = - \nabla (\chi_k P_k) + \chi_k \rho_k g + \nabla \cdot (\chi_k \tau_k)
  \]
  \[
  - (\rho_k n_k - \tau_k \cdot n_k) \cdot \nabla \chi_k
  \]

One-fluid formulation

- 'one-fluid' variables: \( \phi = \sum_k \chi_k \phi_k \)
  \[
  \frac{D \rho u}{Dt} = - \nabla P + \rho g + \nabla \left[ \cdot \mu \left( \nabla u + \nabla^T u \right) \right] + \sigma_k n^i
  \]
Local scale (DNS) / Averaged scale (RANS)

**Local instantaneous description**

- Navier-Stokes equations:
  \[
  \frac{D \rho_k u_k}{Dt} = -\nabla P_k + \rho_k g + \nabla \cdot \left[ \mu_k \left( \nabla u_k + \nabla^T u_k \right) \right]
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  - (\rho_k n_k - \tau_k \cdot n_k) \cdot \nabla \chi_k
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**One-fluid formulation**

- 'One-fluid' variables: \[
  \phi = \sum_k \chi_k \phi_k
  \]
  \[
  \frac{D \rho u}{Dt} = -\nabla P + \rho g + \nabla \left[ \cdot \mu \left( \nabla u + \nabla^T u \right) \right] + \sigma_k n \delta^i
  \]

**Definition of averaging operators**

- Statistical average = temporal average:
  \[
  \phi(x, y, z)^{TX} = \frac{1}{\Delta t} \int_{t-\Delta t/2}^{t+\Delta t/2} \phi(x, y, z, \tau) \, d\tau
  \]

- Phase average:
  \[
  \overline{\phi}^k = \frac{\chi_k \phi_k^{TX}}{\chi_k^{TX}}
  \]

\[M_k\] is the interfacial force exerted on phase \(k\), \(M_l + M_v = \sigma_k n \delta^i\)
Local scale (DNS) / Averaged scale (RANS)

Local instantaneous description
- Navier-Stokes equations:

\[
\frac{D \rho_k u_k}{Dt} = -\nabla P_k + \rho_k g + \nabla \cdot \left[ \mu_k \left( \nabla u_k + \nabla^T u_k \right) \right]
\]

- Interfacial jump conditions:

\[
u_i^i = u_i^v, \quad \sum_k (\rho_k n_k - \tau_k \cdot n_k) = \sigma \kappa n_k
\]

Extension to full space
- Multiply by phase indicator function:

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\chi_k = 1 \text{ in phase } k, \quad 0 \text{ otherwise.}
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\frac{D \chi_k \rho_k u_k}{Dt} = -\nabla (\chi_k P_k) + \chi_k \rho_k g + \nabla \cdot (\chi_k \tau_k)
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\[
- (\rho_k n_k - \tau_k \cdot n_k) \cdot \nabla \chi_k
\]

One-fluid formulation
- 'one-fluid' variables: \( \phi = \sum_k \chi_k \phi_k \)

\[
\frac{D \rho u}{Dt} = -\nabla P + \rho g + \nabla \cdot \left[ \mu \left( \nabla u + \nabla^T u \right) \right] + \sigma \kappa n_\delta
\]

Definition of averaging operators
- Statistical average = temporal average:

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

- Phase average:

\[
\bar{\phi}^k = \frac{\chi_k \phi^k}{\chi_k^{TX}}
\]

Two-fluid averaged formulation
- Note \( \alpha_k = \chi_k^{TX} \)

\[
\frac{D \alpha_k \rho_k \bar{u}_k^k}{Dt} = -\nabla \left( \alpha_k \bar{P}_k^k \right) + \alpha_k \rho_k g + \nabla \cdot \left( \alpha_k \bar{\tau}_k^k \right)
\]

\[
+ \nabla \cdot \left( \alpha_k \bar{R}_k^k \right) - (\rho_k n_k - \tau_k \cdot n_k) \cdot \nabla \chi_k
\]

\[
\underbrace{\alpha_k \cdot \nabla \chi_k}_{M_k}
\]

- \( M_k \) is the interfacial force exerted on phase \( k \)

\[
M_l + M_v = \sigma \kappa n_\delta^{TX}
\]

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Limitation of DNS

Framework hypotheses
- incompressible
- isothermal

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

Physical setup
- Bubble swarm in a flow initially at rest
- Fixed bubble simulation $\rightarrow$ 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
- $\rightarrow \approx 80$ millions of cells
- $\rightarrow \approx 1,000,000$ h CPU a case
Introduction

Direct Numerical Simulations

Results and modelling on swarm calculations
  Turbulent and non turbulent fluctuations
  Spectral analysis
  New turbulence modelling
Turbulent and non turbulent fluctuations

Instantaneous velocity field from DNS with fixed bubbles \textit{SPT}

Following F. Risso et al.
- Frame of reference of bubbles
  - Fixed bubble simulations
  - Spring force
- Total fluctuations

Due to the averaged wake
Due to potential flow around bubbles
It is not turbulence!

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
Turbulent and non turbulent fluctuations

Instantaneous velocity field from DNS with fixed bubbles $SPT$

Temporal average $\rightarrow$ Wake-induced fluctuations (WIF)

Following F. Risso et al.

- Frame of reference of bubbles
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Wake Induced Fluctuations (WIF)

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- Due to potential flow around bubbles
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Turbulent and non turbulent fluctuations

Instantaneous velocity field from DNS with fixed bubbles $SPT$

Temporal average $\rightarrow$ Wake-induced fluctuations (WIF)

Wake-induced Turbulence (WIT)

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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 ≈ 8 million points)
PDF of velocity fluctuations
(On ≈ 8 million points)
Spectral analysis of WIT and WIF

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

Mean temporal spectrum
(on \( \approx 120 \) probes)

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

An innovative splitting of the $R_{ij}$ transport equation

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

Exemple with the dissipation tensor

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

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

$$\epsilon_{11} = -2 \frac{\mu_l}{\rho_l} \chi_l \frac{\partial u_l'}{\partial x_b} \chi_l \frac{\partial u_l'}{\partial x_b}^{TX} \quad (77\%)$$

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Splitting of the fluctuations

An innovative splitting of the $R_{ij}$ transport equation

$$\frac{D R_{ij}}{D t} = -P_{ij} + D_{ij} + \phi_{ij} + \epsilon_{ij}$$

Exemple with the dissipation tensor

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

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

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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
New Turbulence model

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

Formal summary

\[ \mathbf{R}_{ij} = \mathbf{R}_{ij}^{SPT} + \mathbf{R}_{ij}^{WIT} + \mathbf{R}_{ij}^{WIF} \]

\[ \frac{D\mathbf{R}_{ij}^{SPT}}{Dt} = \text{single-phase transport equation} \]

\[ \frac{D\mathbf{R}_{ij}^{WIT}}{Dt} = -\mathbf{P}_{ij}^{WIT} + \mathbf{D}_{ij}^{WIT} + \phi_{ij}^{WIT} + \epsilon_{ij}^{WIT} \]

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

- Sufficient existing models for \( \mathbf{R}_{ij}^{SPT} \)
New Turbulence model

Modelling conclusion:
1 - BIF cannot be modelled as a kinetic energy source term
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Formal summary

\[ R_{ij} = R_{ij}^{\text{SPT}} + R_{ij}^{\text{WIT}} + R_{ij}^{\text{WIF}} \]

\[ \frac{D R_{ij}^{\text{SPT}}}{Dt} = \text{single-phase transport equation} \]

\[ \frac{D R_{ij}^{\text{WIT}}}{Dt} = -P_{ij}^{\text{WIT}} + D_{ij}^{\text{WIT}} + \phi_{ij}^{\text{WIT}} + \epsilon_{ij}^{\text{WIT}} \]

\[ R_{ij}^{\text{WIF}} = \text{algebraic closure} \]

On going work

- Computation of bubble swarms at different void fraction and bubble Reynolds number
- Model for \( R_{ij}^{\text{WIF}} \) 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 \( R_{ij}^{\text{WIT}} \) transport equation in order to find scaling laws for \( P_{ij}^{\text{WIT}} \), \( \phi_{ij}^{\text{WIT}} \) and \( \epsilon_{ij}^{\text{WIT}} \)

Sufficient existing models for \( R_{ij}^{\text{SPT}} \)
Conclusion and prospect

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

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
Conclusion and prospect

Up-scaling process from DNS database

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- 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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