Modeling fast Reactions and Particle Flow
Applications of OpenFOAM in the Pharmaceutical Industry

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Objectives

What Do We Want?

- Prediction of hydrodynamics, **yield, selectivity and particle flow in industrial multiphase systems** (bubble columns, gassed stirred tanks) with fast reactions

The Problem – The Scale Gap

- For fast reactions **all scales are important**
  - macro-mixing
  - meso-mixing
  - micro-mixing
- High-Sc-number problems prevent direct solution

Our Approach

- **LES-LPT with DNS-calibrated particle/particle-cluster models**

Principal sketch highlighting different length scales in a gassed stirred tank
DNS to Establish Interface Model

- 3D DNS is able to **perfectly reproduce correlations** for \( Sc = 1 \)
- For **higher Sc numbers**, extreme **grid refinement** near the interface is needed

Streamlines and distribution of dissolved gas around a spherical bubble

\( \text{H}_2 \) and product distribution in the wake of a spherical bubble
Large- and Meso-scale Simulation of Bubble Swarms

Lagrangian Particle Tracking (LPT) with Large Eddy Simulation (LES)

Governing Equations (Euler Grid)

\[
\frac{\partial \varepsilon_L}{\partial t} + \nabla \cdot (\varepsilon_L \cdot \bar{u}) = 0
\]

\[
\frac{\partial (\varepsilon_L \cdot \rho_L \cdot \bar{u})}{\partial t} + \nabla \cdot (\varepsilon_L \cdot \rho_L \cdot \bar{u} \bar{u}) = -\varepsilon_L \cdot \nabla p - \nabla \cdot (\varepsilon_L \cdot \bar{\tau}_L) + \varepsilon_L \cdot \rho_L \cdot g + \Phi
\]

\[
\frac{\partial (\varepsilon_L \cdot \bar{Y}_i)}{\partial t} + \nabla \cdot (\varepsilon_L \cdot \bar{u} \bar{Y}_i) = \nabla \cdot (\varepsilon_L \cdot D_{eff,i} \cdot \nabla \bar{Y}_i) + \Phi_{\bar{N}_i} + \varepsilon_L \sum_j \nu_{i,j} \cdot r_j
\]

Newton’s Equation of Motion (Lagrangian Grid)

\[
m_p \frac{d \bar{u}}{dt} = F_G + F_p + F_D + F_L + F_A
\]

\[
\bar{\tau}_L = -\left( \mu_L + \mu_{SGS,L} \right) \cdot \left( \nabla \bar{u} + \nabla \bar{u}^T \right) - \frac{2}{3} \cdot I \cdot (\nabla \cdot \bar{u})
\]

valid for dilute and dense systems as we consider \( \varepsilon_L \) on the Eulerian grid!

Sketch of forces acting on a bubble
Bubble Swarms: Scalar Variance in Multiphase Systems

Definition, its Transport Equation and Results

\[ Y_{V,i} = \overline{Y_i Y_i} - \overline{Y_i} \cdot \overline{Y_i} \]

\[ \frac{\partial (\epsilon_L \cdot Y_{V,i})}{\partial t} + \nabla \cdot (\epsilon_L \cdot \overline{u} Y_{V,i}) = \nabla \cdot (\epsilon_L \cdot D_{eff,i} \cdot \nabla Y_{V,i}) \]

\[ + 2 \cdot \epsilon_L \cdot D_{eff,i} \cdot \nabla \overline{Y_i} \cdot \nabla \overline{Y_i} \]

\[ - 2 \cdot \epsilon_L \cdot \overline{s_X} \]

\[ + 2 \cdot \alpha \cdot Y_{V,i} \cdot \frac{\Phi \cdot \dot{N}_i}{Y_i} \]

with:

\[ \overline{s_X} = \frac{C_\Phi}{\tau_\Phi} \cdot Y_{V,i} \]

Dimensionless concentration (a1, a2) and scalar variance (b1, b2) contour plots after 2 [s] (left) and 10 [s] (right) for an inert scalar (\( \alpha = 0 \)).

A Remaining Challenge

To model the generation of variance due to mass transfer

\[ 2 \cdot \alpha \cdot Y_{V,i} \cdot \frac{\Phi \cdot \dot{N}_i}{Y_i} \]
Bubble Swarms: Validation of Flow

Setup
- “Becker” case
- domain size 0.5 x 0.08 x 1.5 [m]
- 1.6 [l/min] gas flow rate
- 1.6 [mm] bubble size
- excentric sparger

Results
- strongly unsteady motion of the gas plume reproduced ($t_{osc} = 40$ [s])
- gas hold-up between 0.24 % and 0.34 % (70k – 95k bubbles in domain)
- “Guiness” effect: small bubbles move downwards near wall

Snapshot of bubble positions for two different times (exp. Data by Sokolichin and Eigenberger, 1999)
Bubble Swarms: Dissolution and Mixing of Gas

Setup
- air is dissolving in water (no reactions)
- $Sc = 500$, $Sc_{SGS} = 0.7$

Quantification of mixing

Contour plots of (a) concentration field $Y$, (b) local distribution of the variance $\sigma^2$, and (c) potential for diffusive mixing $\Phi$ (left: $t=5[s]$, right: $t=15[s]$)
Bubble Swarms: Dissolution and Mixing of Gas

Scale of segregation
- **Very fast dynamic** behavior, for long times perfectly log-normal distributed

Intensity of segregation
- **Intermediate time scale**, strong fluctuations in time
  - $\sigma^2$ and $\Phi$ decrease in time according to $(Y_{eq} - Y_{mean})$, i.e., exponentially

Time profiles for the mixing metrics $\sigma^2$ and $\Phi$

Distribution of the scale of segregation, top: comparison of distributions for different times, bottom: log-normal fit of the distribution after a time of 15 [s]
Fast Reactions in the Liquid Phase

Validation Study for a Presumed PDF Approach

- Structure of sub-grid-scale concentration distribution assumed to be a $\beta$-function.
- Filtered reaction rate pre-calculated & interpolated during simulation.
- Validation data are available for microreactors (hydrolysis of DMP, 4th Bourne)

Geometry of a typical microreactor

Results for flow (a, b) and concentration field (c) of an inert tracer in a vertical cross section of the microreactor

$U_{\text{instantaneous velocity}}$

$U_{\text{mean}}$...time-averaged velocity

$\xi_{\text{Mean}}$...filtered mixture fraction

reactor geometry

inlet velocity

physical properties
Reactions in the Liquid Phase

Validation Study for a Presumed PDF Approach

- Agreement with reference data is excellent

Filtered mixture fraction, variance of the mixture fraction, filtered DMP concentration as well as conversion of DMP (from left to right)

DMP conversion vs. Re-number (diamonds: experiments\(^1\) filled symbols: reference simulations from literature, \(^2\) red circles: our simulations)

\(^1\)Johnson & Prud’homme, AIChE J 43 (2003)
\(^2\)Marchisio, Comp & Chem Eng 33 (2009)
Reactions in the Liquid Phase
Application to Bubble Columns

- DMP hydrolysis in a bubble column.

**Setup**
- “Becker” case
- char. reaction time $\tau_R = 0.05$ s
- char. micro-mixing time in the bulk $\tau_M = 0.2$ s
- acid injected near the inlet

**Results**
- reaction stops (i.e., acid is completely consumed) after approx. 2 s.
- meso-mixing is complete after approx. $\tau_{Meso} = 7$ s
- 0.8% DMP conversion

Instantaneous filtered concentration and flow fields for a characteristic reaction time (Becker case $d_p = 3.2$ [mm], $V_G = 1.6$ [l/min]).
Part II

Outlook to PBE Modeling

(Mahoney et al., 2002)
Precipitation Model

**Precipitation**

is the generation of a **solid phase** due to a **supersaturated liquid phase**

**The Application**

is the production of **polyacrylic-acid / protamine nanoparticles** as carrier system for drugs

**The Solid Phase**

is modeled by the **Population Balance Equation** (transport equation for a particle size distribution)

\[
\frac{\partial n}{\partial t} + \nabla \cdot (\vec{U} \cdot n) = \nabla \cdot (D_T \cdot \nabla n) + J(S) - \frac{\partial (G \cdot n)}{\partial L} + B_{Agg} - D_{Agg}
\]

**Source Terms**

Nucleation  Growth  Aggregation
Precipitation Model

Nucleation Rate  \[ B_{\text{hom}}(S) = 1.5D(cN_A)^{7/3} \left( \frac{\sigma}{kT} \right)^{0.5} v \exp \left( - \frac{16\pi \sigma^3 v^2}{3(kT)^3(\ln S)^2} \right) \]

Growth Rate  \[ G(L, S) = \frac{\partial L}{\partial t} = \frac{2}{Lc_S} ShDc (S - 1) \]

Aggregation

Birth Rate:  \[ B_{\text{agg}}(L) = \frac{L^2}{2} \int_0^L \frac{\beta_{\text{agg}}(\lambda, L^3 - \lambda^3) \cdot n(\lambda) \cdot n^{3/2}(L^3 - \lambda^3)}{(L^3 - \lambda^3)^{2/3}} \cdot d\lambda \]

Death Rate:  \[ D_{\text{agg}}(L) = n(L) \cdot \int_0^\infty \beta_{\text{agg}}(\lambda, L) \cdot n(\lambda) \cdot d\lambda \]

+ Aggregation kernel
+ Collision kernel
+ Aggregation efficiency
+ Stability ratio

**Hydrodynamic** correction

Interaction potentials for **Van der Waals** and **electrostatic forces**
Precipitation Model

Preliminary Results for Homogeneous Nucleation

\[ B_{\text{hom}} = 1.5D (cN_A)^{7/3} \left( \frac{\sigma}{kT} \right)^{0.5} v \exp \left( - \frac{16\pi\sigma^3v^2}{3(kT)^3(\ln S)^2} \right) \]

Try to neglect nucleation!
Part III

Conclusions

DNS of Mass Transfer
resolution is everything - **meshing was an issue** and done with Cubit*
data filtering to provide useful data for LES

LES-LPT for Meso Mixing
**particle-particle collision detection** is an issue, solved by particle list in
each cell and parallelization
**fast reactions require special attention** – look-up table strategy adapted
for mixing in the liquid phase

PBE for Precipitation
**nucleation and aggregation kernels** complex – which phenomenon is
important?
partners welcome to **implement PBE solver** (MoM, classes method?)

*) cubit.sandia.gov
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Recent References

References


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4th Bourne Reaction

\[ A + B \rightarrow P_1 + P_2 \]
\[ C + P_2 \rightarrow Q_1 + 2Q_2 \]

Details
- **A** = sodium hydroxide (NaOH)
- **B** = hydrochloric acid (HCl)
- **C** = dimethoxypropane, \( CH_3C\{OCH_3\}_2CH_3 \), i.e., DMP
- **P_1** = sodium chloride (NaCl)
- **P_2** = water (H2O)
- **Q_1** = acetone (CH3COCH3)
- **Q_2** = methanol (CH3-OH)
- **Solvent** = 25 wt % ethanol aqueous solution