5-24-2016

New hybrid CPU-GPU solver for CFD-DEM simulation of fluidized bed

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New Hybrid CPU-GPU Solver for CFD-DEM Simulation of Fluidized Beds

Presenter

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Fluidization XV
May 22-27, 2016, Montebello, Quebec, Canada

Background

- Main approaches for modeling of fluid-solid flows:
  - TFM
  - **CFD-DEM**
- Advancements in CFD-DEM
  - Theoretical: extension or developing new models for contact forces, torques, fluid-particle interactions and etc.
  - Proposing new coupling methods
  - Adding new sub-models to the main model to investigate reactive flows, cohesive flows and etc.
  - **Developing efficient numerical tools to solve all equations**

Objective

- Developing a solver which has features very close to an ideal solver
- Using the maximum computational power of a simple desktop computer (CPU and GPU)
  - This makes it possible to perform larger simulations on a simple desktop computer.

IMG: http://pngimg.com/upload/computer_pc_PNG7719.png

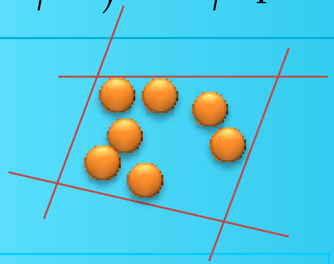
Model

Gas and particle equations

- Gas phase
  - Continuity
  - Momentum
  - Turbulence (k-ε)

$$\frac{\partial\left(\rho_f\varepsilon_f\right)}{\partial t}+\nabla.\left(\rho_f\varepsilon_f\vec{u}\right)=0$$

$$\frac{\partial\left(\rho_f\varepsilon_f\vec{u}\right)}{\partial t}+\nabla.\left(\rho_f\varepsilon_f\vec{u}\vec{u}\right)=-\varepsilon_f\nabla p-\varepsilon_f\nabla.\vec{\tau}_f-\vec{F}+\rho_f\varepsilon_f\vec{g}$$



$$\vec{F}=\frac{1}{V_{cell}}\sum_{i=1}^{k_v}\left(\vec{f}_i^{\,d}+\vec{f}_i^{\,r}\right)$$

- Particle phase
  - Linear
  - Angular

$$m_i\frac{d\vec{v}_i}{dt}=m_i\frac{d^2\vec{x}_i}{dt^2}=\sum_{j\in CL_i}\vec{f}_{ij}^{\,p-p}+\vec{f}_i^{\,f-p}+\vec{f}_i^{\,ext}$$

$$I_i\frac{d\vec{\omega}_i}{dt}=I_i\frac{d^2\vec{\varphi}_i}{dt^2}=\sum_{j\in CL_i}\left(\vec{M}_{ij}^{\,t}+\vec{M}_{ij}^{\,r}\right)$$

$$\vec{f}_i^{\,\nabla p}=-V_i\nabla p$$

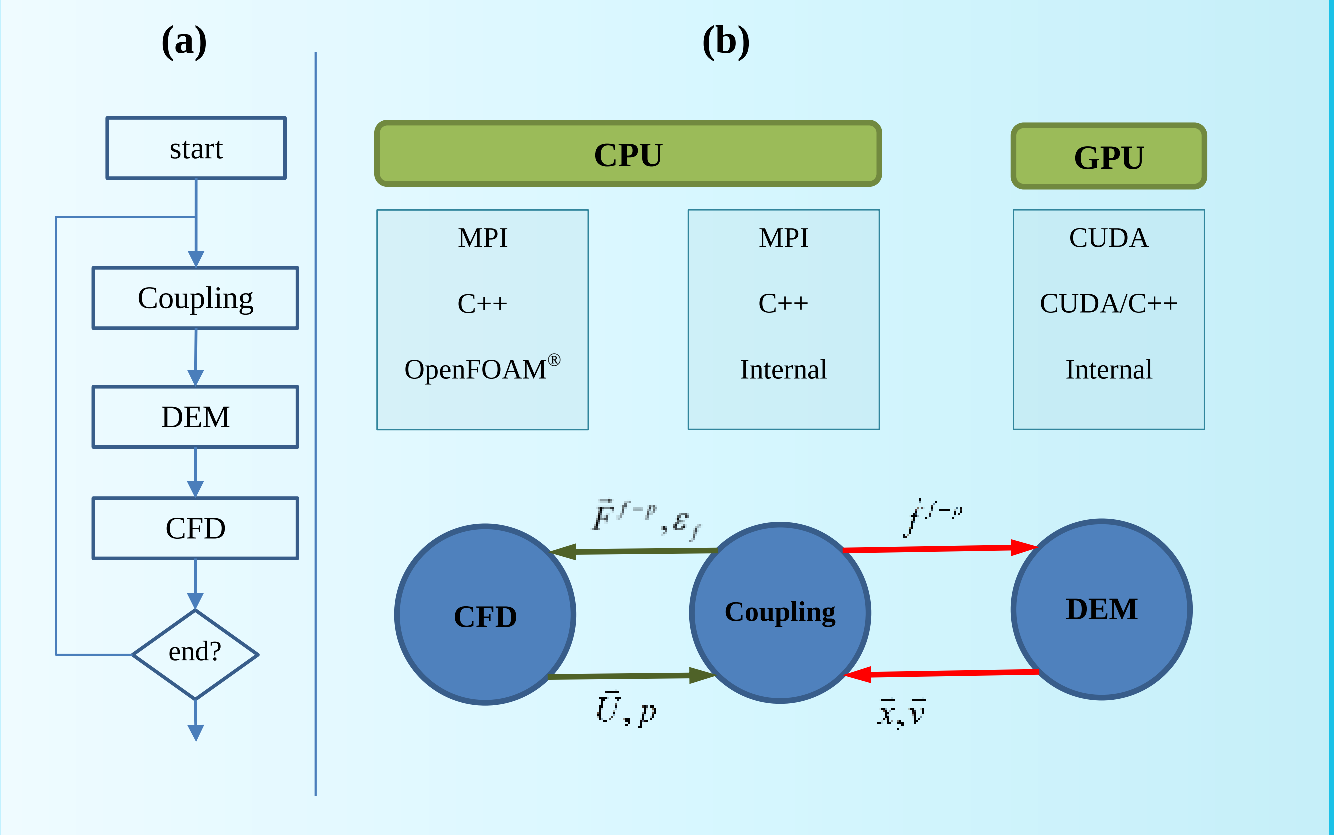
$$\vec{f}_i^{\,f-p}=\vec{f}_i^{\,d}+\vec{f}_i^{\,\nabla p}+\vec{f}_i^{\,\nabla.\vec{\tau}_f}+\vec{f}_i^{\,r}$$

$$\vec{f}_i^{\,d}=3\pi\mu_f\varepsilon_f d_i\left(\vec{u}-\vec{v}_i\right)\left\{\left(\frac{180\varepsilon_p}{18\varepsilon_f^2}\right)+\varepsilon_f^2\left(1+1.5\sqrt{\varepsilon_p}\right)+\left(\frac{0.413}{24\varepsilon_f^2}\right)\left(\frac{\varepsilon_f^{-1}+3\varepsilon_p\varepsilon_f+8.4Re_i^{-0.343}}{1+10^{3\varepsilon_p}Re_i^{-(1+4\varepsilon_p)/2}}\right)Re_i\right\}$$

$$\vec{f}_i^{\,\nabla.\vec{\tau}_f}=-V_i\left(\nabla.\vec{\tau}_f\right)$$

Implementation details

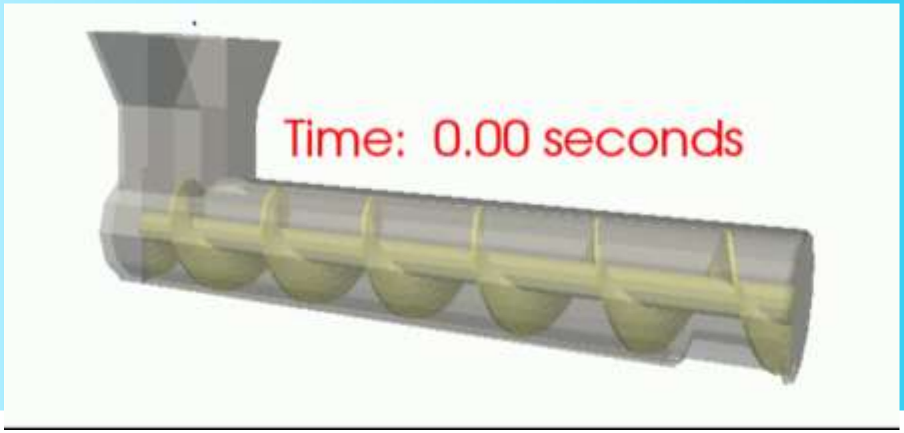
The overview of the solver



Implementation details

DEM part

- All calculation steps were parallelized using CUDA platform (GPU computational resource).
- The parallel algorithm by Mazhar et al. for particle-particle contact search.
- Triangulation for representing wall geometry

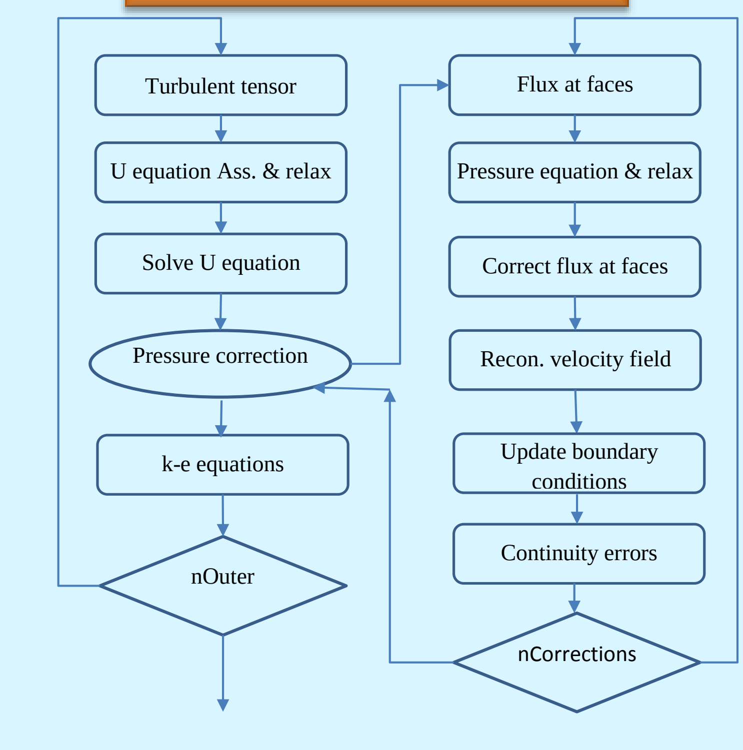


Mazhar, et al. (2011), *Multibody System Dynamics*, **26**(1), 37-55

Implementation details

CFD part

PIMPLE algorithm




```
// main iteration loop
while (runTime.run())
{
    //. . . some code . . .

    // do the coupling stuff
    CPL.do_couplingALL( Epsilon, U, p, T,
                        Conct,   mu, rhof,
                        SUSu, SPSp, ST, SConct )
    // iterate DEM
    CPL.DEM_iterate();

    #include "TEqn.H"

    #include "ConctEqn.H"

    // pimple loop starts here
    while (pimple.loop())
    {
        #include "UEqn.H"

        // --- PISO loop
        while (pimple.correct())
        {
            #include "pEqn.H"
        }

        if (pimple.turbCorr())
        {
            turbulence->correct();
        }
    }

    // output . . . .
}
```

OpenFOAM

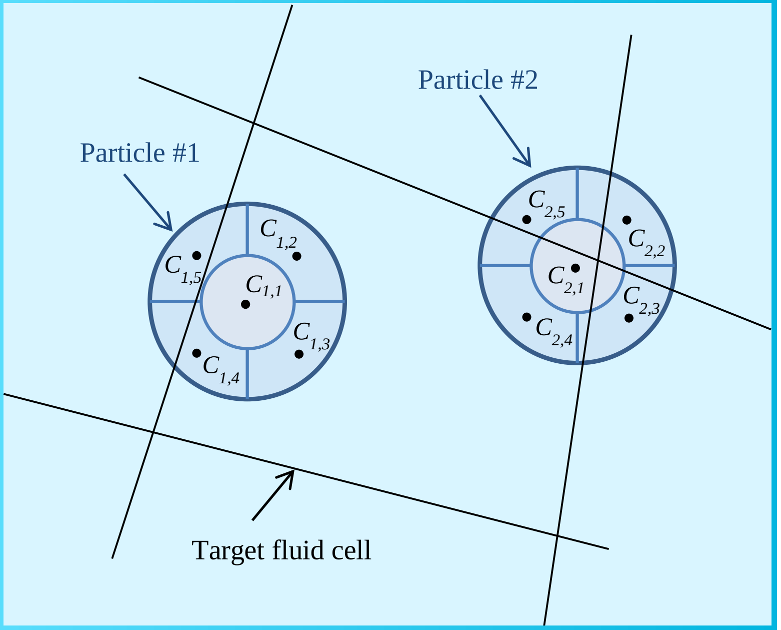
Implementation details

Coupling part

- Calculation of fluid porosity

$$\varepsilon_f = 1 - \frac{1}{V_{cell}} \sum_{i=1}^{k_V} \varphi_i V_i$$

PIC | Analytical | **Sub-division**



Hilton, J.E., Mason, L.R., and P.W. Cleary (2010), Chemical Engineering Science, 65, 1584-1596.

Test runs

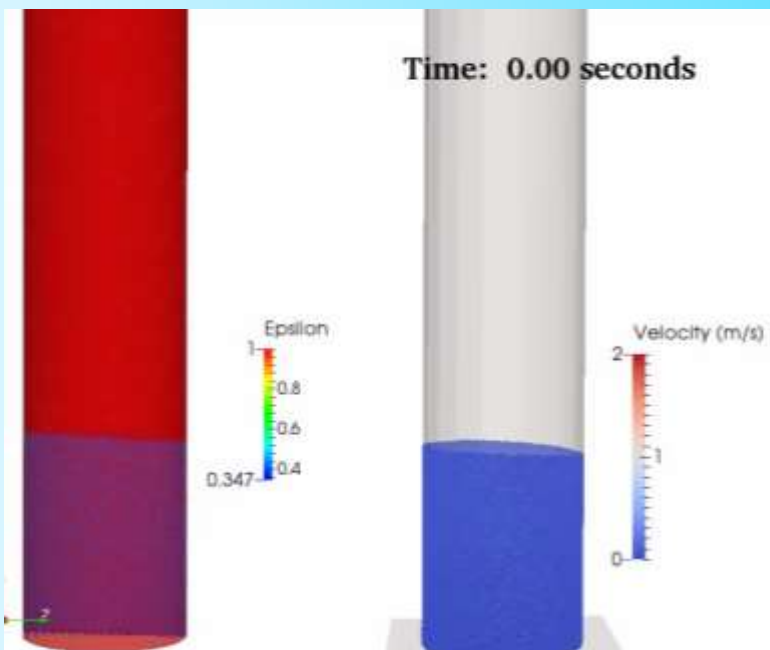
Desktop computer

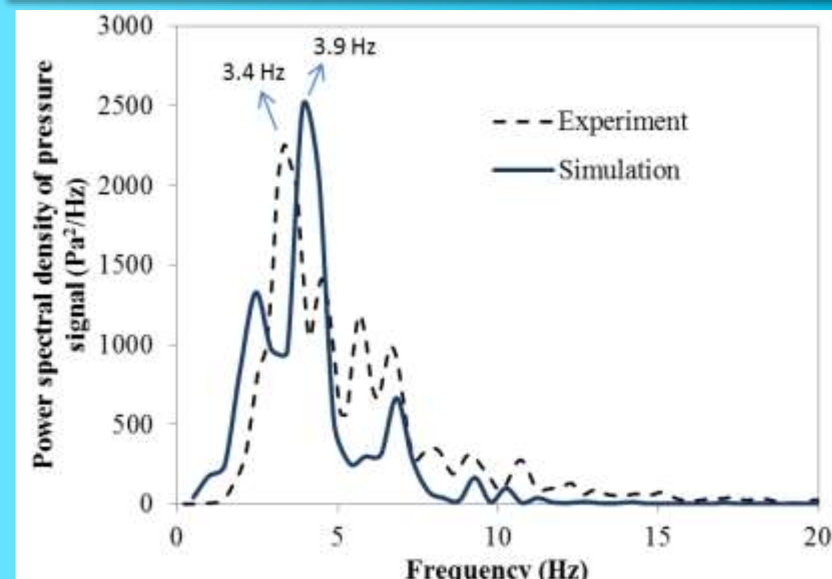
- Intel® core^{TM}-i7 processor with 4 3.6-GHz cores.
- NVIDIA GeForce® 660Ti GPU
- Compiler: g++ compiler on Ubuntu 14.04
- OpenFOAM® 2.3

Bubbling fluidized bed

Pressure fluctuations

No. of particles: 880 k, Max. Co = 0.44, Run time = 6 hr per sec on 1 CPU core

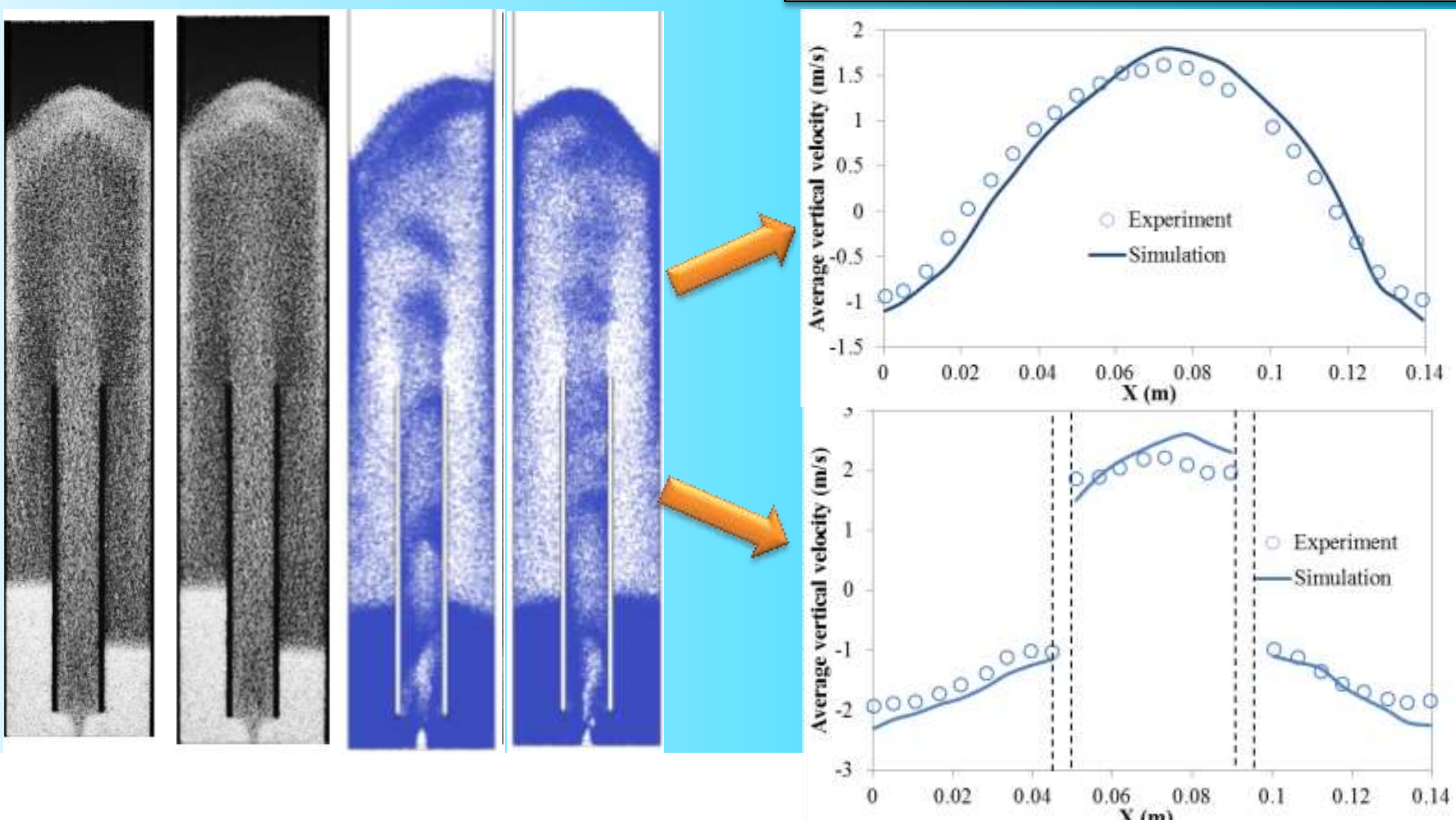




Spout-fluid bed

Particle velocity profile

No. of particles: 460 k, Max. Co = 1.59, Run time = 6.5 hr. per sec. on 2 CPU cores

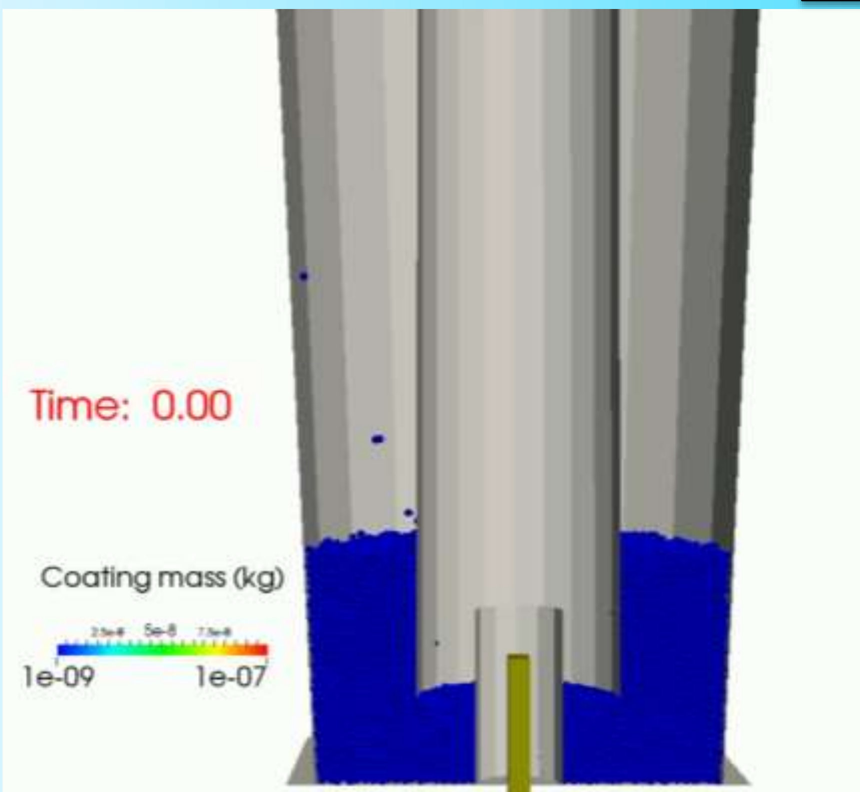


Sutkar, V.S., Deen, N.G., Mohan, B., Salikov, V., Antonyuk, S., Heinrich, S., and Kuipers, J.A.M. (2013), Chemical Engineering Science, 104, 790-807

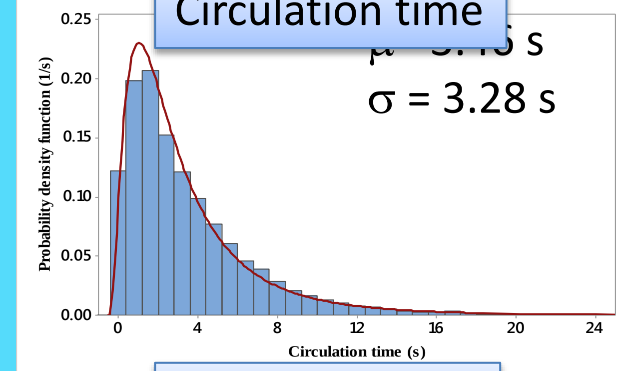
Wurster bed

Velocity profile #1

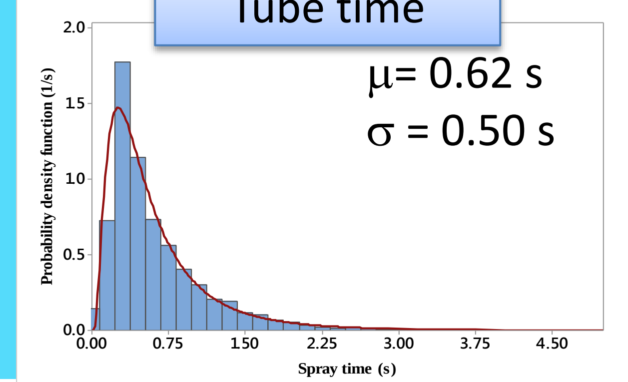
No. of particles: 47 k, Max. Co = 1.02, Run time = 45 min per sec on 1 CPU core



Circulation time



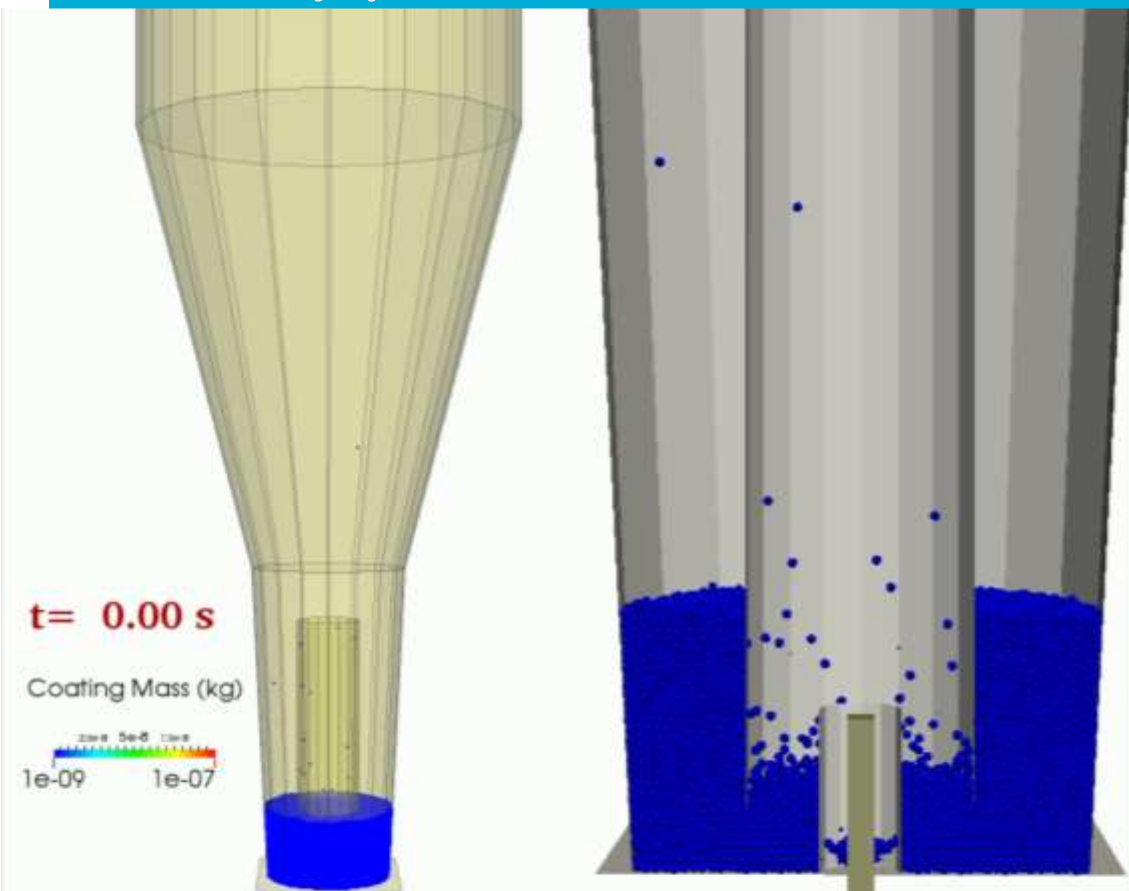
Tube time



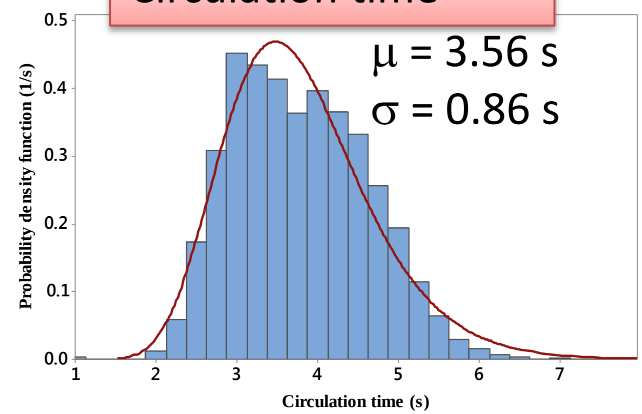
Central 11.5 m/s | annulus 4.5 m/s

Wurster bed

Velocity profile #2



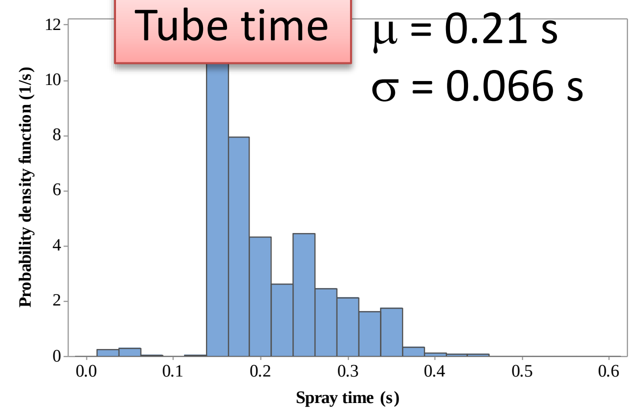
Circulation time



μ = 3.56 s

σ = 0.86 s

Tube time



μ = 0.21 s

σ = 0.066 s

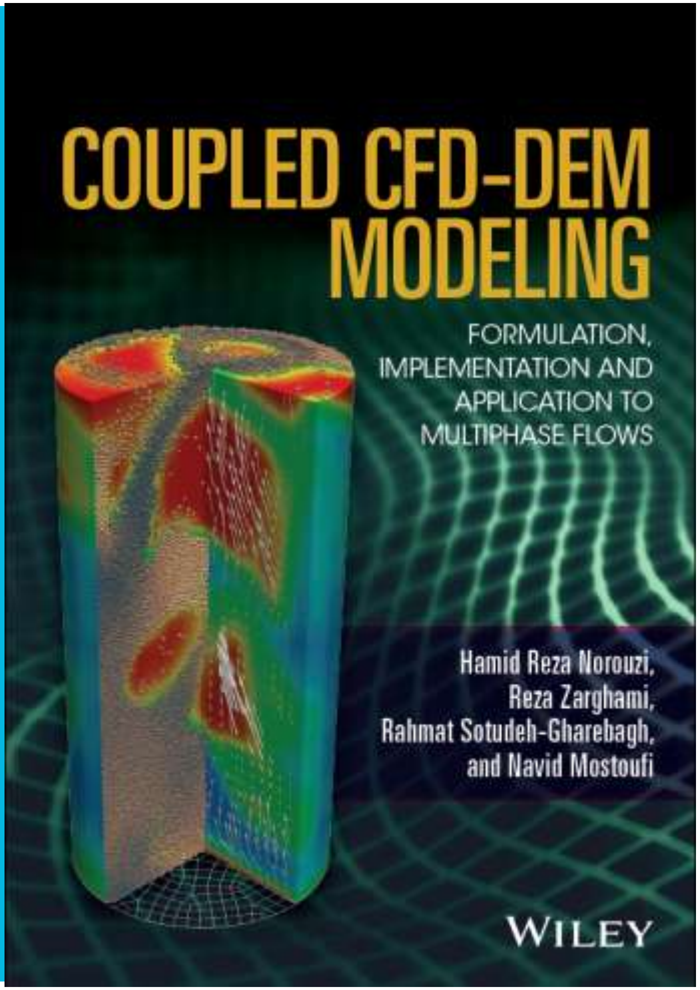
Central 14.0 m/s | annulus 1.0 m/s

New book on CFD-DEM with Wiley

- Ch. 1: Introduction

- Ch. 2: DEM Formulation
- Ch. 3: DEM Implementation
- Ch. 4: Non-Spherical Particles
- Ch. 5: DEM Applications to Granular Flows

- Ch. 6: CFD-DEM Formulation and Coupling
- Ch. 7: CFD-DEM Applications to Multiphase Flow
- Ch. 8: Interparticle Forces and External Fields



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Thanks for Your Attention