

Do we need subgrid drag models for continuum and discrete simulations?

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Collaborations

- Research was conducted in collaboration with two groups:
 - Filtered drag models: Y. Igci and S. Sundaresan¹ (Princeton University)
 - EMMS drag model: W. Wang and J. Li² (Institute of Process Engineering, Chinese Academy of Sciences)

¹ Igci, Y.; Andrews, A.T.; Sundaresan, S.; Pannala, S.; O'Brien, T. *AIChE J.* 2008; 54; 1431-1448.

² Lu, B.; Wang, W.; Li, J. *Chem. Eng. Sci.* 2009; 64; 3437-3447.



Goals, Objectives, and Challenges

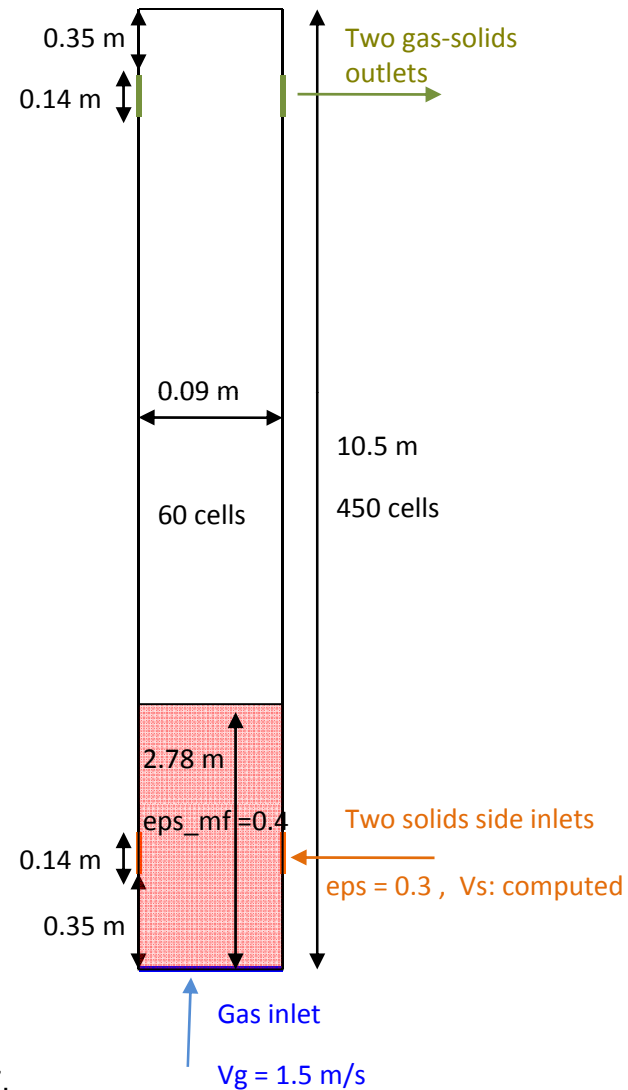
- Conduct fast and accurate gas-solids flow simulations using coarse grids.
- Implement EMMS and filtered drag models in MFIX
- Conduct comparative study of these drag models with experimental data³
- **Challenges:**
 - Subgrid models are still being developed
 - Lack extensive validation
 - Consideration of other effects (e.g. polydispersity, particle-wall interaction)



³ Benyahia, S. On the effect of subgrid drag closures. *Ind. Eng. Chem. Res.* DOI: 10.1021/ie900658k

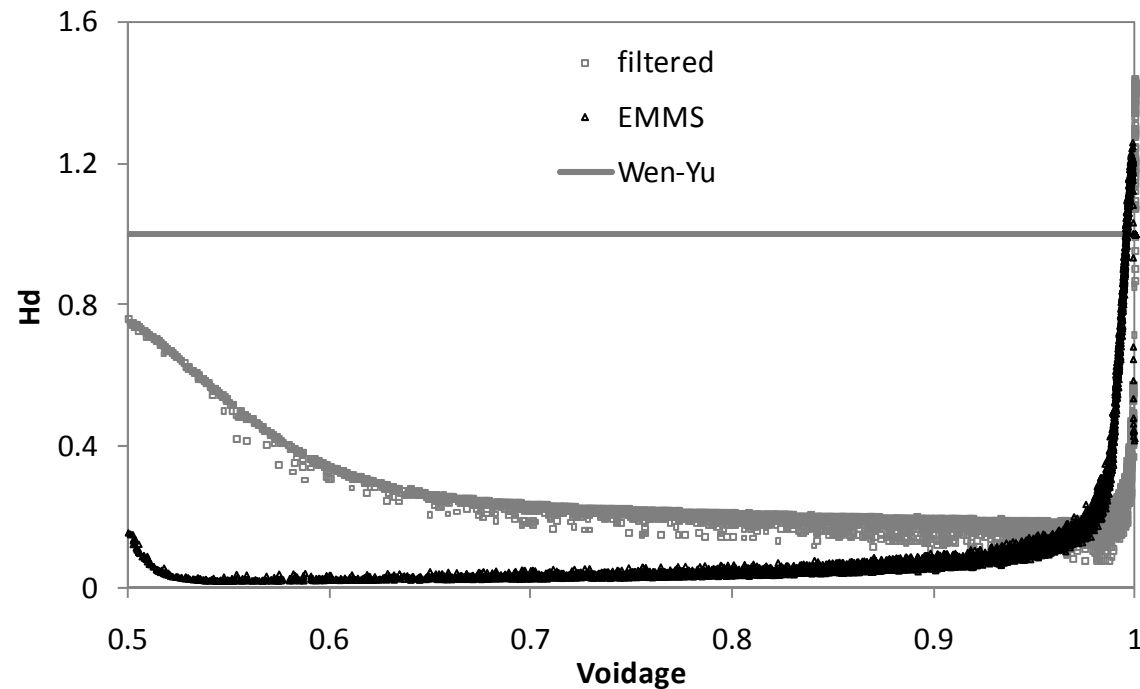
Simulation Conditions²

Process temperature	297 K
Process pressure	1.01×10^5 Pa
Air density	~ 1.2 kg/m ³
Air viscosity	1.8×10^{-5} Pa·s
Gas-phase turbulence length-scale	0.01 m
Solids density	930 kg/m ³
Particle diameter	54 micron
Single-particle terminal velocity	0.074 m/s
Particle-particle restitution coefficient	0.9
Particle-wall restitution coefficient	0.7
Specularity coefficient	0.0001
Particle-particle angle of internal friction	$\pi/6$
Particle-wall angle of friction	$\pi/16$
Void fraction at maximum packing	0.4
Void fraction at minimum fluidization	0.6

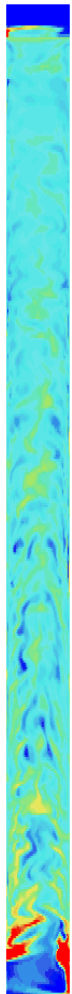


² Lu, B.; Wang, W.; Li, J. *Chem. Eng. Sci.* 2009; 64; 3437-3447.

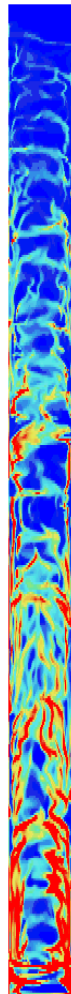
Instantaneous values of friction coefficient



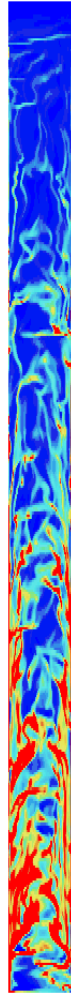
Void fraction contour profiles



Wen-Yu drag



Filtered drag



EMMS drag

Instantaneous



Wen-Yu drag



Filtered drag

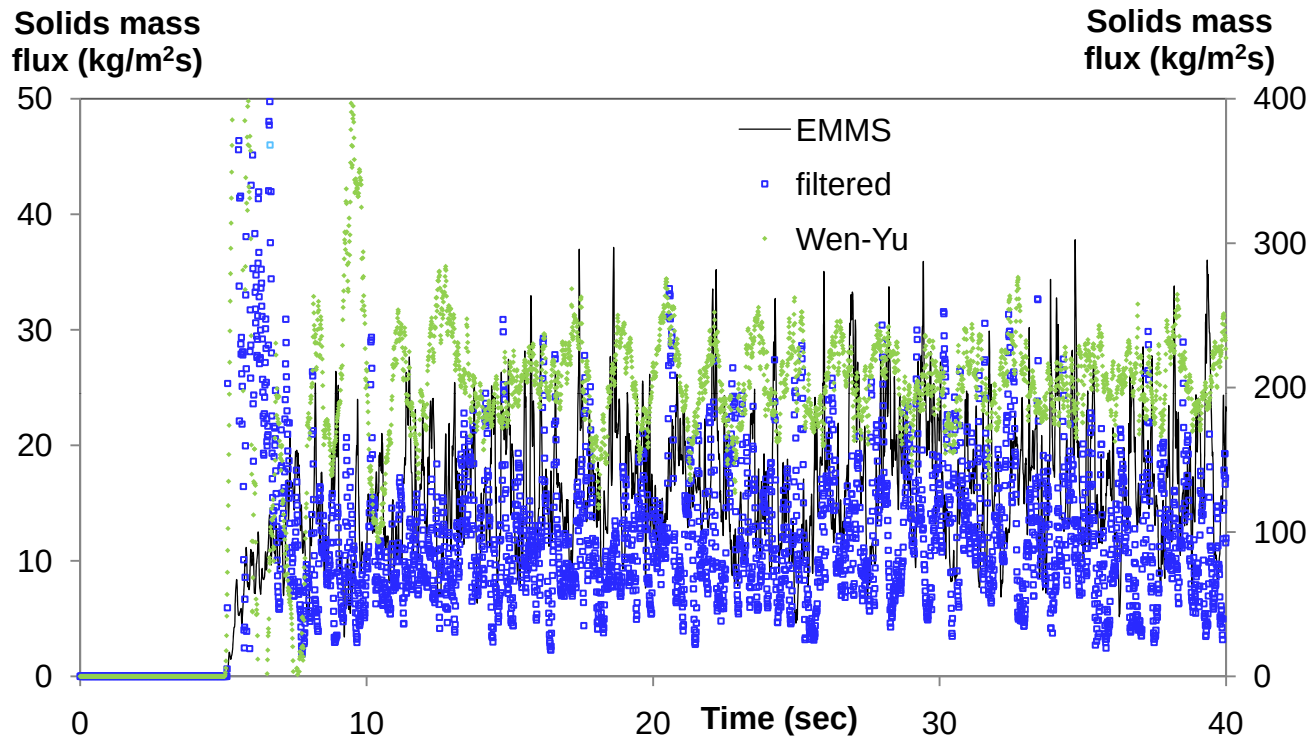


EMMS drag

Time-averaged



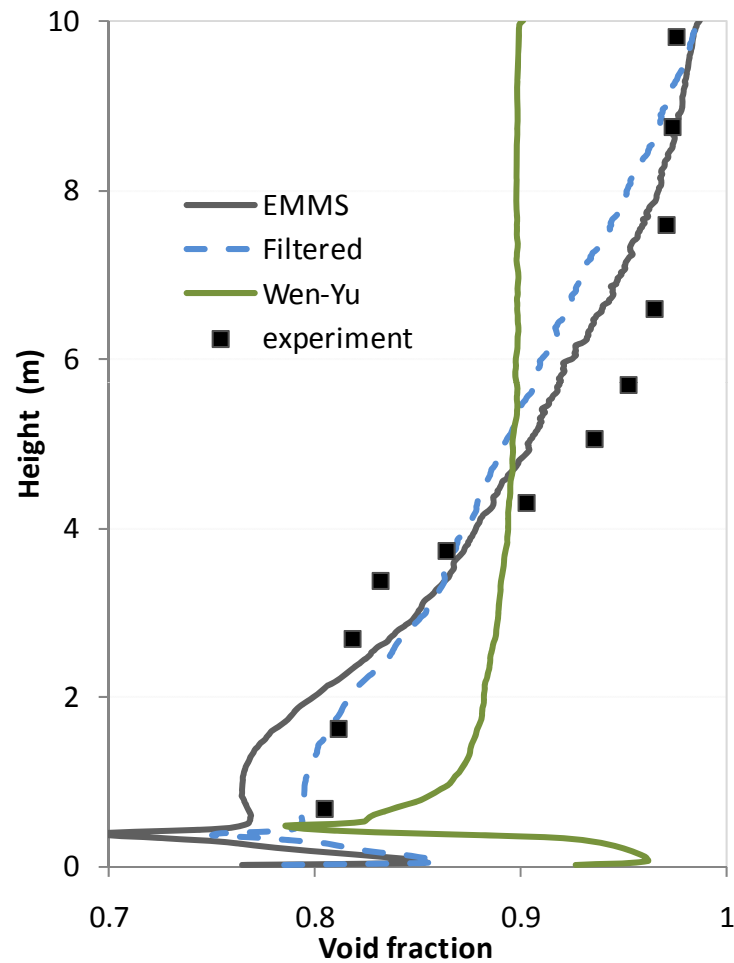
Solids mass flux through outlets



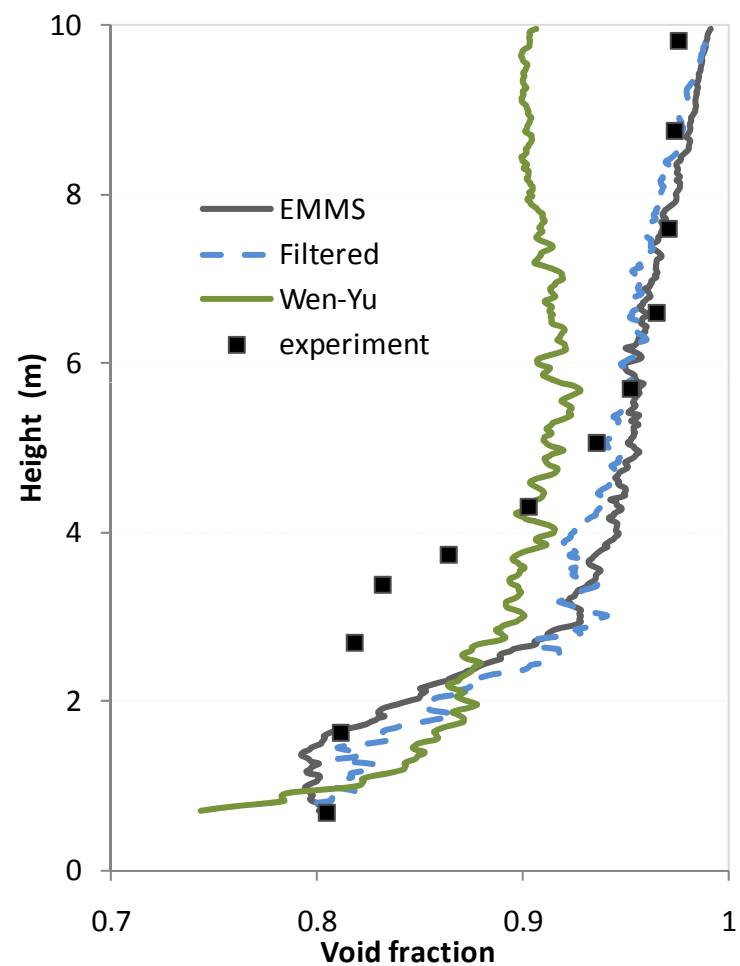
Drag model	Wen-Yu	Filtered	EMMS	Experimental
Solids mass flux (kg/m ² s)	205	12.3	16.9	14.3
Standard deviation (kg/m ² s)	25.2	5.64	5.59	-



Vertical void fraction profiles



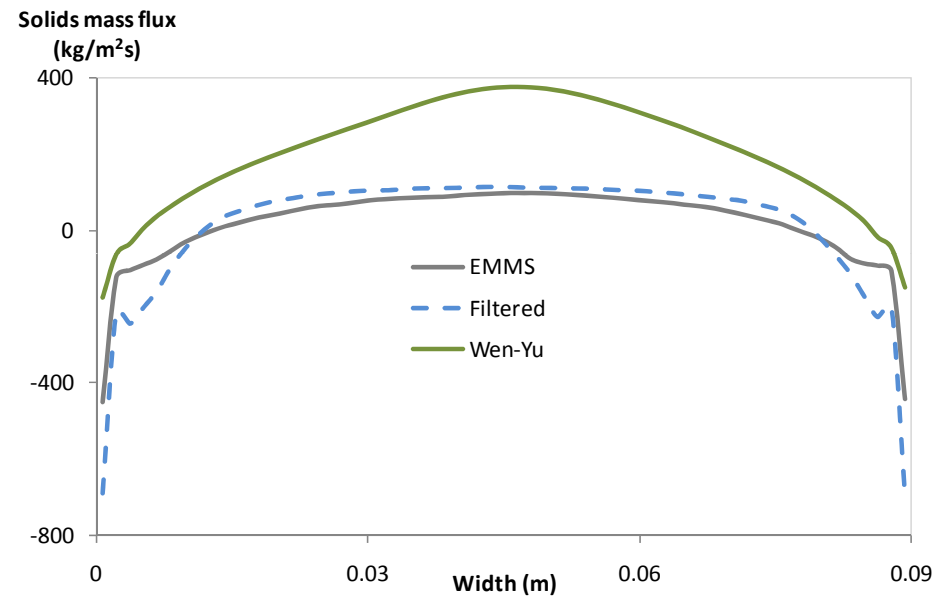
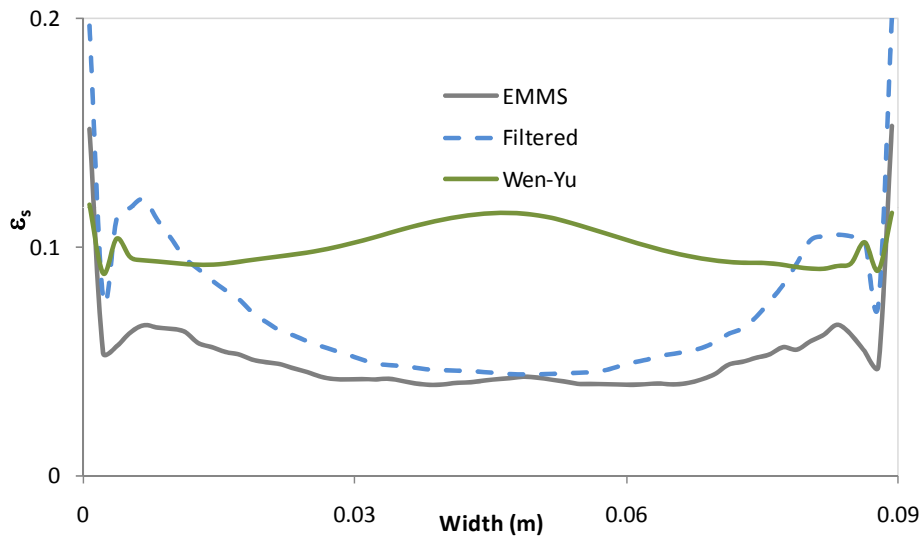
Numerical data based on
computed void fraction



Numerical data based on
computed pressure gradient

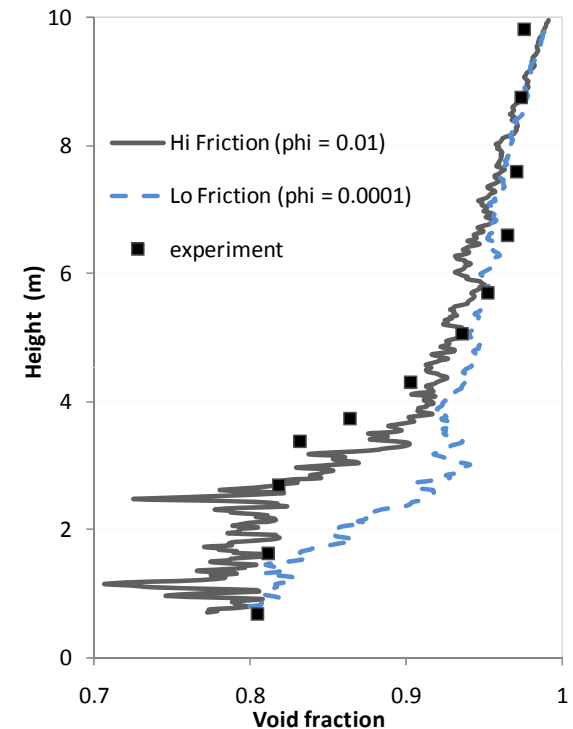


Horizontal profiles at 7 m above inlet



Future work

- Why is the pressure gradient under-predicted at the bottom section of riser?
 - Increase particle-wall friction in Johnson-Jackson BC
 - Effect of polydispersity is currently investigated by considering three particle sizes of 30, 60, and 120 microns



Are subgrid models needed for discrete particle simulations?

- There is no reason why not if fluid flow is not properly resolved (coarse grids)
- The same approach³ used for continuum models can be applied for discrete models, i.e. does the slip velocity increase from that of homogeneous state as Eulerian grid is refined?



³ Agrawal et al. The role of meso-scale structures in rapid gas-solids flows. *J. Fluid Mech.* 445 (2001) 151.

MP-PIC and continuum models

$$\frac{\partial(\rho_g \varepsilon_g)}{\partial t} + \nabla \cdot (\rho_g \varepsilon_g \vec{V}_g) = 0$$

$$\left[\frac{\partial(\rho_g \varepsilon_g \vec{V}_g)}{\partial t} + \nabla \cdot (\rho_g \varepsilon_g \vec{V}_g \vec{V}_g) \right] = -\varepsilon_g \nabla P_g + \nabla \cdot \vec{\tau} - \sum_{p=1}^{N_T} \beta_p \frac{\phi_p}{\phi_c} (\vec{V}_g(\vec{x}_p) - \vec{V}_p) + \varepsilon_g \rho_g \vec{g}$$

Continuum gas-phase
conservation equations

$$\left[\frac{\partial(\rho_s \varepsilon_s \vec{V}_s)}{\partial t} + \nabla \cdot (\rho_s \varepsilon_s \vec{V}_s \vec{V}_s) \right] = -\varepsilon_s \nabla P_g - \nabla P_s + \varepsilon_s \beta_p (\vec{V}_g - \vec{V}_s) + \varepsilon_s \rho_s \vec{g}$$

Continuum solids-phase
momentum equation

$$\frac{d\vec{V}_p}{dt} = \vec{g} - \frac{\nabla P_g}{\rho_p} + \frac{\beta_p}{\rho_p} (\vec{V}_g(\vec{x}_p) - \vec{V}_p) - \frac{\nabla P_s}{\rho_p \varepsilon_s}$$

Newton's law of motion for
discrete particles

$$\beta_p = \frac{3}{4} C_D \frac{\rho_g \varepsilon_g |\vec{V}_g(\vec{x}_p) - \vec{V}_p|}{d_{pt}} \varepsilon_g^{-2.65}$$

$$P_s = \begin{cases} P^* \frac{\varepsilon_s^\beta}{\varepsilon_s^{\max} - \varepsilon_s} & \varepsilon_s < \varepsilon_s^{\max} \\ P_s^{old} & \varepsilon_s \geq \varepsilon_s^{\max} \end{cases}$$

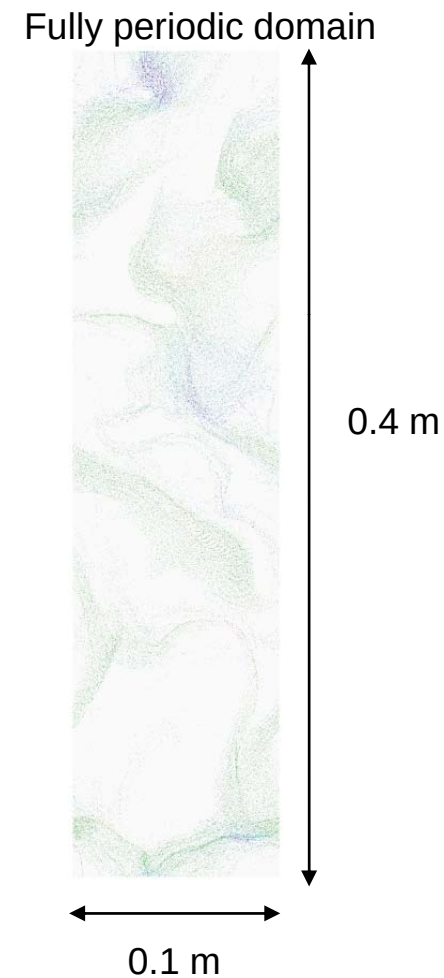
$$\varepsilon_s < \varepsilon_s^{\max}$$

$$\varepsilon_s \geq \varepsilon_s^{\max}$$

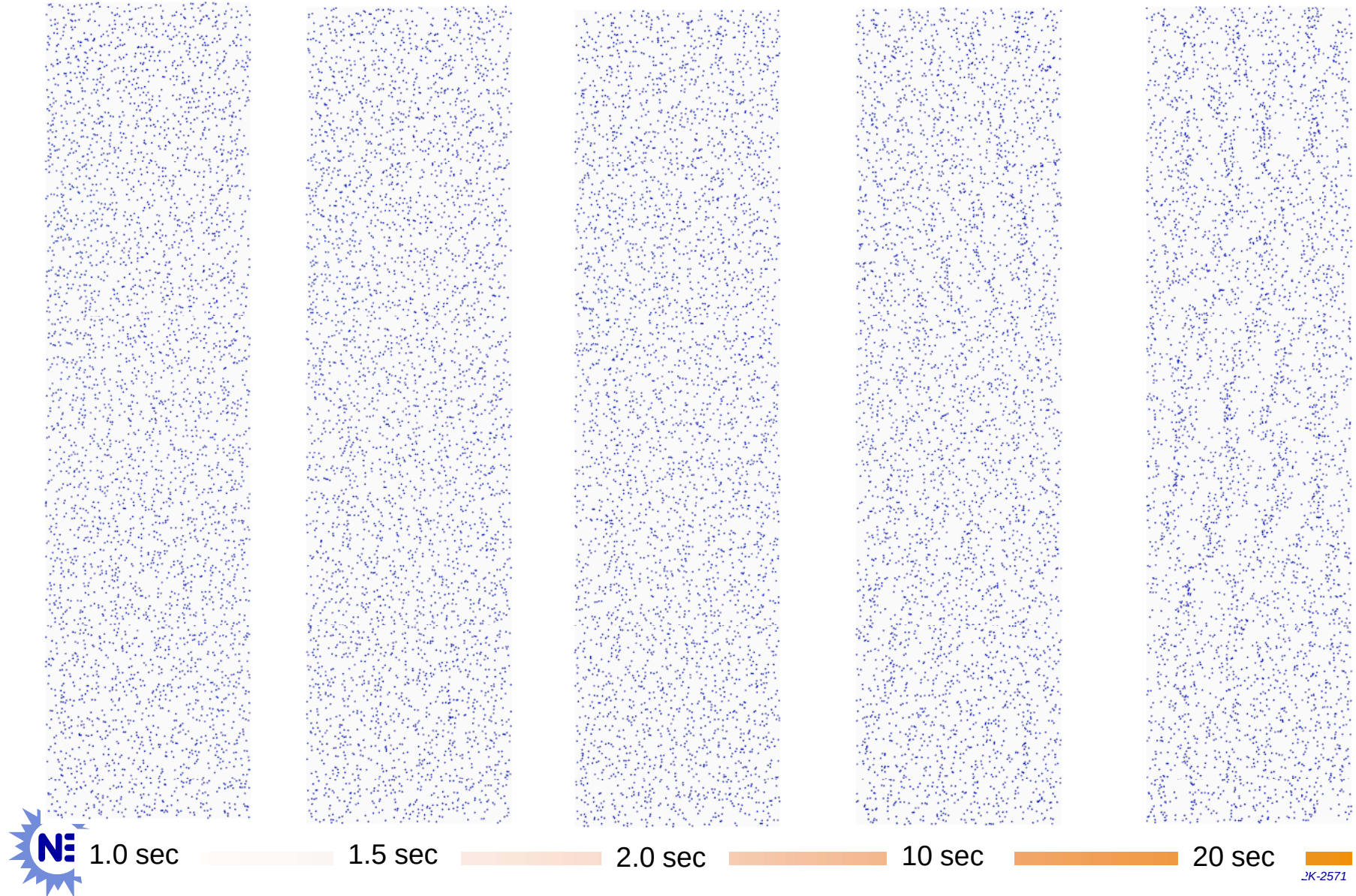


Simulation conditions

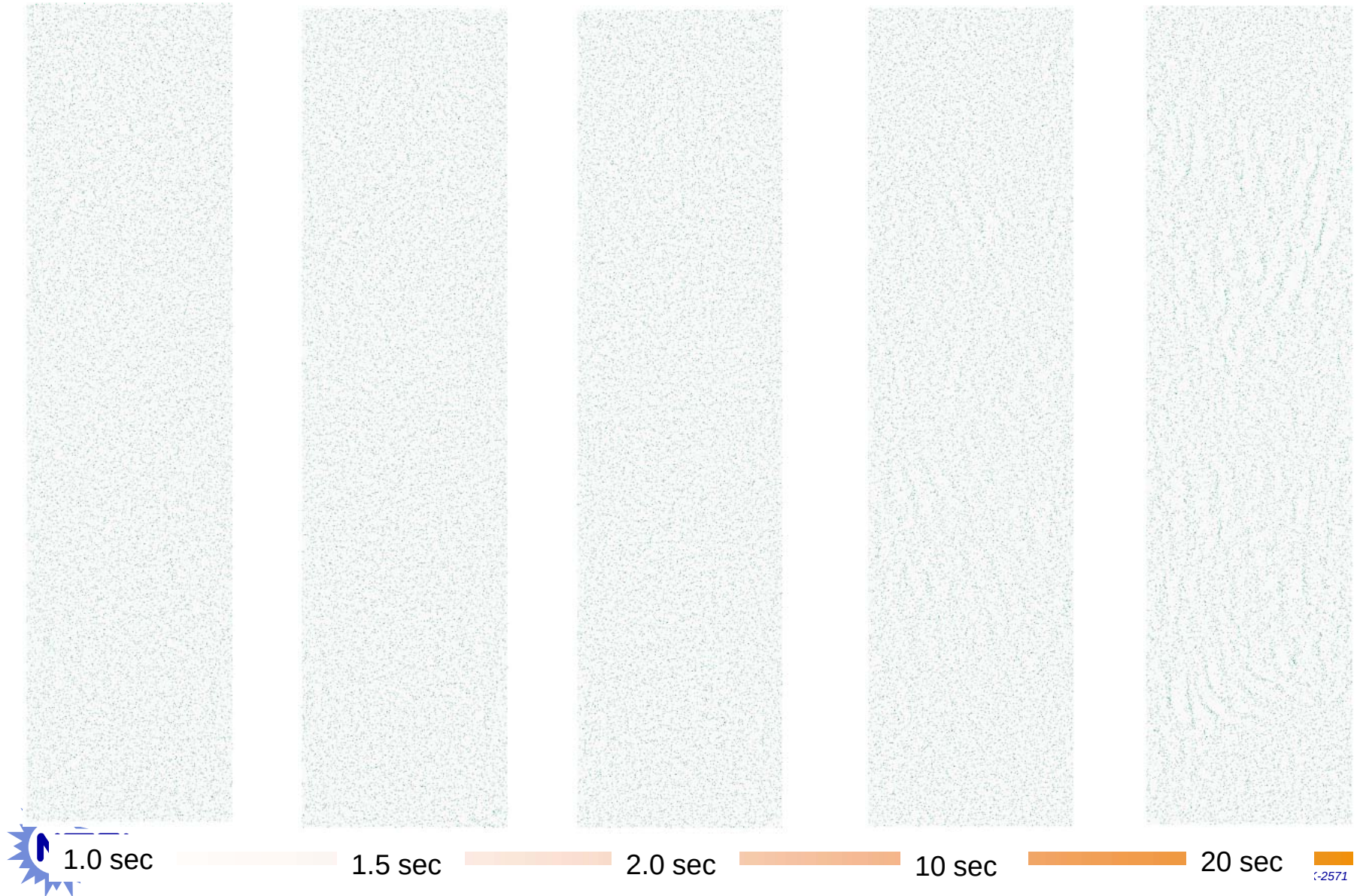
Air density	1.3 kg/m ³
Air viscosity	1.8 x 10 ⁻⁵ Pa·s
Solids density	1500 kg/m ³
Particle diameter	75 micron
Void fraction at maximum packing	0.4
Eulerian grid density	8x32, 16x64, 32x128, 64x256



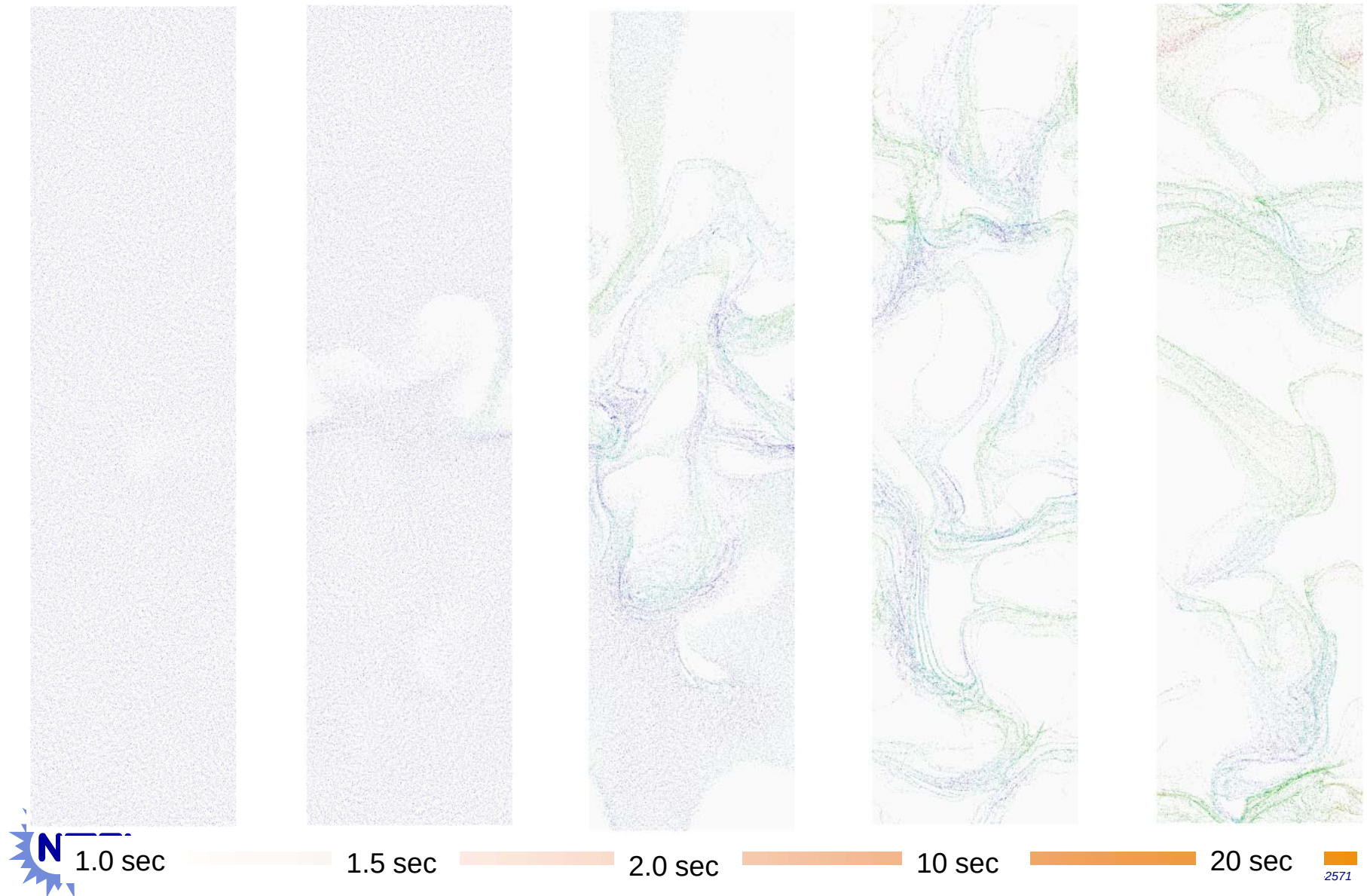
Snapshots of particle position-velocity (8x32)



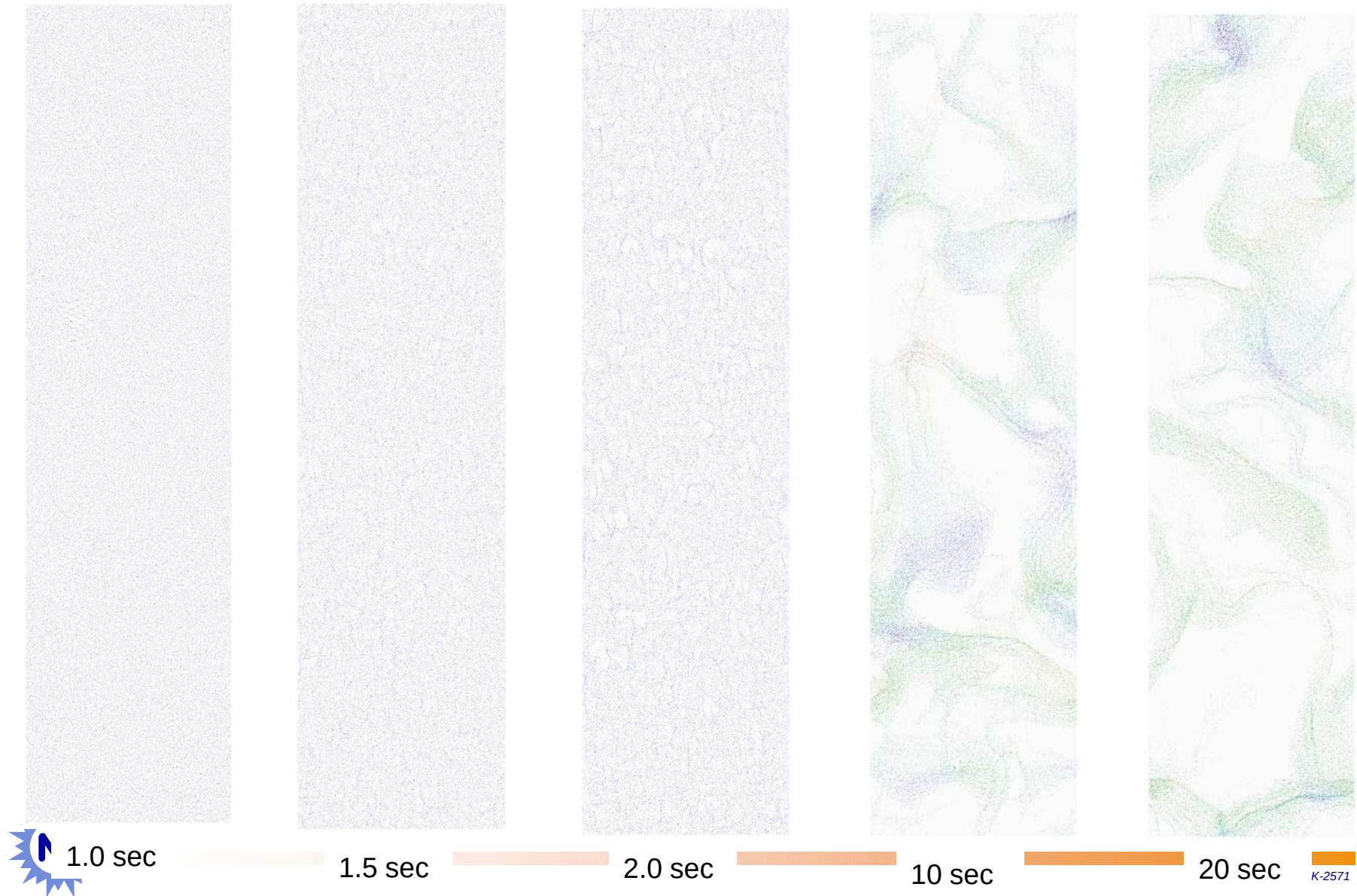
Snapshots of particle position-velocity (16x64)



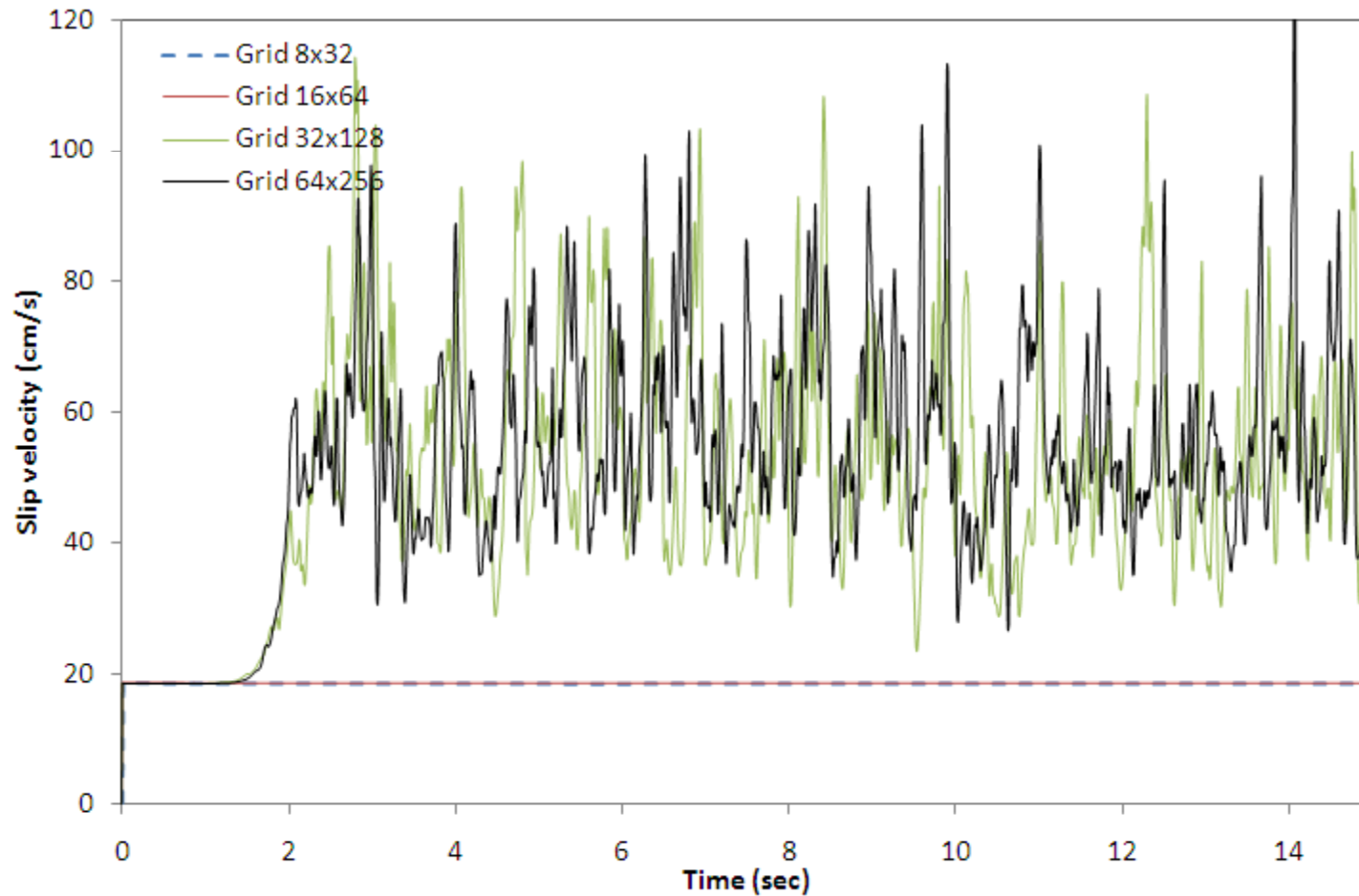
Snapshots of particle position-velocity (32x128)



Snapshots of particle position-velocity (64x256)



Transient Favre-averaged slip velocity



Slip-velocity for continuum & MP-PIC models

Grid size	8x32	16x64	32x128	64x256
Continuum slip velocity & St. Dev. (cm/s)	18.7 0.16	22.6 3.9	49.6 10.8	52.0 8.7
MP-PIC slip velocity & St. Dev. (cm/s)	18.5 0.005	18.5 0.005	50.7 15.1	55.4 13.8



Summary

- Sub-grid corrections are demonstrated to be both needed and useful for both continuum and discrete approaches to gas-solids flow modeling
- Our limited quantitative analysis indicates that the same subgrid corrections developed for continuum models may be used with DPM

