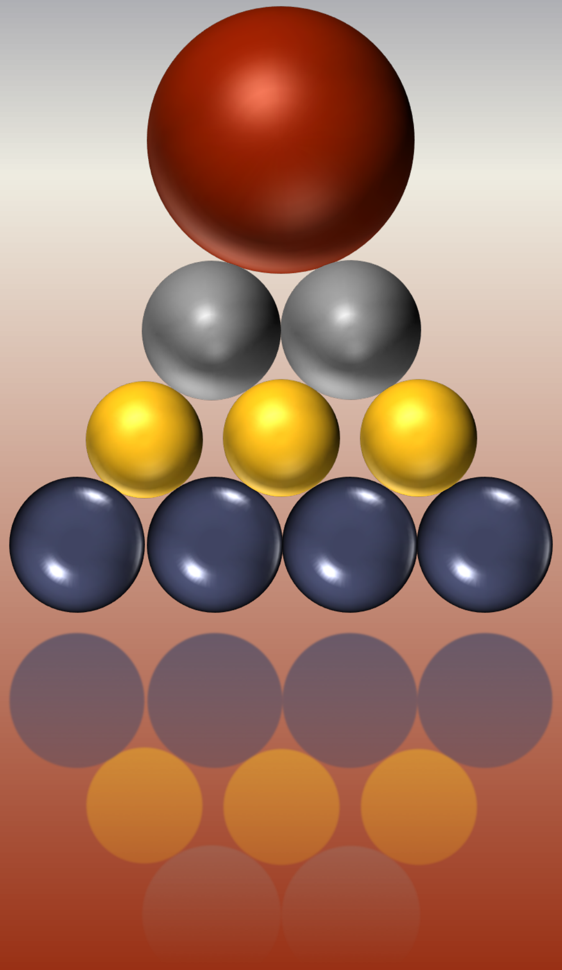
Campus di Arcavacata UNIVERSITÀ DELLA CALABRIA

UNIVERSITÀ DELLA CALABRIA DIPARTIMENTO DI INGEGNERIA INFORMATICA, MODELLISTICA, ELETTRONICA E SISTEMISTICA



Evaluation of coarse graining strategy and degree in DEM-CFD simulations of cyclone flow

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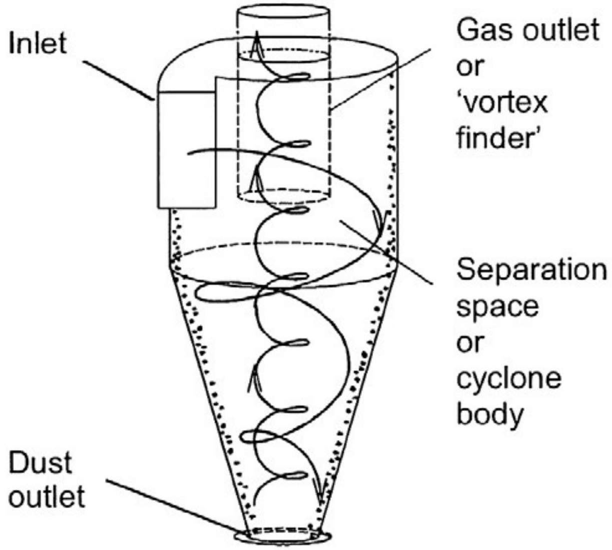
Detailed modelling of cyclones

Requirements for cyclone modelling

- Capture gas-solid complex swirling flow
- Model particle-wall and particle-particle collisions to obtain solids accumulation and descent
- Consider particle pickup by the upflowing vortex (inefficiency)
- Take polydispersion into account



DEM is attractive for its ability to provide detailed and good collision representation. DEM-CFD applied to large particle DMC (Chu et al., 2016)

For the industrial scale, e.g. 1 m barrel diameter, 15 m/s inlet velocity, 0.2%vol loading of 100 μm particles:
$\text{No. of particles/sec} \sim 10^9 \div 10^{10}$ (UNFEASIBLE)

- **AIM: Explore whether *coarse-grain* DEM can be a solution**

Chu K., Chen J., Yu A.B., *Min. Eng.* (2016)

Modelling fluid-particle flow using DEM-CFD

Lagrangian discrete elements (**DEM**)

$$m_i \frac{d\boldsymbol{v}_i}{dt} = \sum_{j=1}^{Nc} \boldsymbol{f}_{c,ij} + \boldsymbol{f}_{d,i} + \boldsymbol{f}_{b,i} + \boldsymbol{f}_{g,i}$$

$$I_i \frac{d\omega_i}{dt} = \sum_{j=1}^{Nc} \boldsymbol{T}_{c,ij}$$

Hertz-Mindlin contact

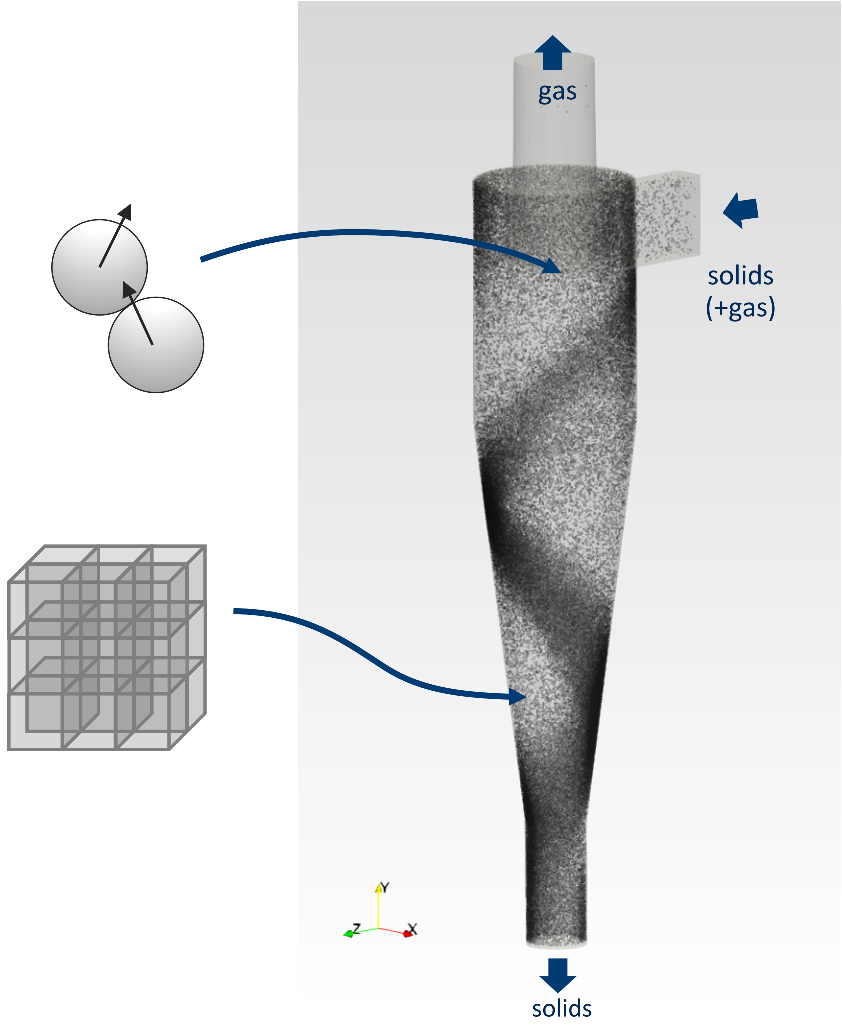
Di Felice drag model

Eulerian local-average Navier-Stokes (**CFD**)

$$\frac{\partial \varepsilon \rho_f}{\partial t} + \boldsymbol{\nabla} \cdot (\varepsilon \rho_f \boldsymbol{u}) = 0$$

$$\frac{D\varepsilon \rho_f \boldsymbol{u}}{Dt} = -\boldsymbol{\nabla} p + \boldsymbol{\nabla} \cdot \boldsymbol{\tau} + \boldsymbol{F}_{fp} + \varepsilon \rho_f \boldsymbol{g}$$

$$\boldsymbol{F}_{fp} = -\frac{1}{\Omega} \sum_i (\boldsymbol{f}_{d,i} + \boldsymbol{f}_{b,i})$$



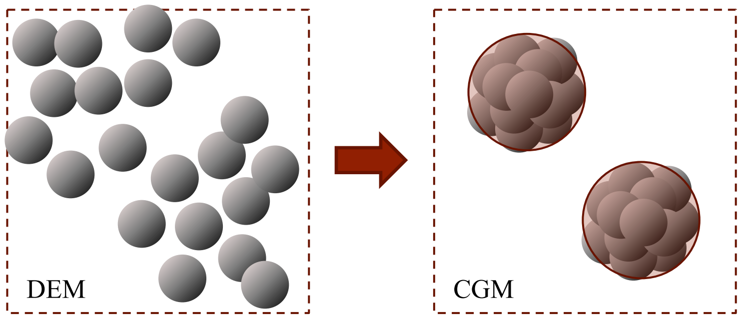
MFiX DEM + own implementations

v. 18.1.5
http://mfix.netl.doe.gov/mfix/

Coarse-grain methodology

- Principle of CG-DEM:
  DEM particles lumped into *f* times bigger, representative computational grains (*parcels*)
- Concept: still discrete entities with scaled, *equivalent* properties.
- Preservation of total gravitational and fluid-particle force, of translational and rotational kinetic energy before/after collisions, including dissipation.
- Original derivations (but many subsequent users)

Paper	Concepts	Application
Kuwagi et al. (2004)	"Similar particle assembly" (SPA)	Fixed and fluidized beds of free and cohesive particles
Sakai and Koshizuka (2009)	Coarse-graining based on energy preservation	Pneumatic conveying – linear contact model
Bierwisch et al. (2009)	Coarse-graining based on stress and energy preservation	Cohesive powder flow in cavity filling – Hertz with cohesion (JKR-like) model
Hilton and Cleary (2012)	Similar to SPA with rotation by Sakai	Bubbling fluidized beds



Particles in a CFD cell

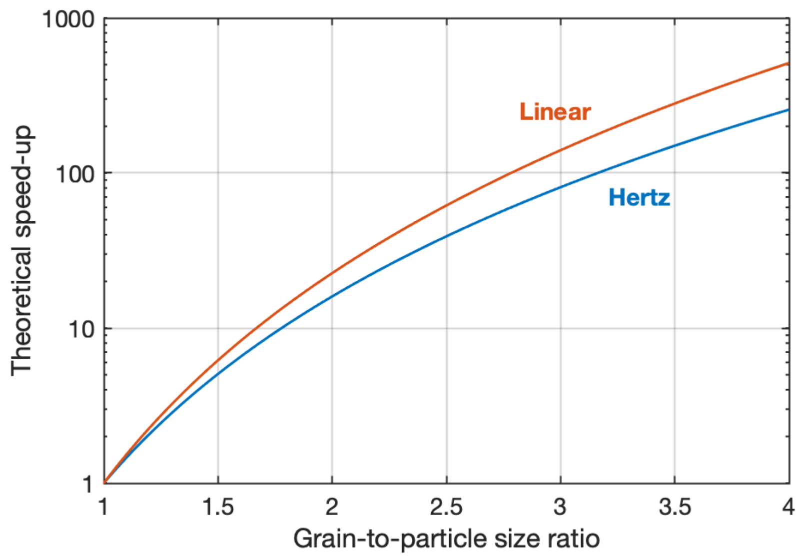
Grains (*parcels)* in the same cell

Kuwagi, Takeda & Horio, *Fluidization XI* (2004)
Sakai & Koshizuka *Chem. Eng. Sci.* (2009)
Bierwisch et al. *J. Mech. Phys. Sol.* (2009)
Hilton & Cleary, *9th Int. Conf. CFD in Min. Proc. Ind.* (2012)

Modelling using *coarse-grain* DEM-CFD

Advantages

- Highly reduced computational cost
  - The total number of particles depends on the cubic power of the grain-to-particle size ratio
  - Also, the contact time (limiting the integration time step) scales positively
  - Reported overall speed-up of $O\left(\frac{d_G}{d_P}^{4.5}\right)$ for the linear contact model and $O\left(\frac{d_G}{d_P}^{4}\right)$ for Hertz-based model.



- Still detailed results

Disadvantages

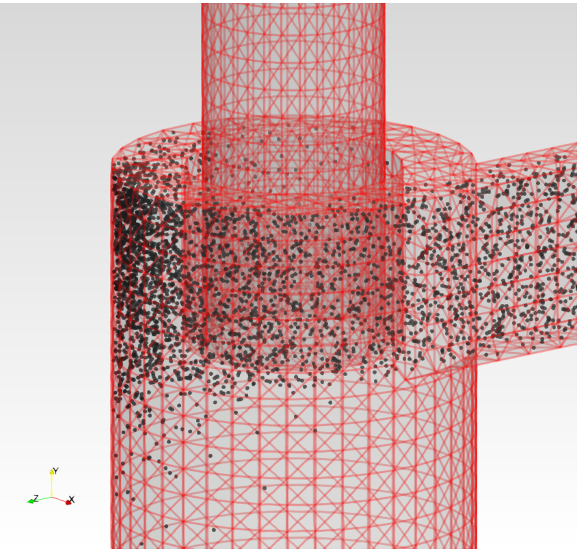
- Loss of fidelity (<u>to be quantified</u>)
- Need for sub-grain corrections?

Modelling cyclones flow using DEM-CFD

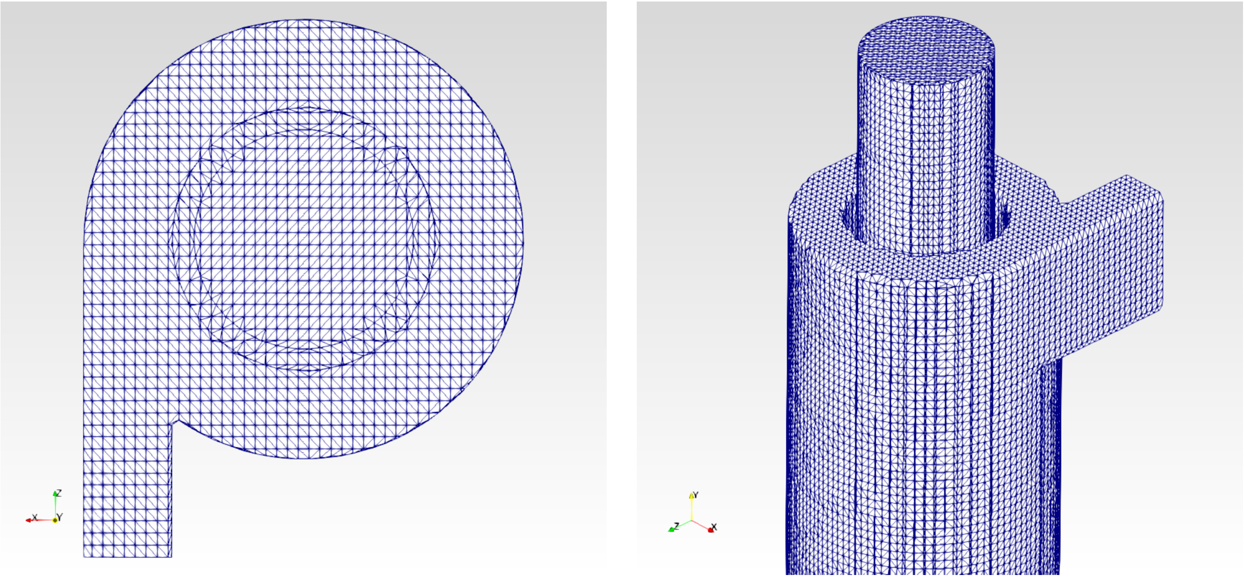
Fluid flow limited by grid resolution:

Compressible, *no turbulence* (but *gas-particle interaction accounts for high-Re flows*)

Complex geometry:



Particle contacts with triangulated surface (STL)

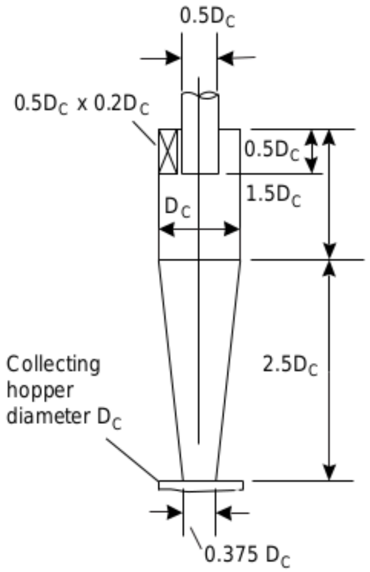


Cartesian cut-cell technique (113k cells) for the gas phase flow

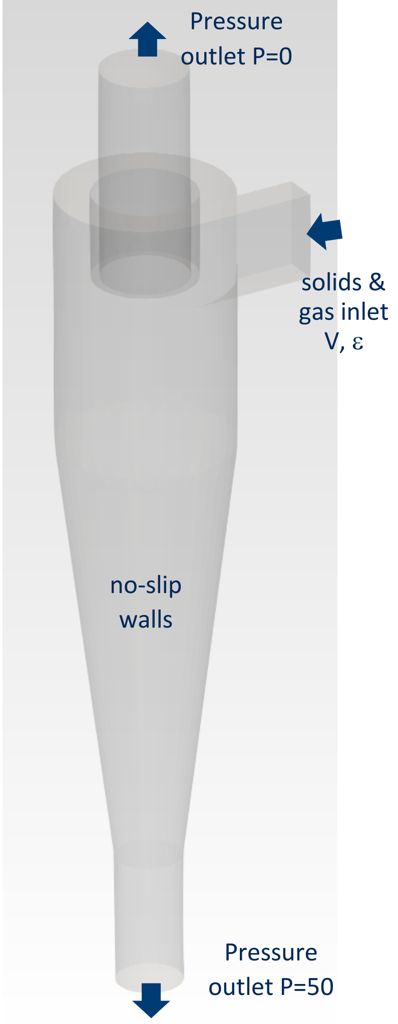
Testing the *coarse-grain* DEM-CFD on cyclone

Simulated lab-scale tangential (Stairmand HE) design

Cyclone type/size	Stairmand high efficiency/ D_{barrel}=90 mm			
Tangential inlet (width × heigth)	18 × 45 mm (0.2D x 0.5D)			
Grid size (diameter × height)	2.5 × 3 mm			
Particle properties	$D = 500$ μm, $\rho = 2500$ kg m^{-3}			
Contact model	Hertz, $E = 5{\cdot}10^7$ Pa, $e_n = 0.9$			
Solids loading (%vol)	0.1%, 0.2%, 0.5%, 1%			
Inlet velocities	10, 14, 20 m/s			
Particle or grain size, d [μm]	500	1000	1500	2000
Particles per grain, NPG [-]	**1 (DEM)**	**8**	**27**	**64**
Grain-to-particle size ratio	**1**	**2**	**3**	**4**
Holdup in number of grains, [-]	**136k–717k**	**11k–94k**	**6k–25k**	**2.8k–10.6k**
Solid-phase time-step, Δt_s [10^{-6} s]	**0.6**	**1.9**	**3.1**	**4.1**
Fluid-phase (typical) time-step	$5{\cdot}10^{-4}$ s			



Cyclone design

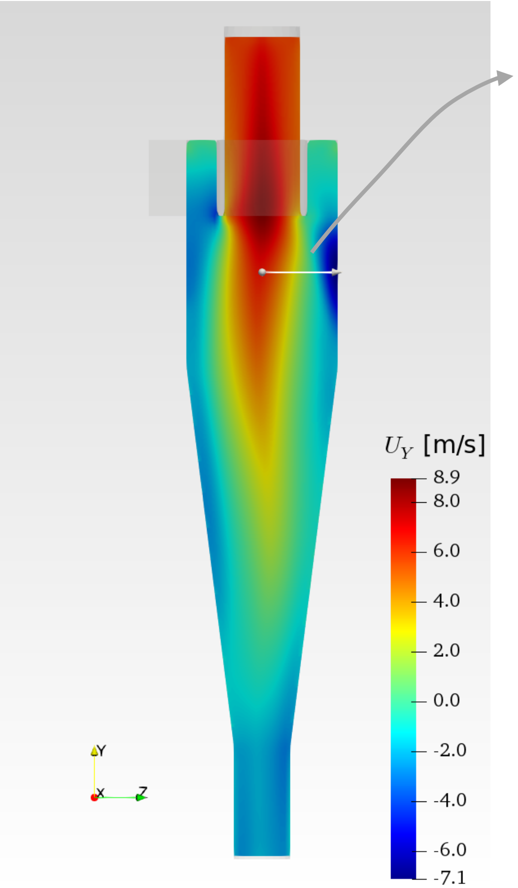


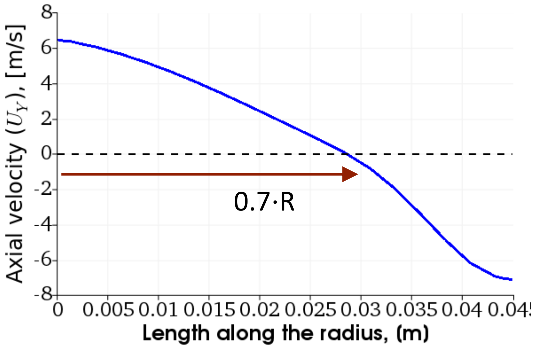
Boundary conditions

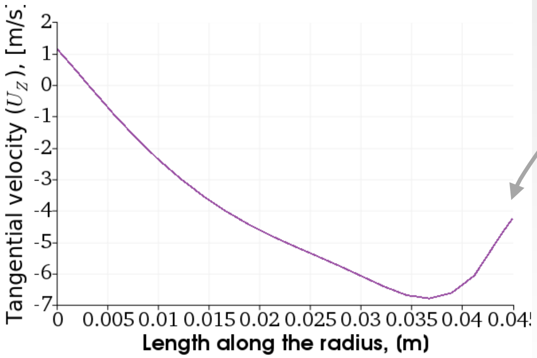
CFD of single-phase fluid flow inside the cyclone

Flow properties at $u_{inlet} = 14$ m/s

Axial velocity

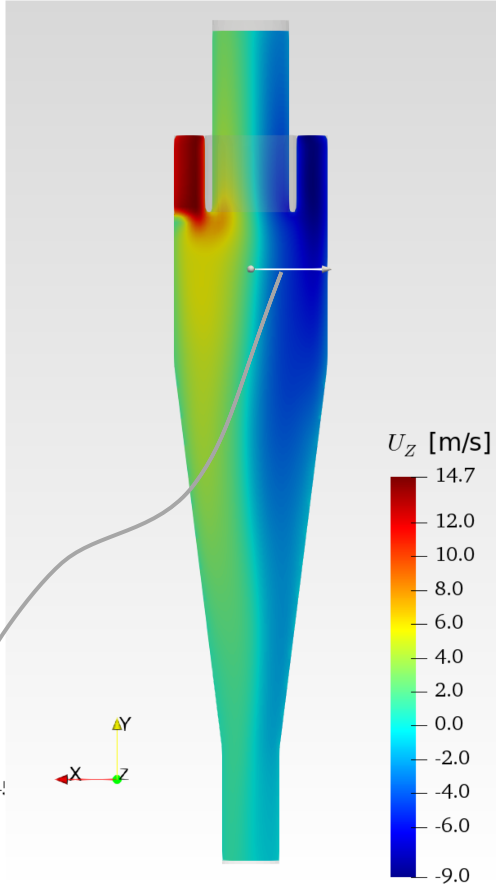


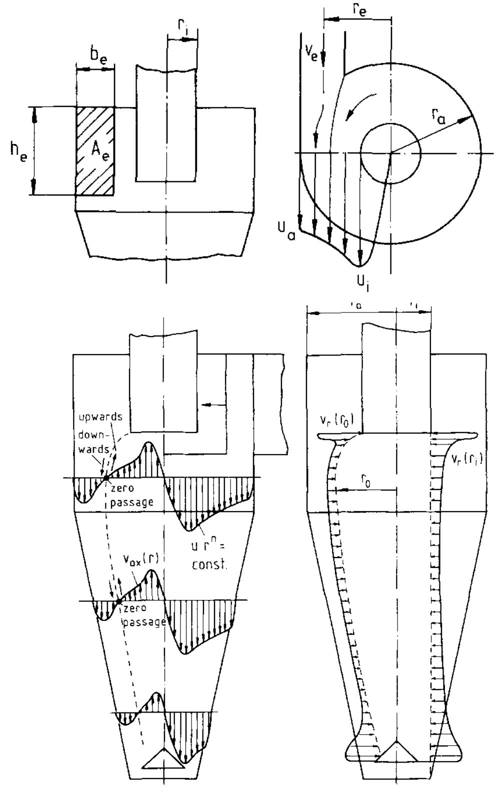




No $U_Z r^n = c$!

Tangential velocity



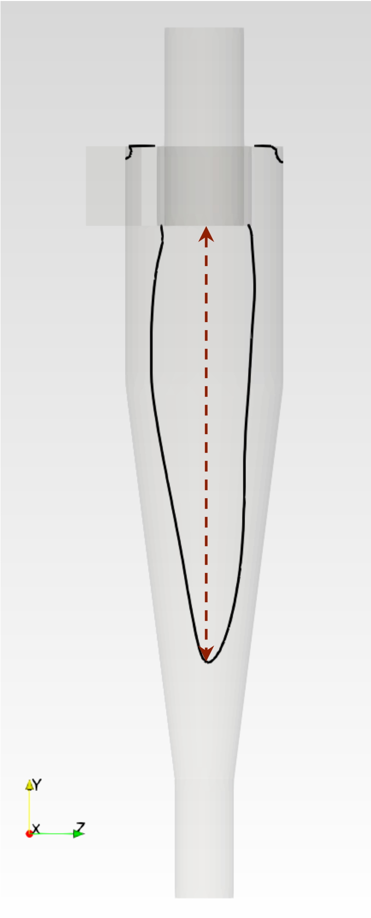


Cyclone theory

Trefz & Muschelknautz, *CET*, 1993

Analysis of the physical features of the flow

Vortex shape and length

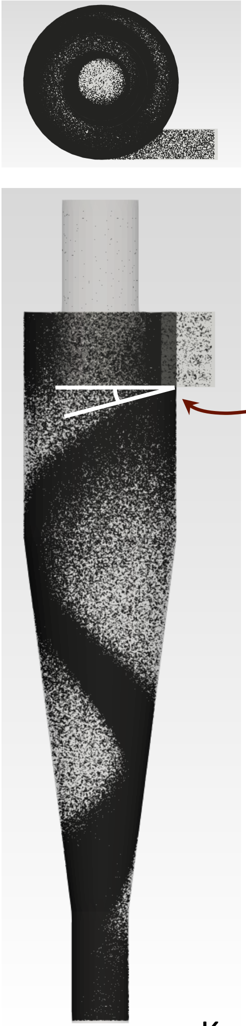


Gas-solid flow

DEM (NPG = 1)

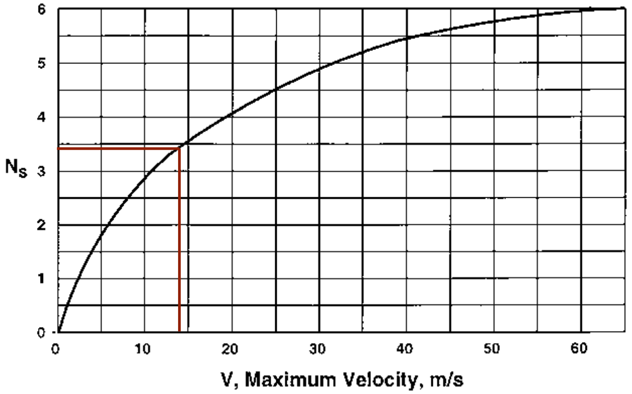
$\varepsilon_s = 0.5\%$

$u_{in} = 14 \text{ m/s}$



Strand formation at ~15°

Number of turns

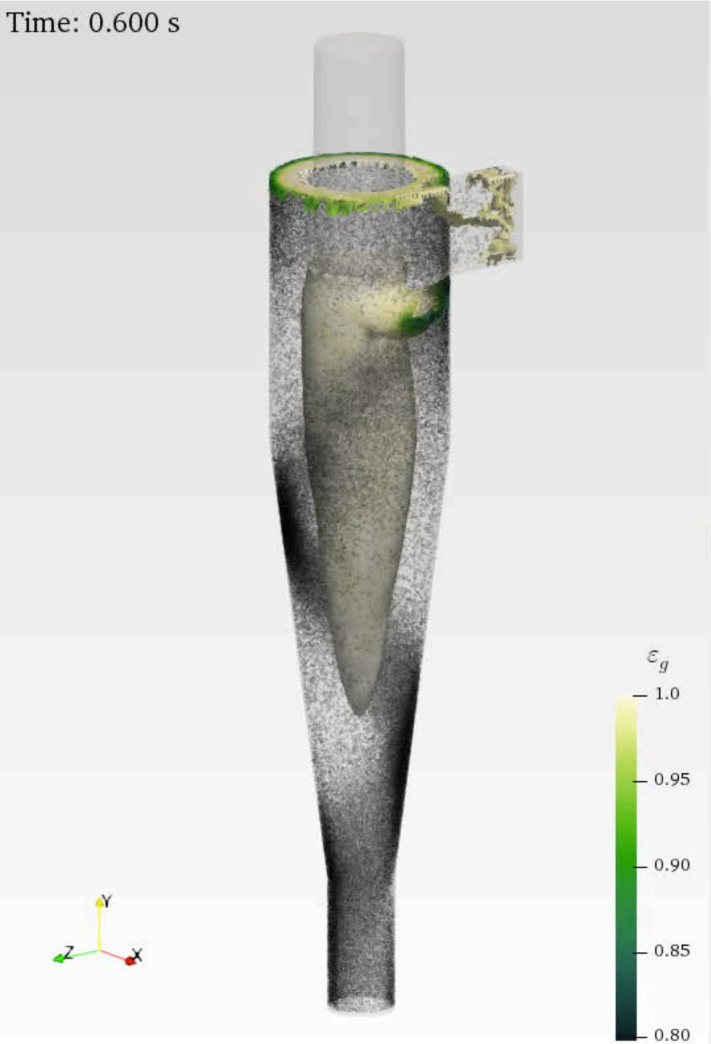


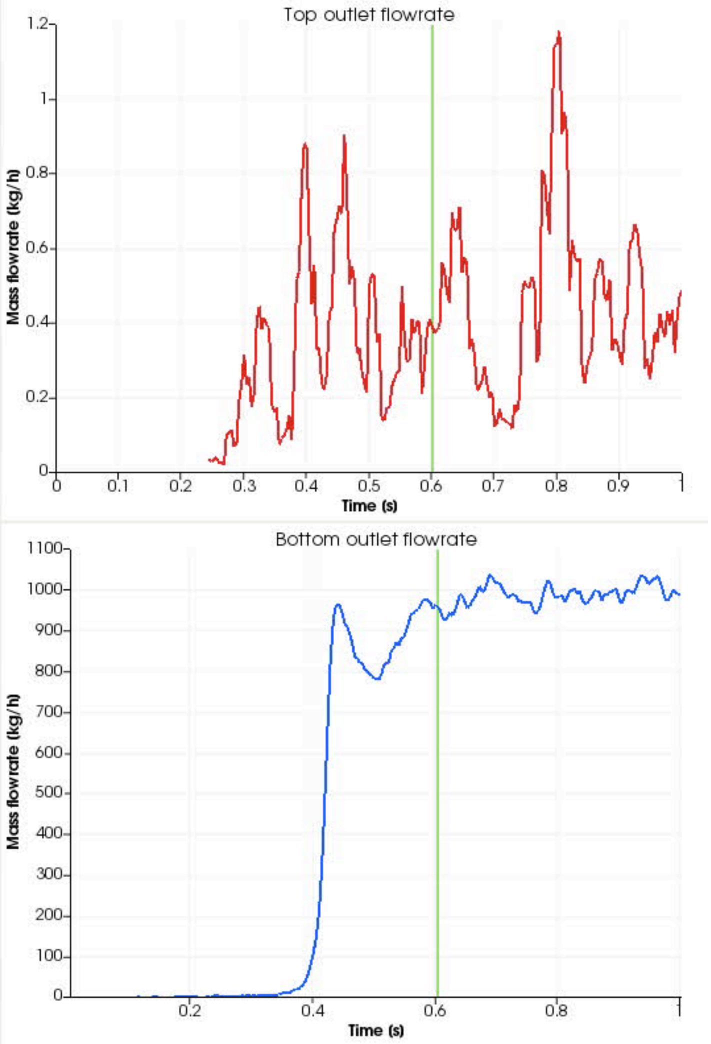
Knowlton, Chap. 22, *Handbook Fl. & F-P systems* (2003)

Two-phase flow dynamics

In the simulations, fluid and particle motions are tracked, with special attention to solids separation

DEM (NPG = 1)
$\varepsilon_s = 1\%$
$u_{in} = 14\ \mathrm{m/s}$



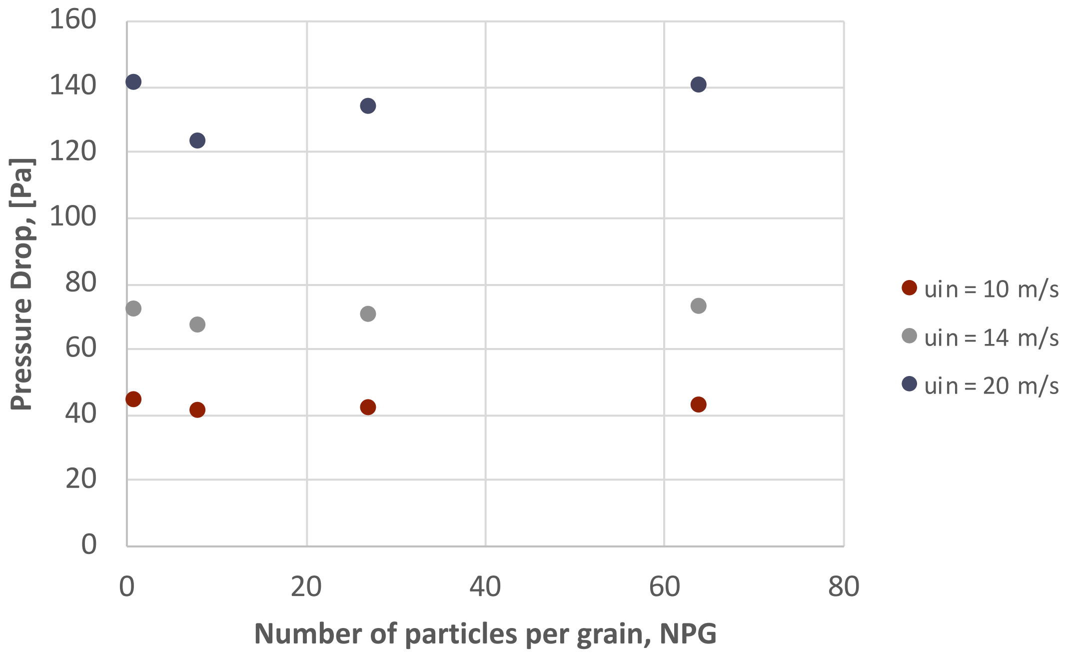


Starting from approximately 0.6 s the cyclone operates steadily

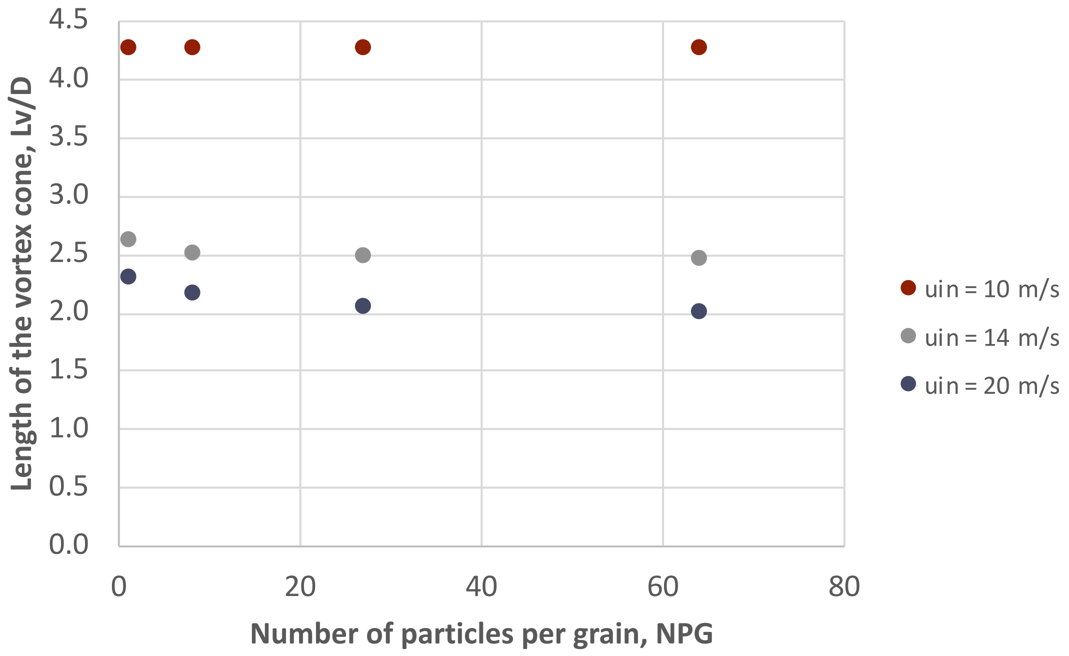
Effect of the coarse graining degree: macro-scale

Loading $\varepsilon_s = 0.5\%$

Pressure drop



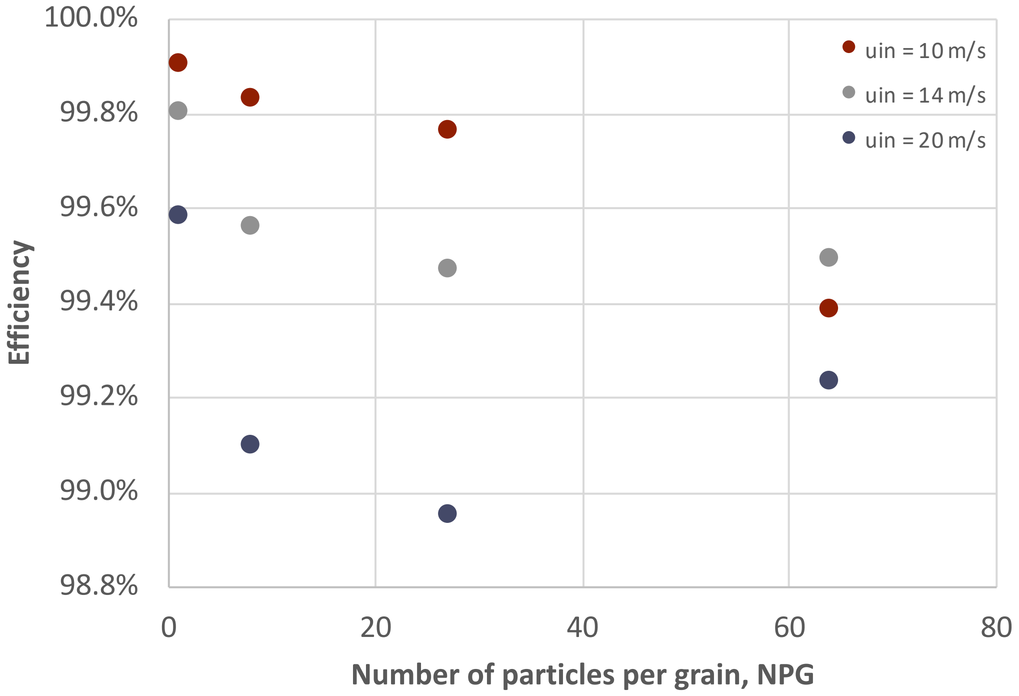
Vortex length



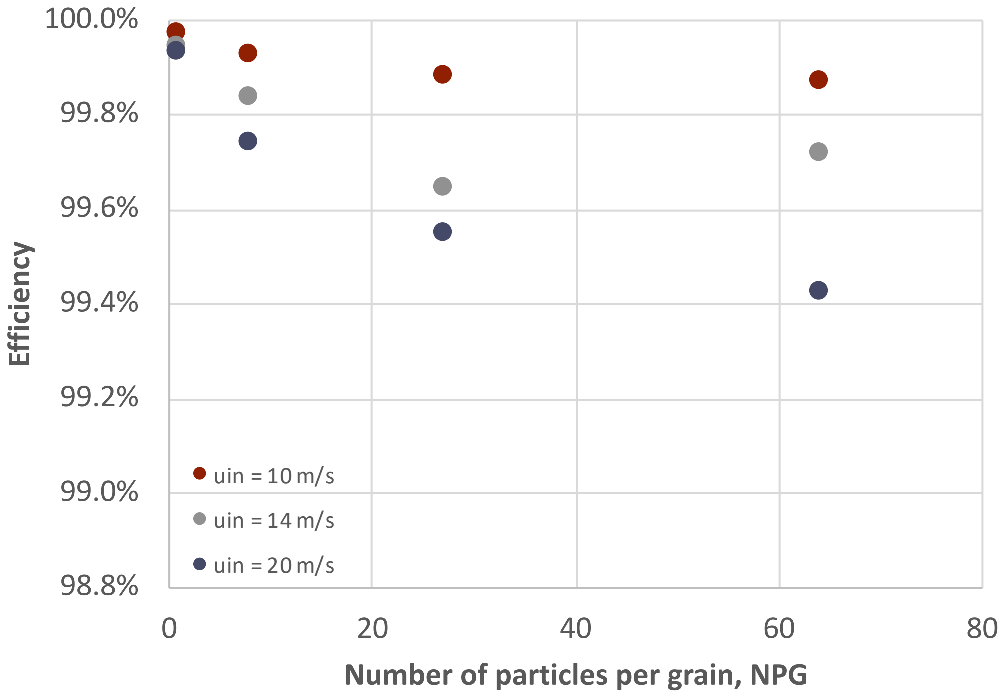
Effect of the coarse graining degree: macro-scale

Overall separation efficiency

Loading $\varepsilon_s = 0.2\%$



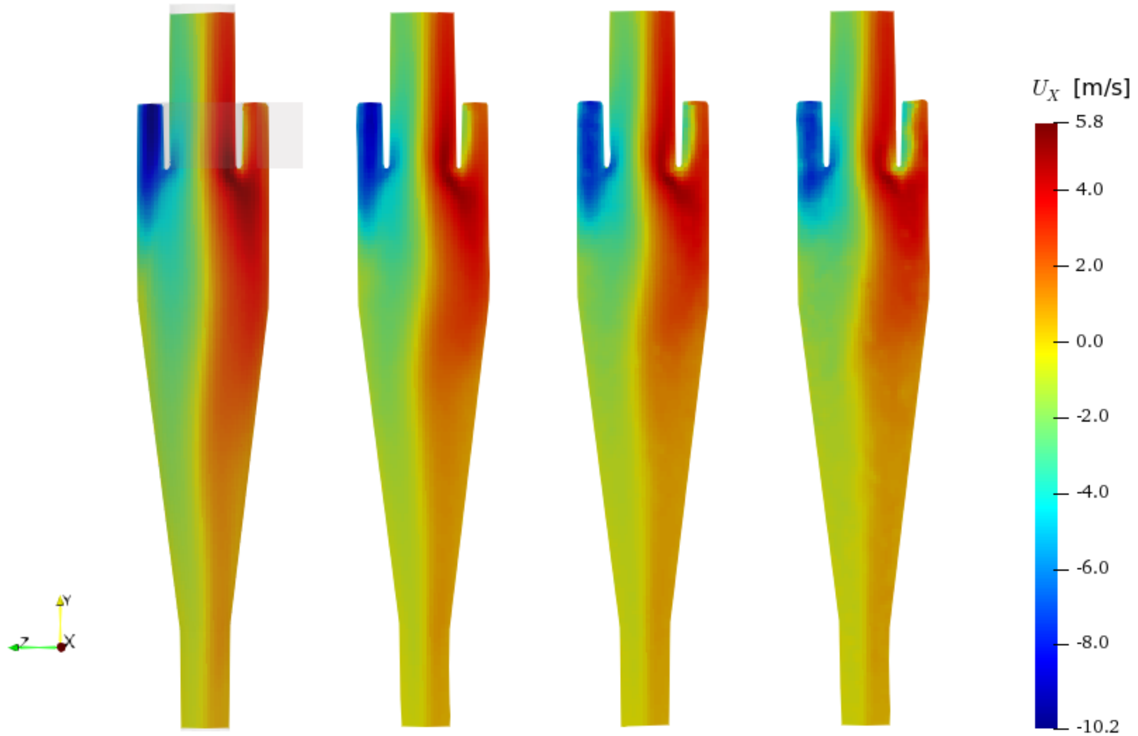
Loading $\varepsilon_s = 0.5\%$



Effect of the coarse graining degree: gas flow

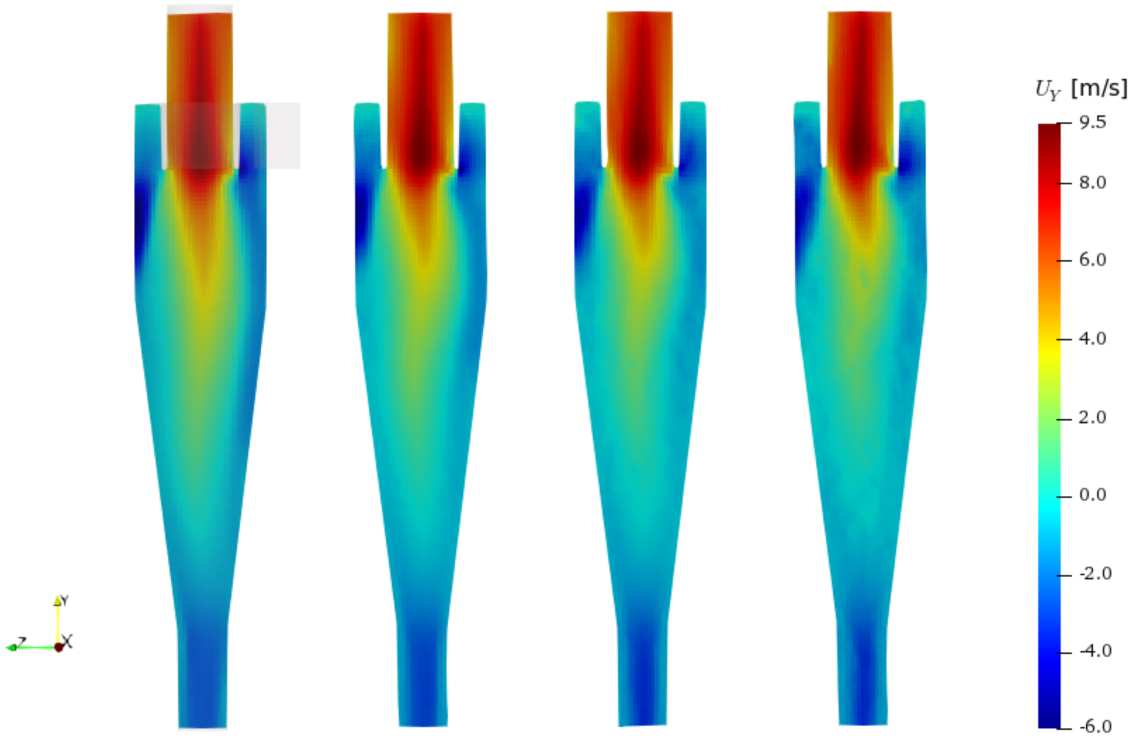
$\varepsilon_s = 0.5\%,\ U_{in} = 14\ \mathrm{m/s}$

Tangential velocity



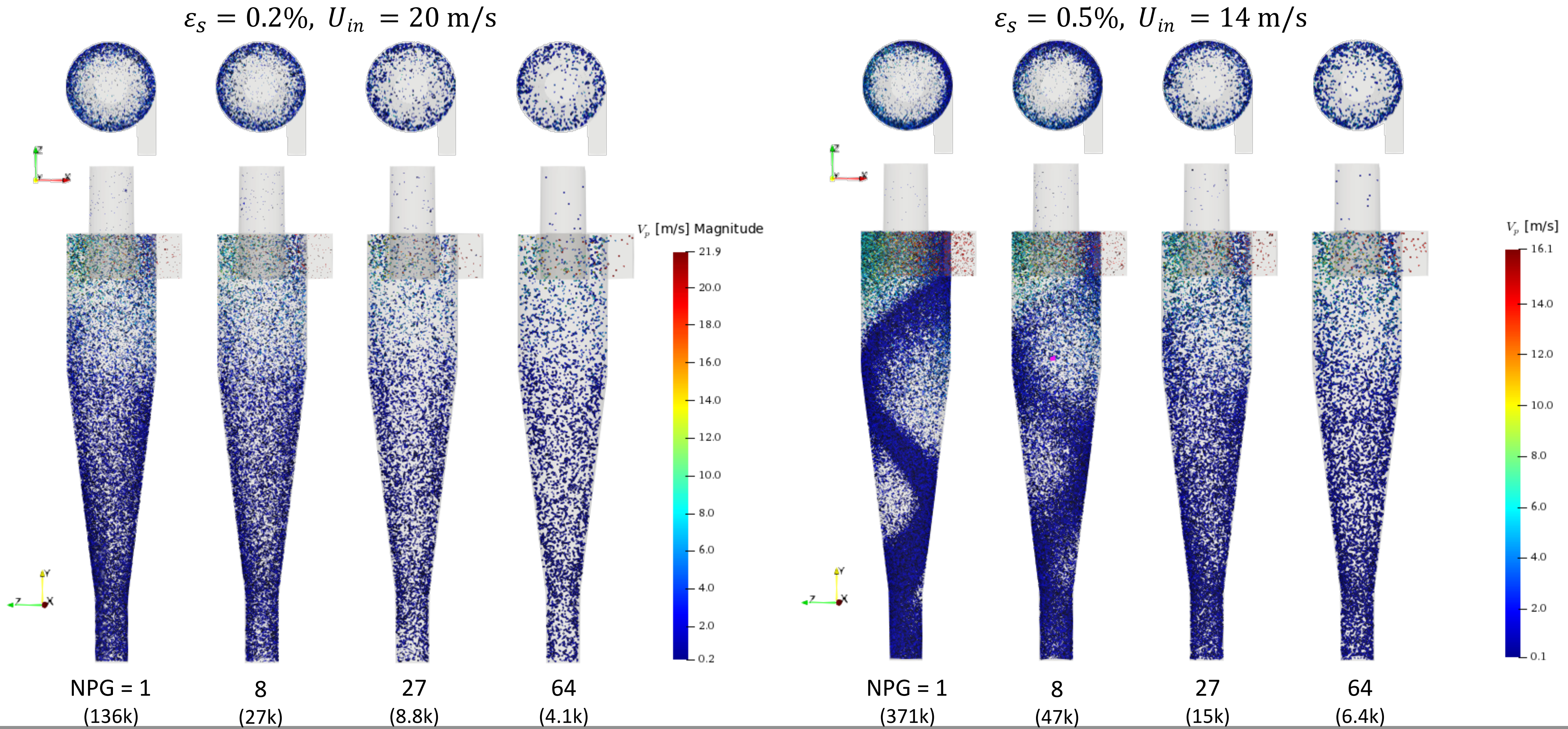
NPG = 1 | 8 | 27 | 64

Axial velocity



NPG = 1 | 8 | 27 | 64

Effect of the coarse graining degree: solids flow



Expected possible applications

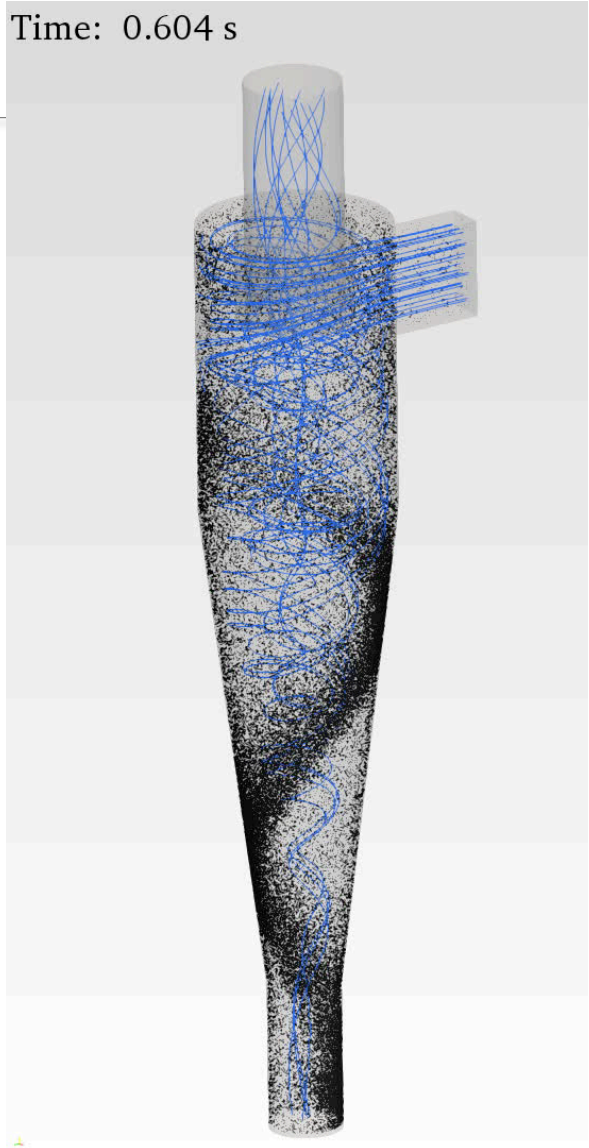
Running test on 9-cm dia. cyclone flow of 125 μm diameter particles with CG factor $f = 4$ $(NPG = 64)$.

$\varepsilon_s = 0.1\%$

$u_{in} = 14\ \mathrm{m/s}$

Steady-state solids holdup of 78600 grains corresponding to >5M particles.

Simulation time was 9 h / simulated s on 32 cores of our cluster.



Conclusions

- Cyclones on the large scale or treating very fine particles is prohibitive for reasonable DEM-CFD simulations due to the number of particles and the small time-step.
- Coarse graining DEM particles provides speedup with the grain-to-particle size ratio to the **power of 4 or 4.5**, thereby appearing highly attractive.
- Our simulations showed that the physics into the coarse graining method (scaling parameters) is sufficient to guarantee preservation of macroscopic variables – compared to pure DEM – up to CG factor $f = 3$ (NPG=27). However, in one case the solids flow field appeared deeply modified (no strands) already at $f = 3$, denoting profound differences in the microdynamics of the particles/grains.
- Overall: in DEM-CFD models of cyclones there is a huge potential in CPU-time savings but reasonable accuracy is obtained below $f = 3$, further development and testing at $f = 3$ and beyond is required.

Perspectives

Most important challenges and open problems in CG:

- Fully characterize grain-grain collision and grain-wall collisions
- Develop and test CG parameter rules for rolling friction
- Further test the coarse graining degree to identify limits of applicability and assess how well quantities of interest are preserved
- Develop and test a reliable CG method for polydisperse solids, possibly with reaction and heat/mass transfer