University of Twente

Front Tracking simulations on liquid-liquid systems; an investigation of the drag force on droplets

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Fundamentals of Chemical Reaction Engineering

CFD2008-071 – June 12th, 2008

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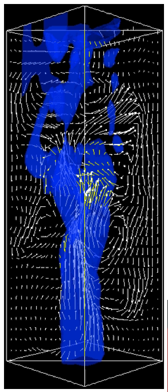
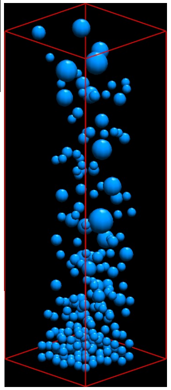
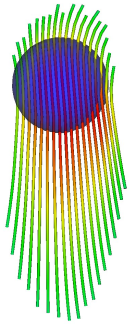
Multi-level modelling strategy for multiphase flow







Multi-fluid continuum model

Discrete element model

Direct numerical simulations

Large scale structures

Medium scale structures

Closures for:
- **Drag**, lift, virtual mass
- Swarm effects
- Mass transfer coefficients

Introduction

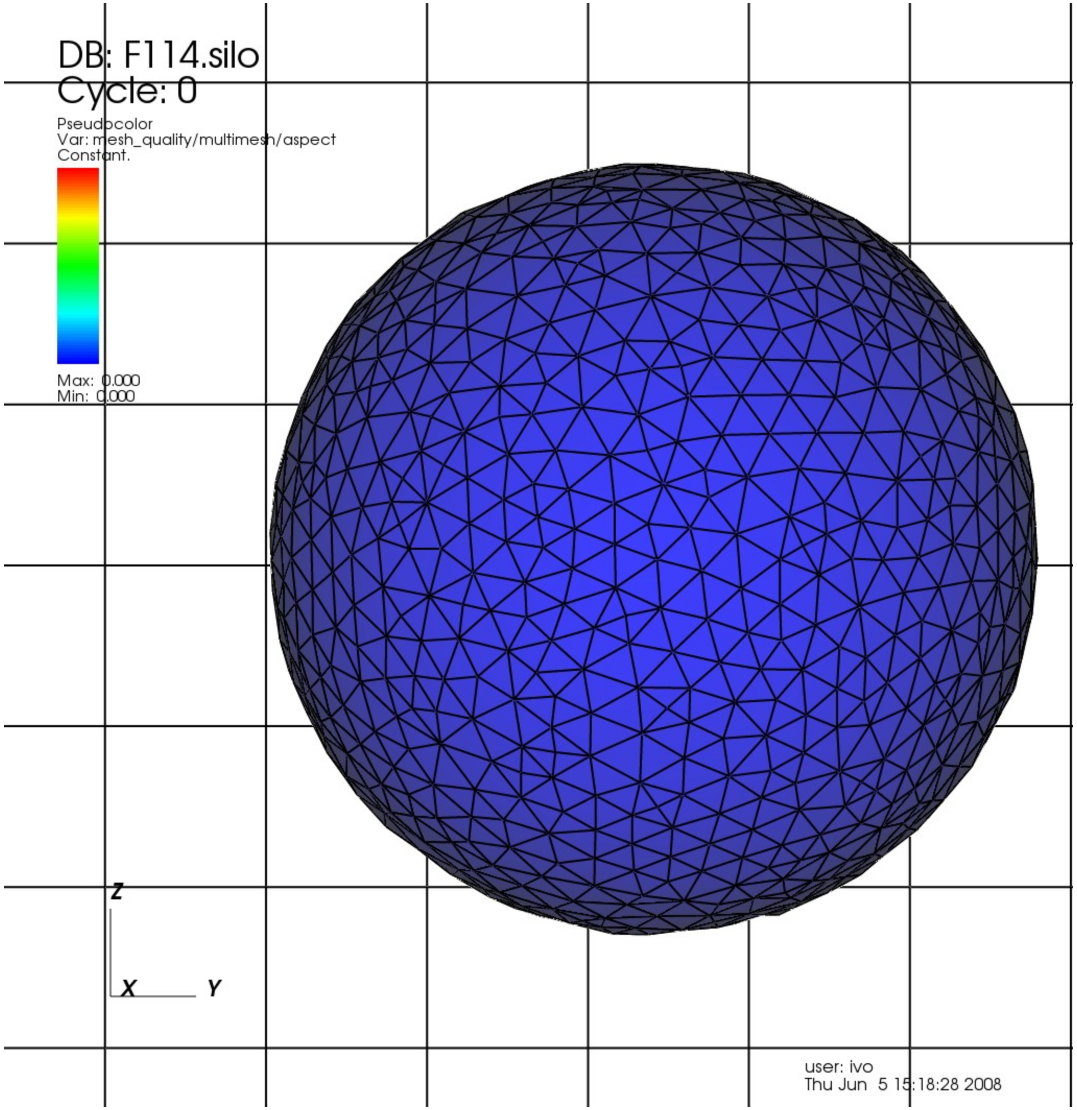
Direct Numerical Simulations (DNS)

- Fully resolved
  - Based only on fundamental equations for fluid flow
    - Navier-Stokes + continuity equation for incompressible flow
  - Can be used to derive closures for forces on
    - Bubbles
    - **Droplets**
    - Particles
- Only valid when grid independence can be shown!

Front tracking

- Incompressible fluids
- Fixed Eulerian grid
- Interface consists of Lagrangian marker points that build up a triangular mesh
  - Points are moved with the interpolated fluid flow
  - Straightforward surface tension force calculation
- Advantages
  - Calculation of surface tension force with sub-grid accuracy.
  - No numerical coalescence of dispersed phase elements

Front tracking



Drag force

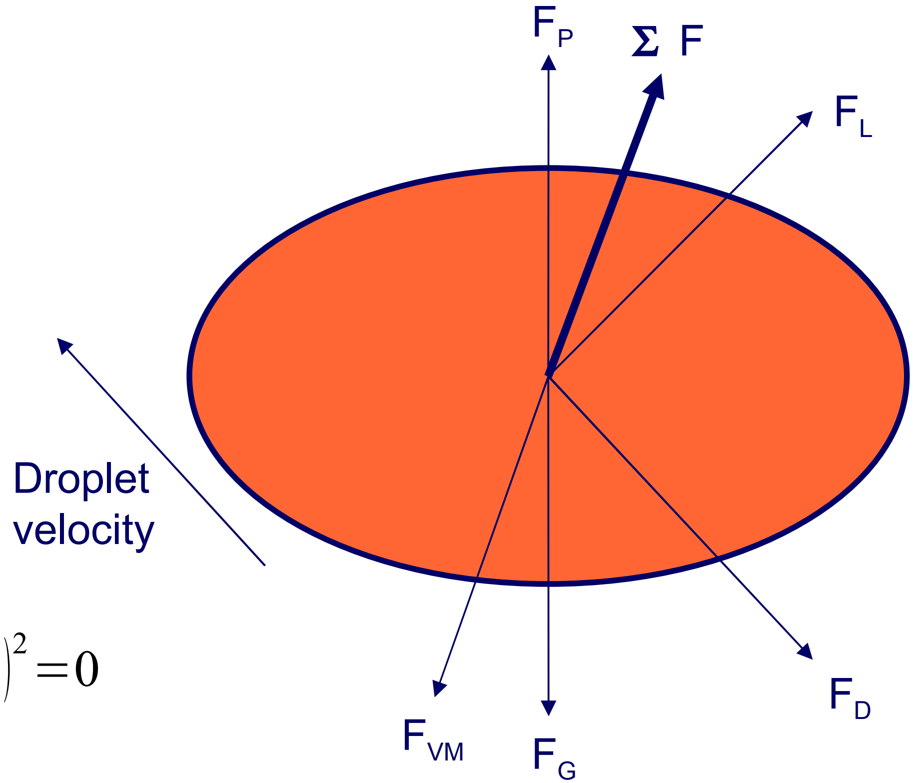
Forces acting on a droplet

$$m_b \frac{d\vec{v}_b}{dt} = \vec{F}_G + \vec{F}_P + \vec{F}_D + \vec{F}_L + \vec{F}_{VM} = \sum \vec{F}$$

Stationary force balance in the rise direction

$$(\rho_c - \rho_d) g \frac{\pi}{6} d_{eq}^3 - \frac{1}{2} C_D \rho_c \frac{\pi}{4} d_{eq}^2 \left(\vec{u_{d,z}} - \vec{u_{c,z}} \right)^2 = 0$$

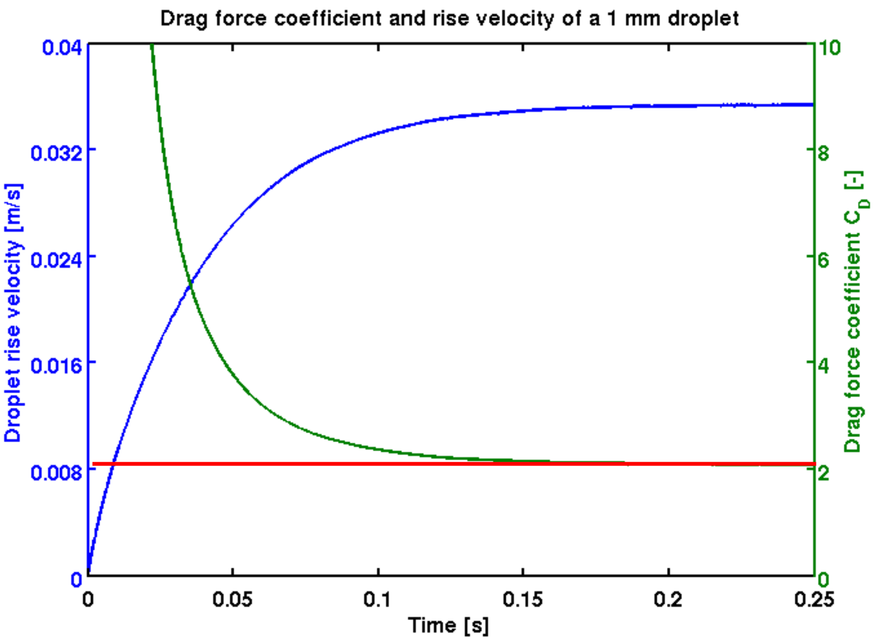
$$C_D = \frac{4 \left(\rho_c - \rho_d \right) g \, d_{eq}}{3 \rho_c \left(\vec{u_{d,z}} - \vec{u_{c,z}} \right)}$$



Drag force

- Determine drag force coefficient by different averaging procedures
  - Average rise velocity, then determine C_D
  - Determine C_D as a function of time, average this value

→ No difference



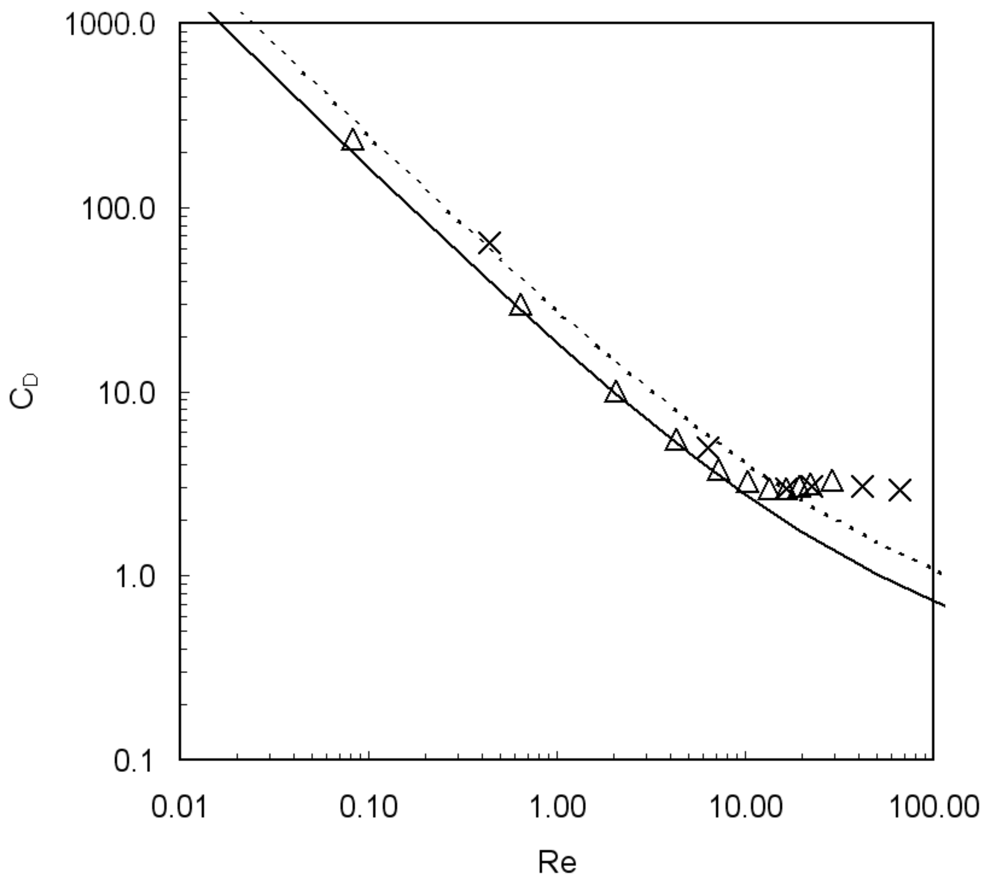
Correlations from literature (bubbly flow)

- **Rigid sphere:** $$C_D = \frac{24}{Re}$$
- **Mei et al. (1994):** $$C_D = \frac{16}{Re}\left(1 + \frac{2}{1 + \frac{16}{Re} + \frac{3.315}{Re^{0.5}}}\right)$$
- **Tomiyama (1998):**
  - **Pure** $$C_D = max\left[min\left[\frac{16}{Re}\left(1 + 0.15\,Re^{0.687}\right), \frac{48}{Re}\right], \frac{8}{3}\frac{Eo}{Eo+4}\right]$$
  - **Contaminated** $$C_D = max\left[\frac{24}{Re}\left(1 + 0.15\,Re^{0.687}\right), \frac{8}{3}\frac{Eo}{Eo+4}\right]$$

$$Re = \frac{\rho_c \vec{u}_d d_{eq}}{\mu_c} \qquad Eo = \frac{\left(\rho_c - \rho_d\right) g\, d_{eq}^2}{\sigma}$$

Drag force

- Experiments and simulations on drag force for bubbly flow



From:
Wouter Dijkhuizen, PhD thesis, University of Twente, 2008

Objectives

- Investigate the behavior of the Front Tracking model for liquid-liquid systems
- Simulate droplets in an infinite quiescent liquid to derive drag force closures
- Investigate the relation between gas-liquid and liquid-liquid drag force and their dependencies

Grid dependency

- Vary resolution in droplet, domain 5 times droplet size
- Vary resolution in droplet, keep domain at 100^3 cells
- Keep resolution in droplet at 20 cells, vary domain size

Simulation parameters:

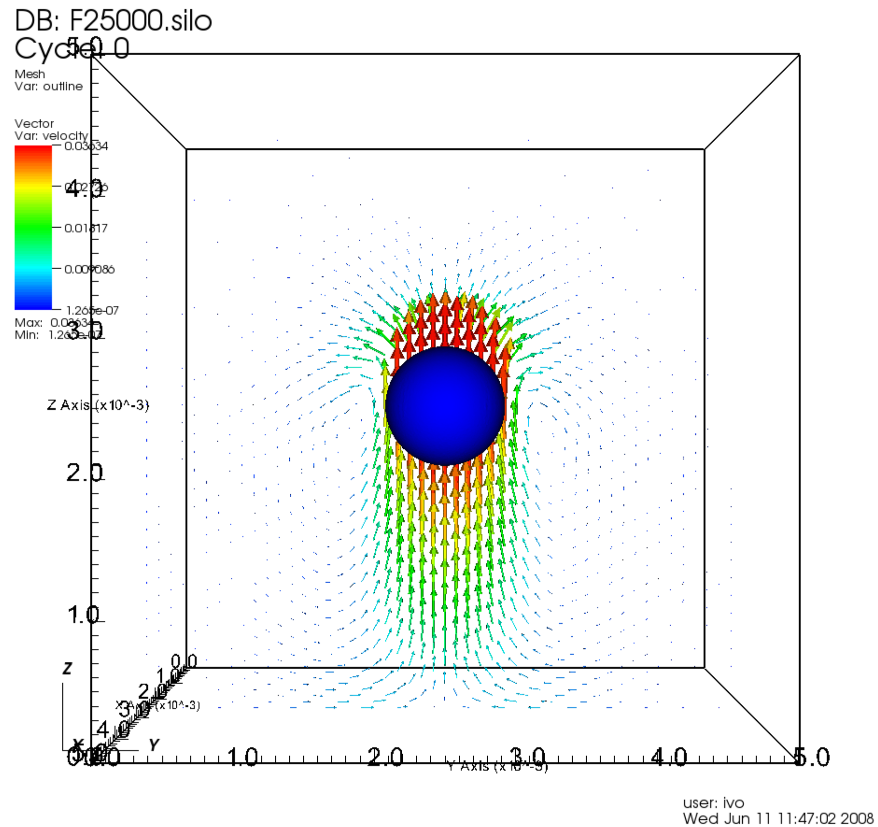
ρ_c = 1000 kg/m^3, $\mu_c = 10^{-3}$ Pa·s

ρ_d = 800 kg/m^3, $\mu_d = 10^{-1}$ Pa·s

σ = 52.9 mN/m, d_{eq} = 1 mm

t_{end} = 1 s

$dt = 10^{-5}$ s



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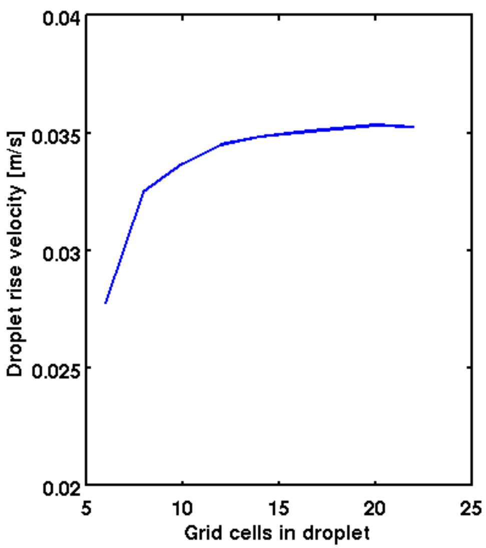

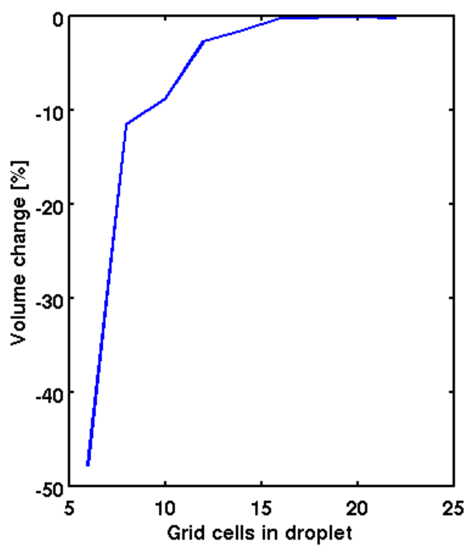

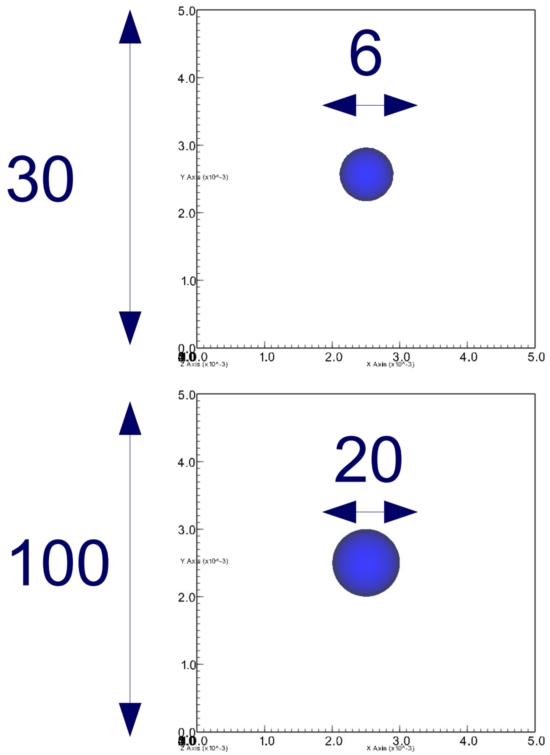

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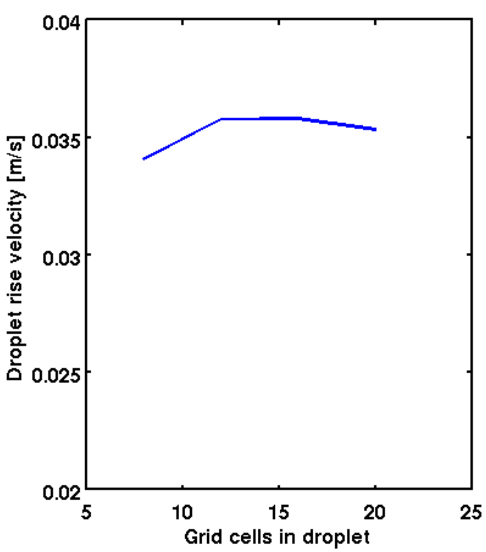

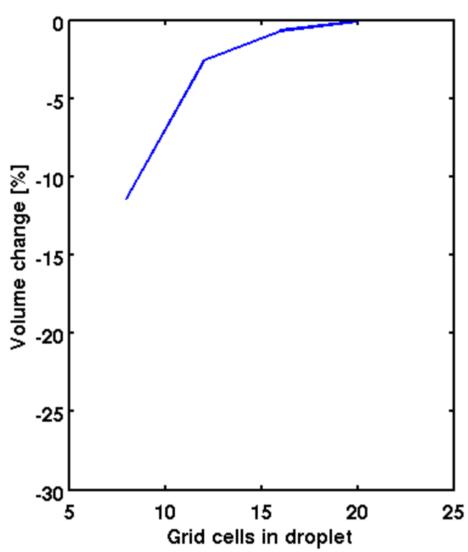

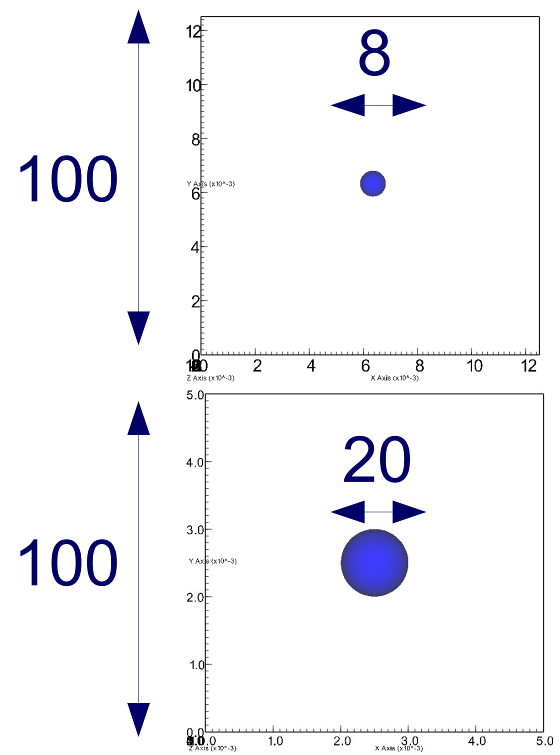

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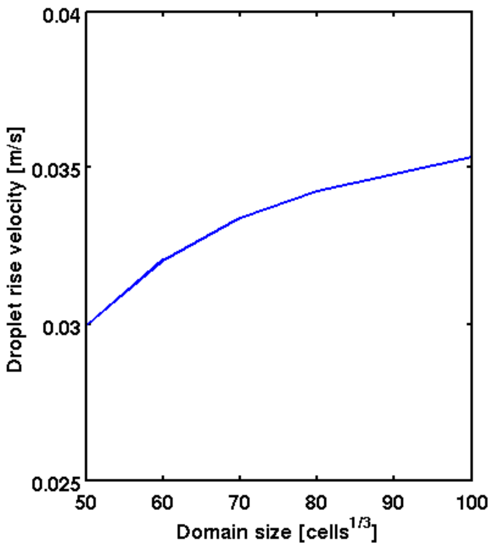
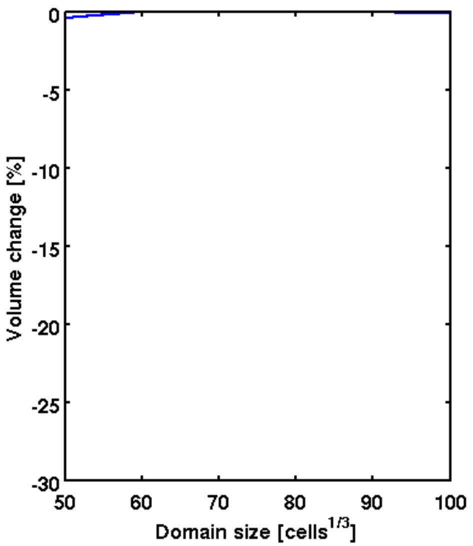
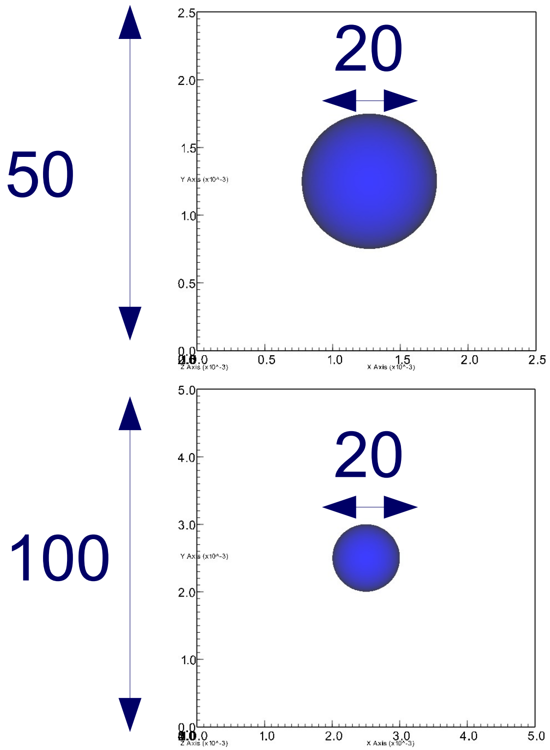




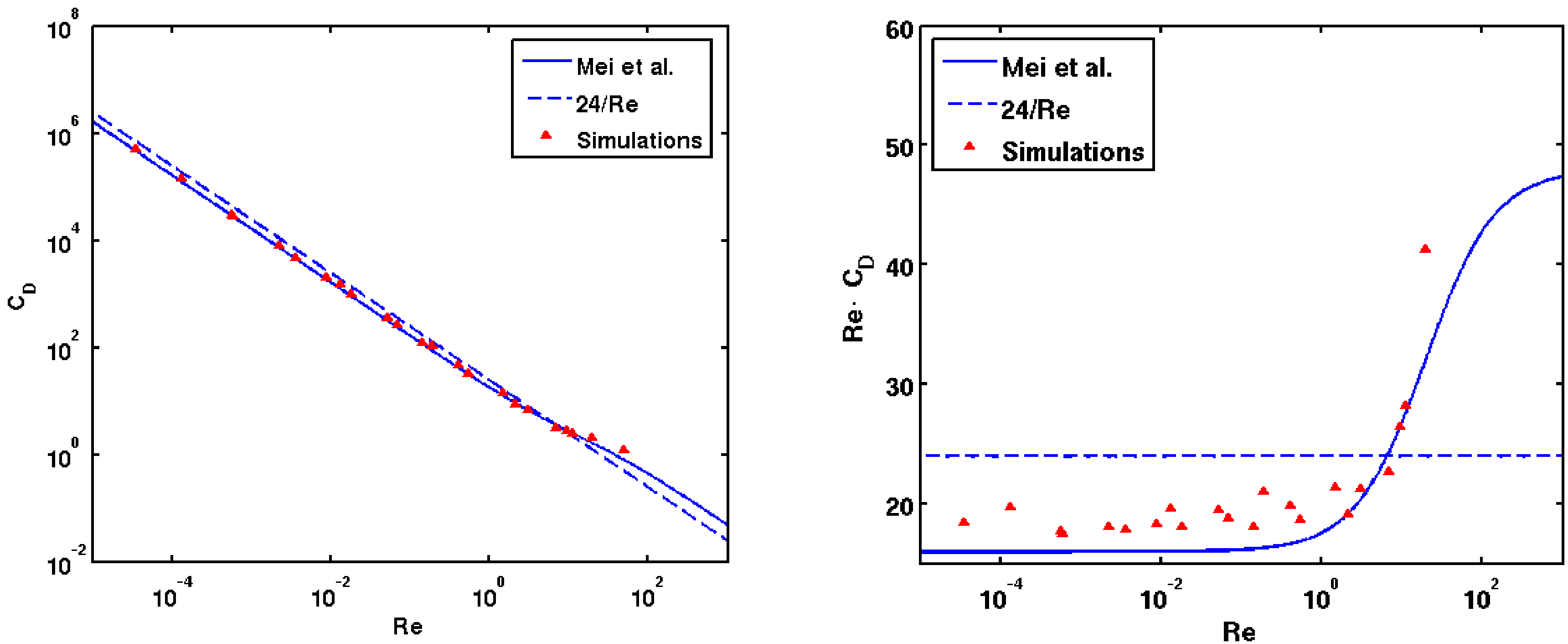


Drag force simulations

- Used settings:
  - 20 grid cells in droplet diameter
  - 100^3 grid cells in domain
- Variation of continuous phase viscosity between 0.001 - 0.2 Pa·s
- Variation of equivalent droplet diameter between 0.2 – 5 mm
- "Dodecane droplet in water" system:
  - ρ_c = 1000 kg/m3;
  - ρ_d = 746 kg/m3; $\mu_d = 1.34\cdot10^{-3}$ Pa·s
  - σ = 0.0529 N/m;

Drag force simulations

- Variation of continuous phase viscosity

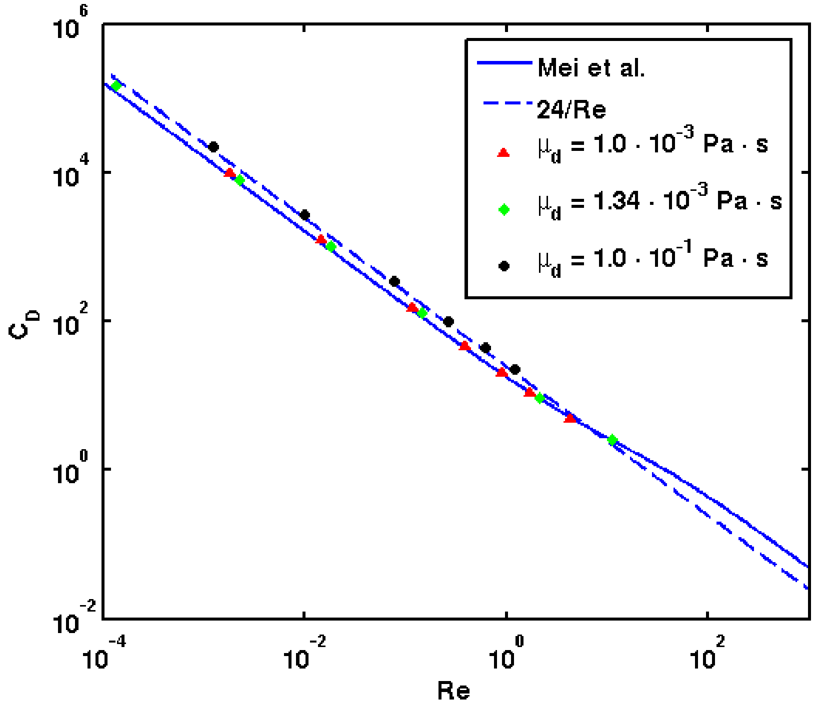


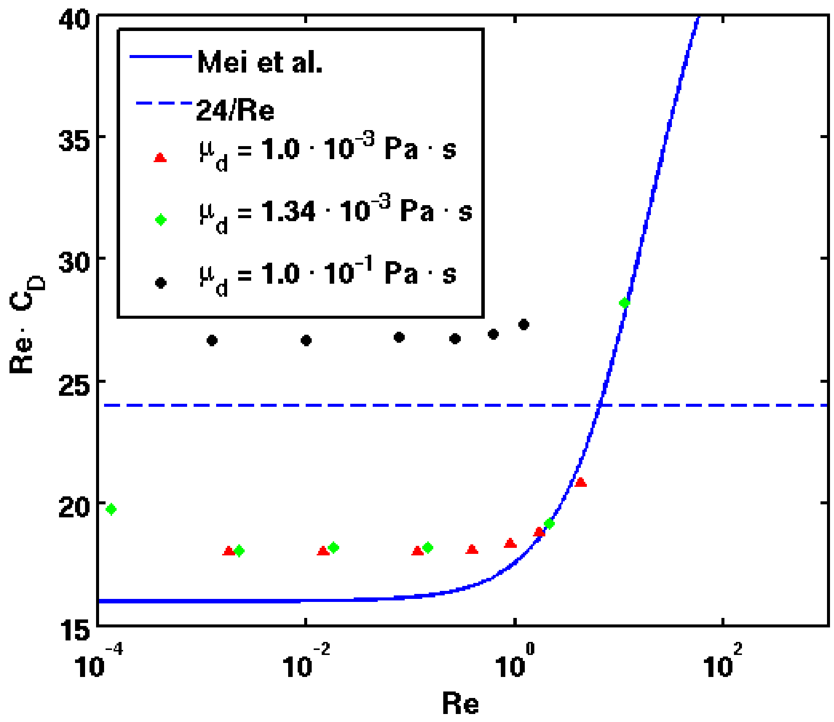
Drag force simulations

- Variation of dispersed phase viscosity between 10^{-3} – 10^{-1} Pa·s
- Variation of equivalent droplet diameter between 0.2 – 7 mm
- Physical properties
  - ρ_c = 1000 kg/m^3; μ_c = 10^{-1} Pa·s
  - ρ_d = 800 kg/m^3;
  - σ = 0.0529 N/m;

Drag force simulations

- Variation of dispersed phase viscosity

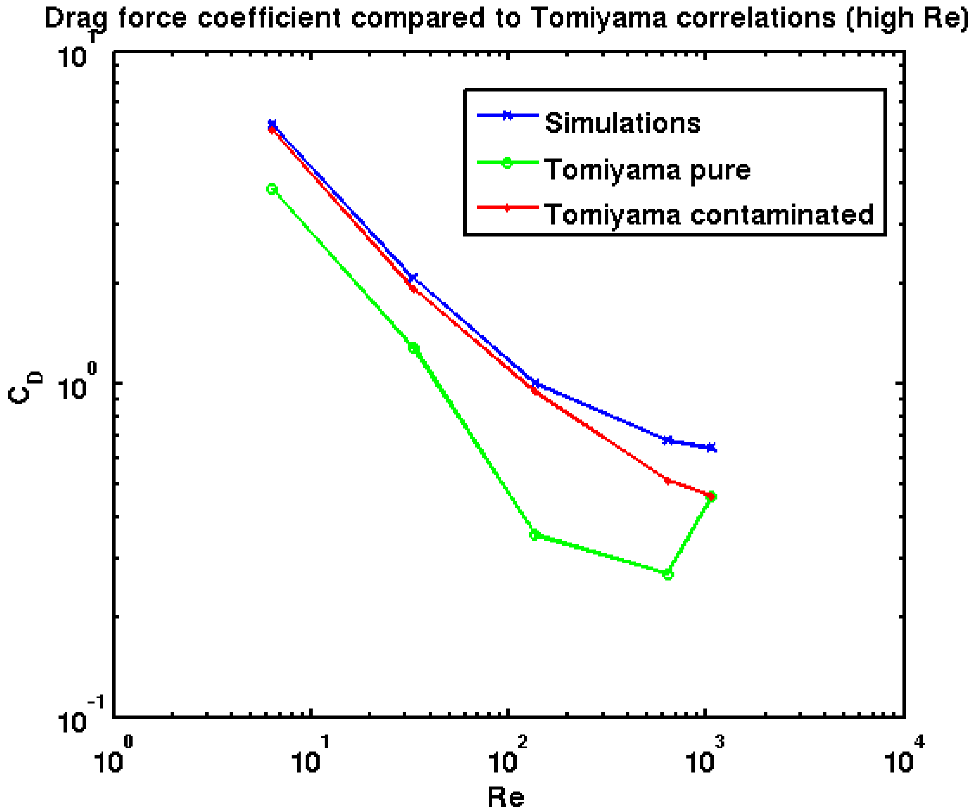




Drag force simulations

- Due to volume losses more detailed simulations:
  - Computational grid 150^3 cells
  - 30 cells within droplet diameter
  - Higher surface tension

Drag force simulations



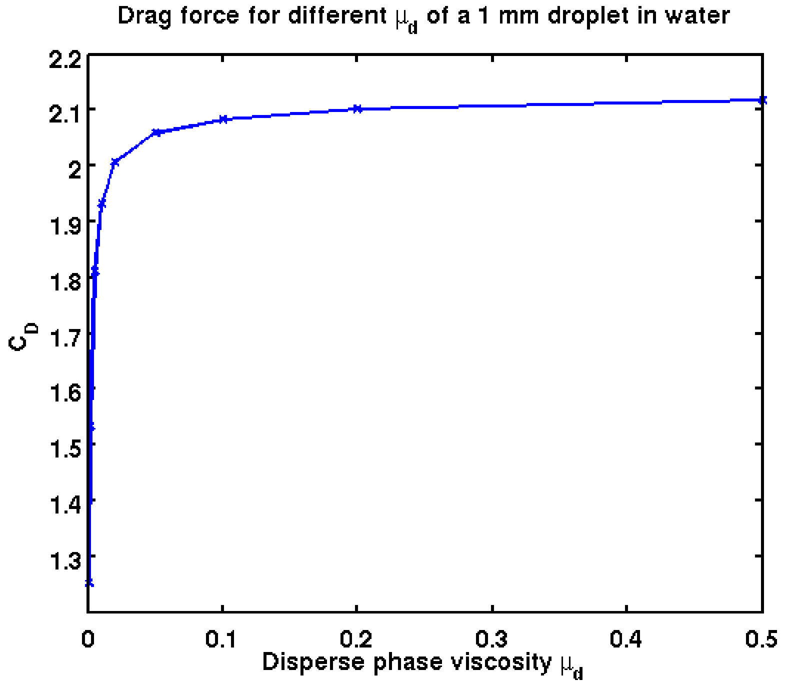
Simulation parameters:

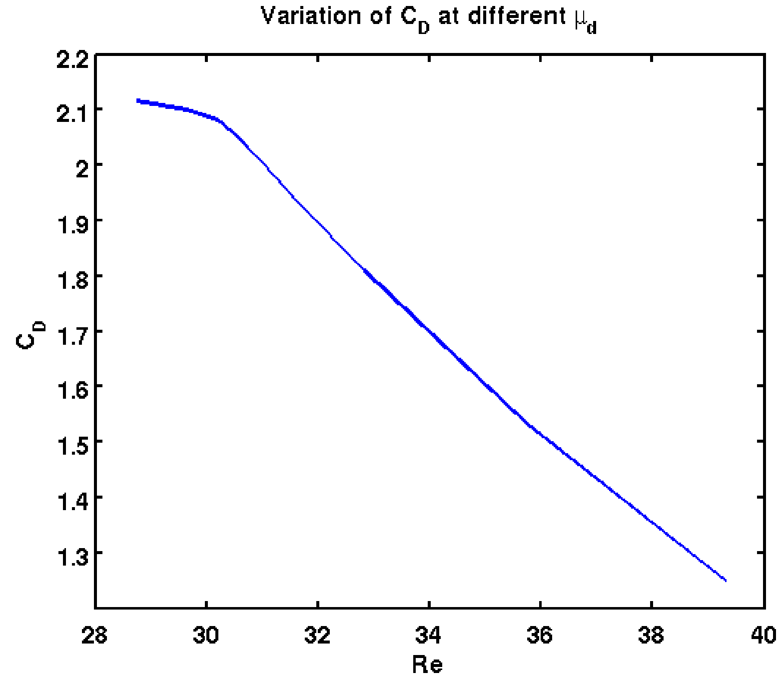
ρ_c = 1000 kg/m^3; μ_c = 10^{-3} Pa·s

ρ_d = 800 kg/m^3; μ_d = 10^{-1} Pa·s

σ = 0.1 N/m; d_{eq} = 0.5 - 7 mm

Drag force simulations





Simulation parameters:

ρ_c = 1000 kg/m^3; μ_c = 10^{-3} Pa·s

ρ_d = 800 kg/m^3; μ_d = 10^{-3} - 0.5 Pa·s

σ = 0.1 N/m; d_{eq} = 1 mm

Conclusions and outlook

- Front tracking model can simulate dispersed liquid phases but a high resolution is required
- Volume loss strongly depending on droplet resolution
- Correlations of Mei et al. and Tomiyama for bubbly flow are well predicted
  - Some overshoot due to wall effects
- Transition of free-slip to no-slip condition as a function of μ_d shown

- Outlook:
  - Eo dependence of drag force coefficient
  - Droplet and bubble swarms

Thank you

Thank you for your attention

Front tracking

Surface tension is mapped from the interface mesh to the Eulerian grid.

$$\vec{F}_a = \sigma \left(\vec{t}_{m,a} \times \vec{n}_a \right)$$

$$\vec{F}_b = \sigma \left(\vec{t}_{m,b} \times \vec{n}_b \right)$$

$$\vec{F}_c = \sigma \left(\vec{t}_{m,c} \times \vec{n}_c \right)$$