Filtered Model For Energy Transport in Gas-Solid Flows

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Industrial Application of Computational and Numerical Approaches to Particle Flow II

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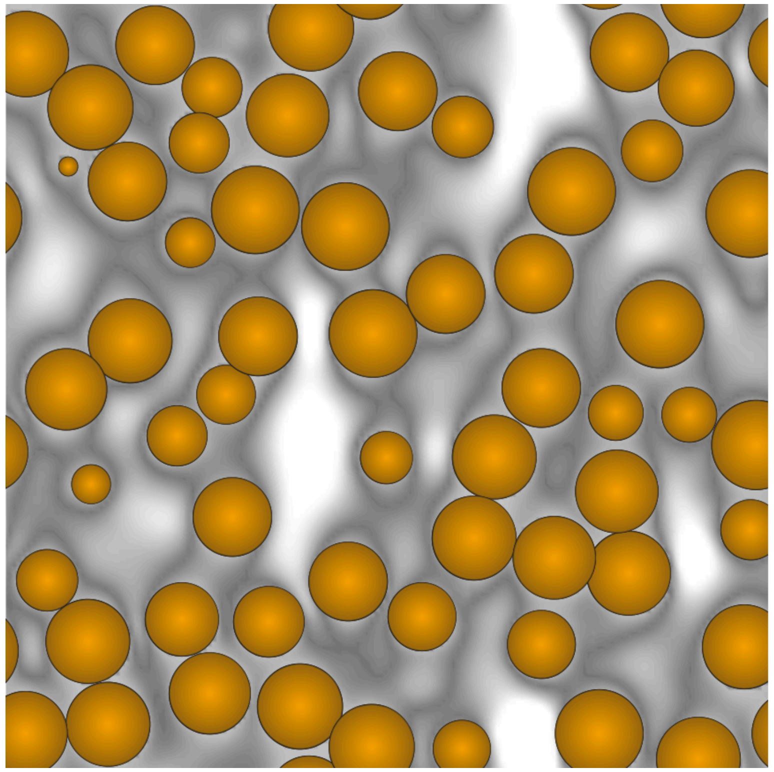
Simulation of Gas-Particle Flows Across Length Scales

MICRO-SCALE
~ 50μ*m*-*mm*



Newton's equations of motion for each particle, Navier-Stokes equations for the fluid flow in the interstices.

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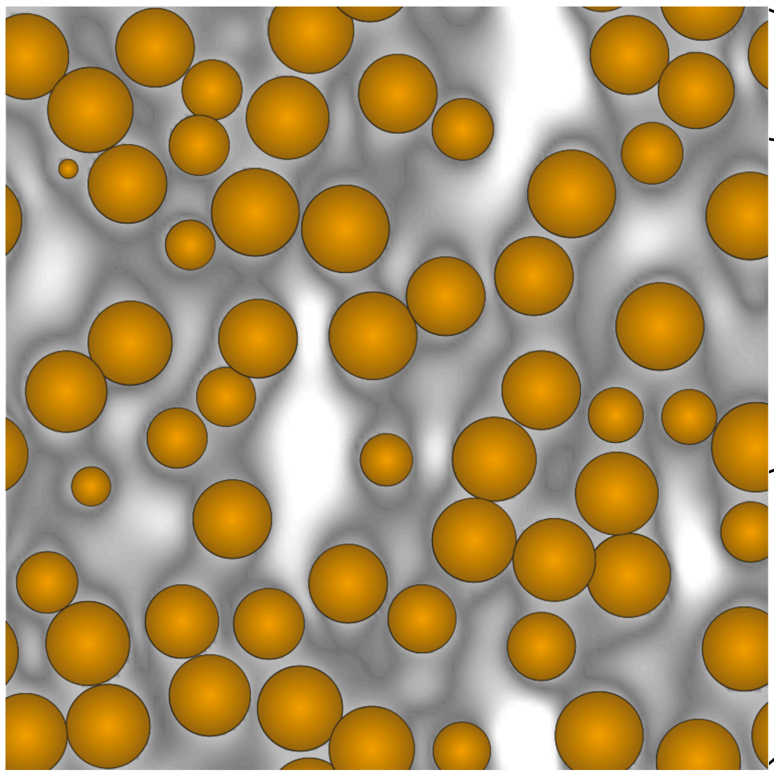

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MESO-SCALE
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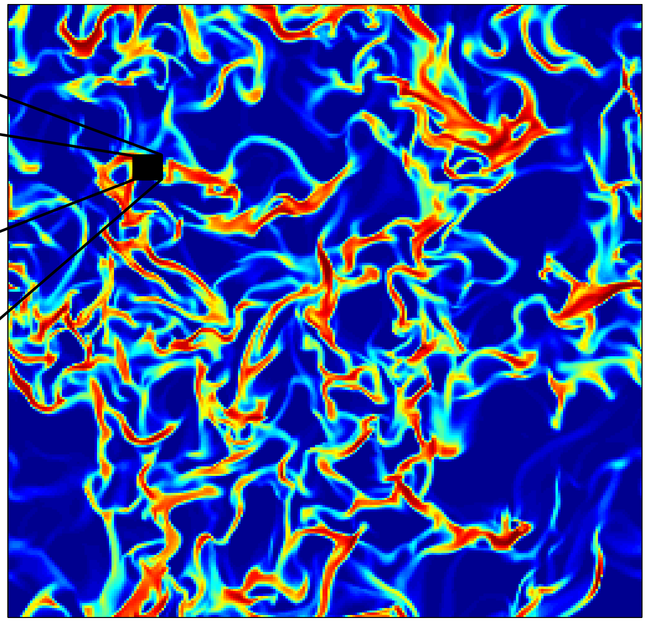

Volume-averaged hydrodynamic models for fluid and particle phases.

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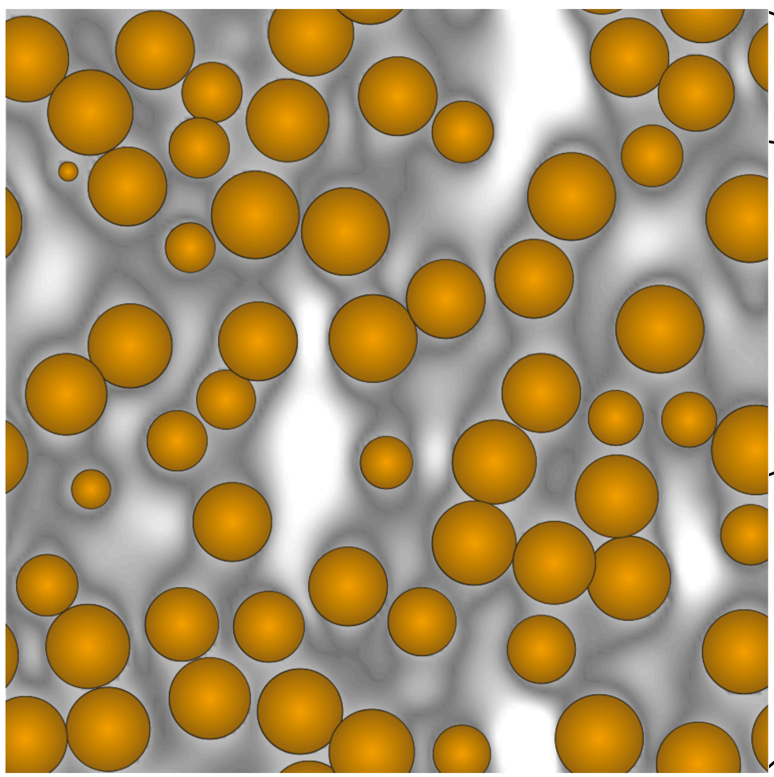

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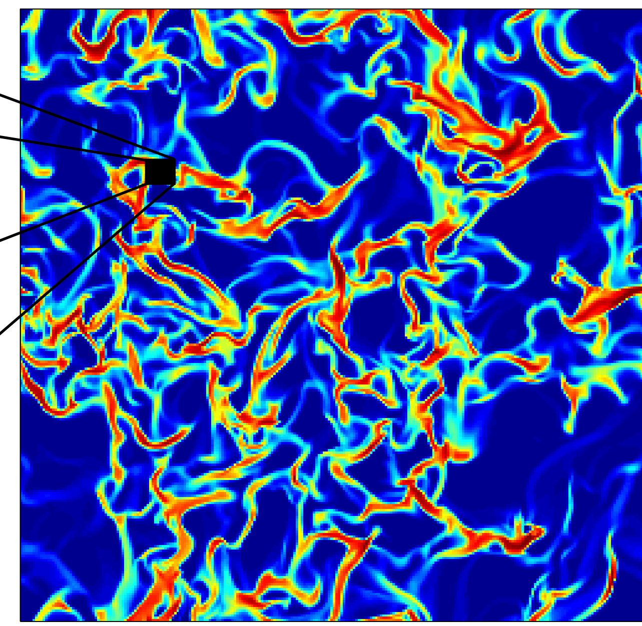

Volume-averaged hydrodynamic models for fluid and particle phases.

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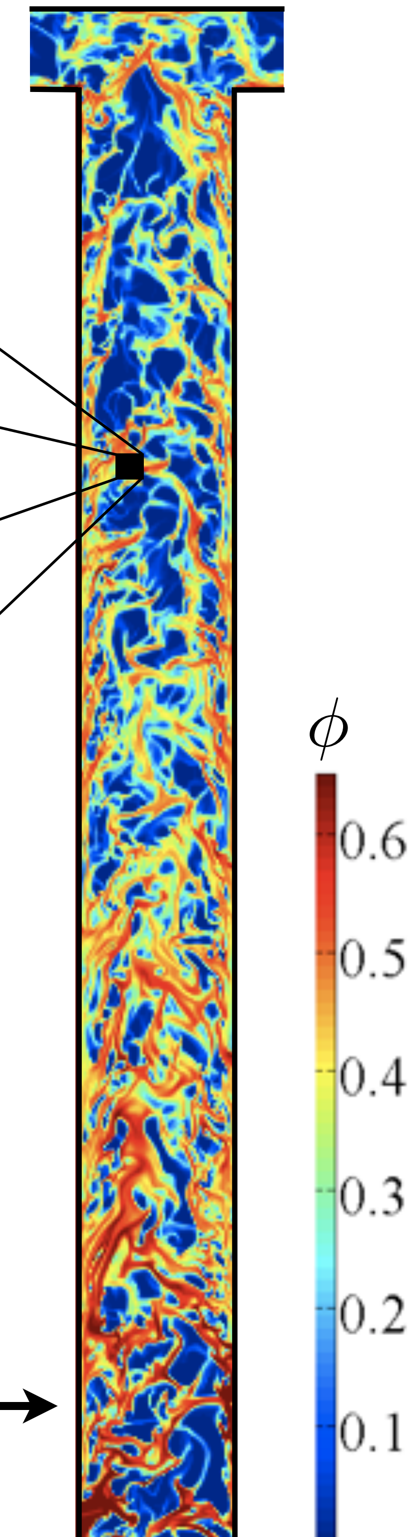

Filtered volume-averaged hydrodynamic models for fluid and particle phases.

Development of Filtered Two-Fluid Models

- Hydrodynamics (*Igci et al, 2011*)
  - Filtered drag *
  - Filtered pressure
  - Filtered viscosity

**Li & Kwauk, 1994; Parmentier et. al, 2011*

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- Hydrodynamics (*Igci et al, 2011*)
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  - Filtered pressure
  - Filtered viscosity
- Reacting flows (*Holloway & Sundaresan, 2012*)
  - Filtered reaction rate
- Thermal energy & interphase transport (present work)
  - Filtered energy dispersion
  - Filtered interphase heat transfer
  - Filtered scalar dispersion (no interphase transport)
    - Helium Tracer/Solid Particle Tracer

**Li & Kwauk, 1994; Parmentier et. al, 2011*

Two-Fluid Model Equations

Continuity

$$\frac{\partial(\rho_s\phi_s)}{\partial t} + \nabla\cdot(\rho_s\phi_s\boldsymbol{v}_s) = 0$$

$$\frac{\partial(\rho_g\phi_g)}{\partial t} + \nabla\cdot(\rho_g\phi_s\boldsymbol{v}_g) = 0$$

Granular kinetic theory

Momentum

$$\frac{\partial}{\partial t}(\rho_s\phi_s\boldsymbol{v}_s) + \nabla\cdot(\rho_s\phi_s\boldsymbol{v}_s\boldsymbol{v}_s) = -\nabla\cdot\boldsymbol{\sigma}_s - \phi_s\nabla\cdot\boldsymbol{\sigma}_g + \boldsymbol{f} + \rho_s\phi_s\boldsymbol{g}$$

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Wen & Yu (1966)

Thermal Energy

$$\rho_s C_{p_s}\left[\frac{\partial}{\partial t}(\phi_s T_s) + \nabla\cdot(\phi_s\boldsymbol{v}_s T_s)\right] = \nabla\cdot(k_s\nabla T_s) + \gamma(T_s - T_g)$$

Gunn (1978)

$$\rho_g C_{p_g}\left[\frac{\partial}{\partial t}(\phi_g T_g) + \nabla\cdot(\phi_g\boldsymbol{v}_g T_g)\right] = \nabla\cdot(k_g\nabla T_g) - \gamma(T_s - T_g)$$

Filtered Equations

Filter $$\overline{\phi_s}(\boldsymbol{x},t) = \int_{V_\infty} G(\boldsymbol{x},\boldsymbol{y})\phi_s(\boldsymbol{x},t)d\boldsymbol{y}$$ $$\int_{V_\infty} G(\boldsymbol{x},\boldsymbol{y})(\boldsymbol{x},t)d\boldsymbol{y} = 1$$

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Favre Filter

$$\widetilde{\alpha_s}(\boldsymbol{x},t) = \frac{\displaystyle\int_{V_\infty} G(\boldsymbol{x},\boldsymbol{y})\alpha_s(\boldsymbol{x},t)\phi_s(\boldsymbol{x},t)d\boldsymbol{y}}{\displaystyle\int_{V_\infty} G(\boldsymbol{x},\boldsymbol{y})\phi_s(\boldsymbol{x},t)d\boldsymbol{y}}$$

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Filtered Solids Thermal Energy Equation

$$\rho_s C_{p_s}\left[\frac{\partial}{\partial t}(\overline{\phi_s}\widetilde{T_s}) + \nabla\cdot(\overline{\phi_s}\widetilde{\boldsymbol{v}_s}\widetilde{T_s})\right] = \nabla\cdot(\overline{k_s\nabla T_s}) + \overline{\gamma(T_s - T_g)} + \rho_s C_{p_s}\nabla\cdot\left[\overline{\phi_s}\widetilde{\boldsymbol{v}_s}\widetilde{T_s} - \overline{\phi_s}\widetilde{\boldsymbol{v}_s T_s}\right]$$

'dispersive' flux

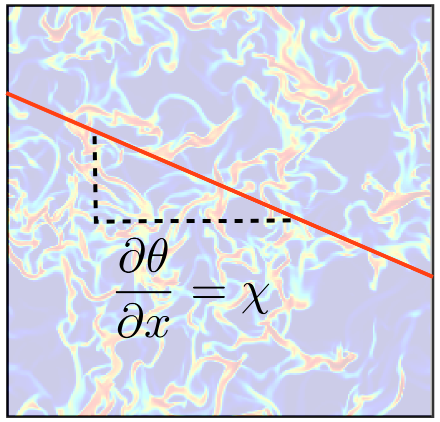
Applying Mean Temperature Gradient

Temperature Gradient

$$T_s = T_s^{'} + \theta(x)$$

$$T_g = T_g^{'} + \theta(x)$$

$$\frac{\partial \theta}{\partial x} = \chi = constant$$



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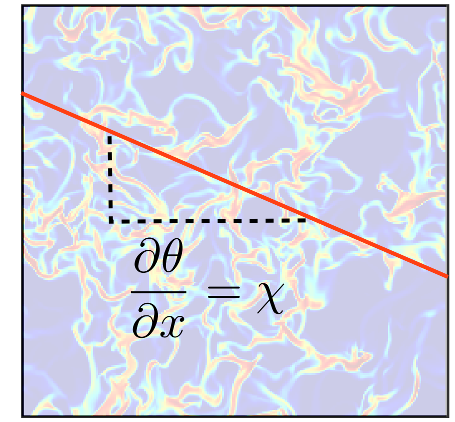


Thermal Energy

$$\rho_s C_{p_s} \left[\frac{\partial}{\partial t}(\phi_s T_s^{'}) + \nabla \cdot (\phi_s \boldsymbol{v}_s T_s^{'}) \right] = \nabla \cdot (k_s \nabla T_s^{'}) + \gamma (T_s^{'} - T_g^{'}) + \chi \frac{\partial k_s}{\partial x} - \rho_s C_{p_s} \phi_s v_{s_x} \chi$$

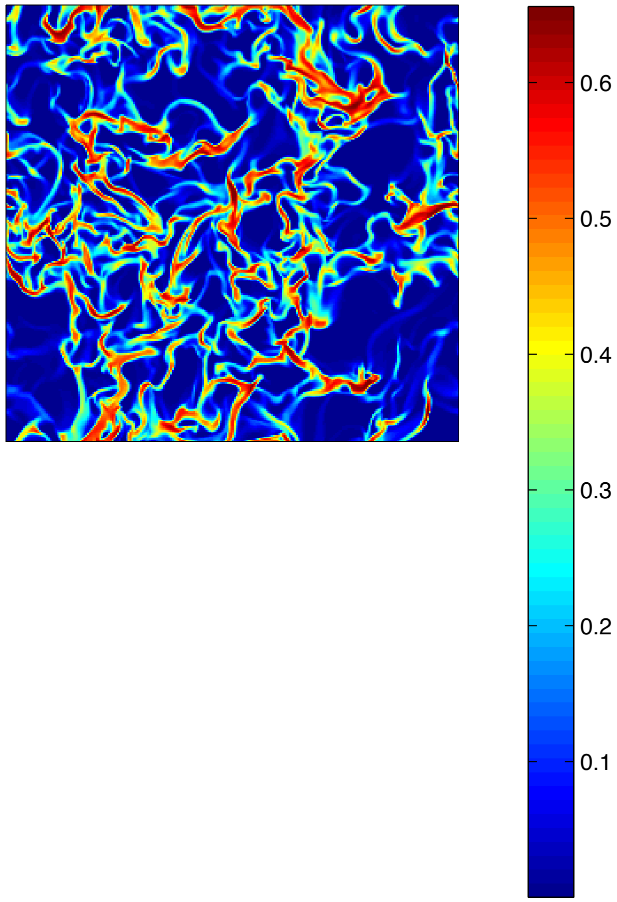
$$\rho_g C_{p_g} \left[\frac{\partial}{\partial t}(\phi_g T_g^{'}) + \nabla \cdot (\phi_g \boldsymbol{v}_g T_g^{'}) \right] = \nabla \cdot (k_g \nabla T_g^{'}) - \gamma (T_s^{'} - T_g^{'}) + \underbrace{\chi \frac{\partial k_g}{\partial x} - \rho_g C_{p_g} \phi_g v_{g_x} \chi}_{\text{‘New’ source terms}}$$

‘New’ source terms

Applying Heat Sources/Sinks

Solids Heat Source

$\dot{Q}_s \phi_s$ $\int_D \dot{Q}_s \phi_s dV = \dot{Q}_s \overline{\phi}_s V$ ϕ_s



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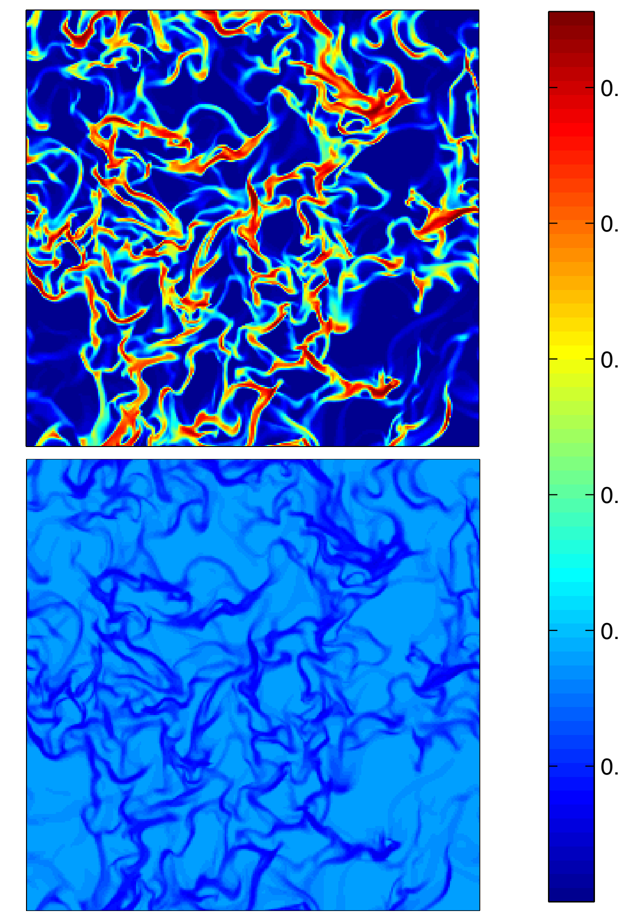
$$\dot{Q}_s \phi_s \qquad \int_D \dot{Q}_s \phi_s dV = \dot{Q}_s \overline{\phi}_s V \qquad \phi_s$$

Gas Heat Sink

$$\dot{Q}_g \phi_g = \dot{Q}_s \frac{\overline{\phi}_s}{\overline{\phi}_g} \phi_g \qquad \int_D \dot{Q}_g \phi_g dV = \dot{Q}_s \overline{\phi}_s V \qquad \frac{\overline{\phi}_s}{\overline{\phi}_g} \phi_g$$



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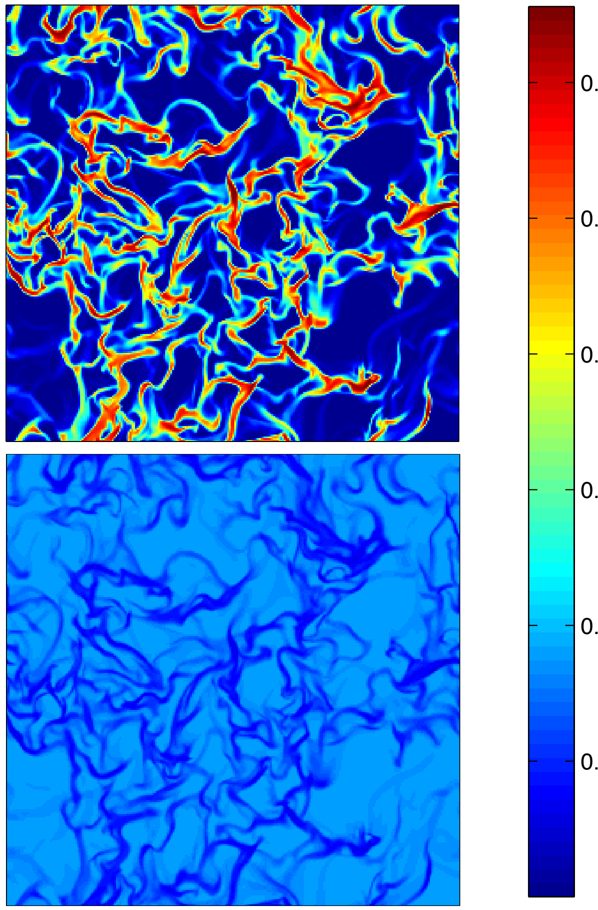


Thermal Energy

$$\rho_s C_{p_s} \left[\frac{\partial}{\partial t}(\phi_s T_s) + \nabla \cdot (\phi_s \boldsymbol{v}_s T_s) \right] = \nabla \cdot (k_s \nabla T_s) + \gamma (T_s - T_g) + \dot{Q}_s \phi_s$$

$$\rho_g C_{p_g} \left[\frac{\partial}{\partial t}(\phi_g T_g) + \nabla \cdot (\phi_g \boldsymbol{v}_g T_g) \right] = \nabla \cdot (k_g \nabla T_g) - \gamma (T_s - T_g) - \dot{Q}_g \phi_g$$

'New' source/sink terms

Simulations and Filtering Procedure

2-D periodic domain with mean vertical pressure drop in gas phase set to balance weight of mixture.

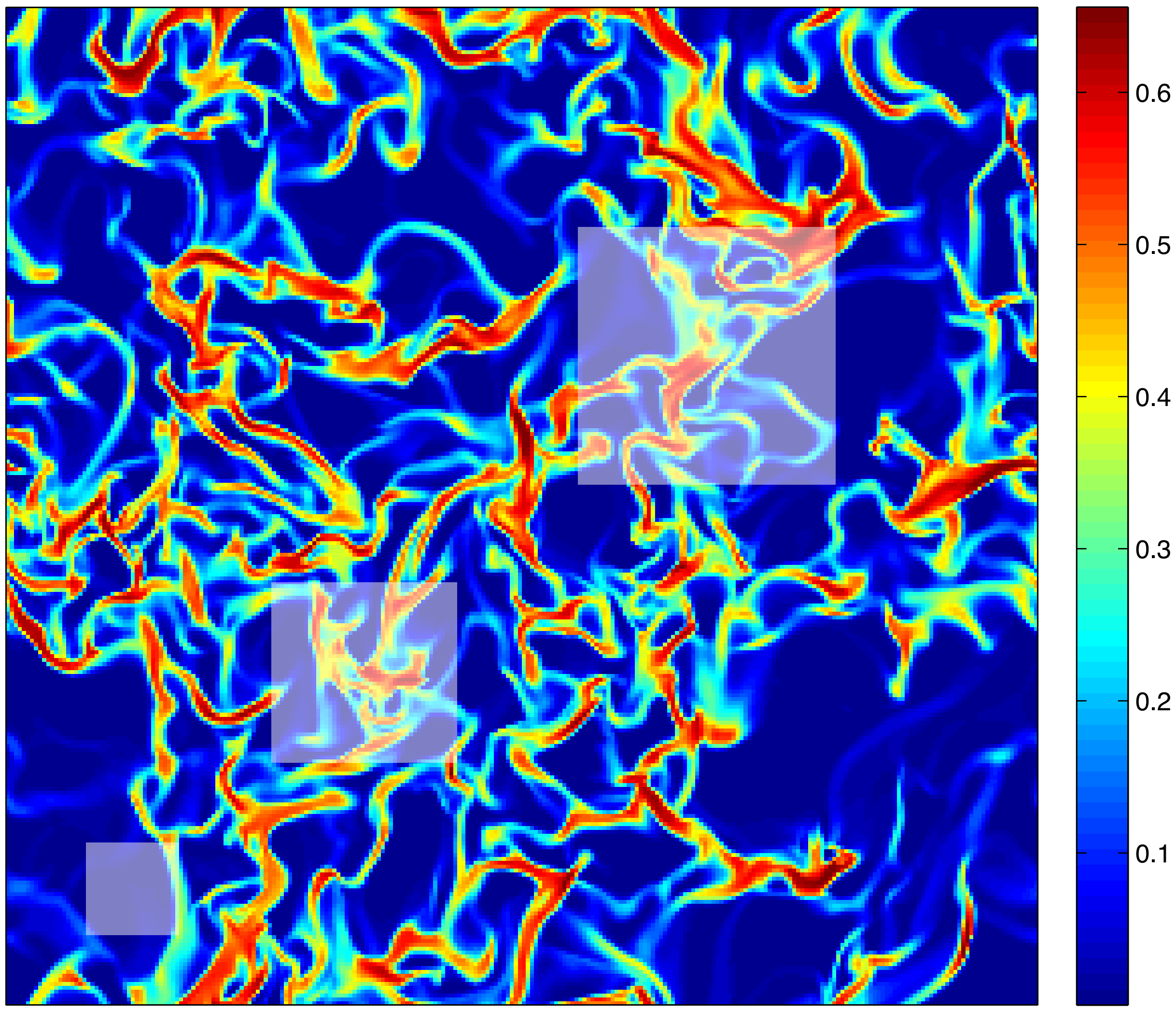
Computational Domain: 32cm x 32cm
Discretization: 256 x 256 cells
Particle diameter: 75μm

Simulations are for FCC particles in air.
Results are suitably scaled so that they are applicable to other systems.

Simulations and Filtering Procedure

2-D periodic domain with mean vertical pressure drop in gas phase set to balance weight of mixture.

Snapshot of solids volume fraction field obtained from highly resolved simulations. →



Shaded squares illustrate regions over which a filtering operation is performed.

Filtered Solids Thermal Dispersion

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$$\alpha_{s_{filt}} = \frac{k_{s_{filt}}}{\rho_s C_{p_s}} = \frac{\overline{\phi_s}\left(\widetilde{\boldsymbol{v}_{s_x}}\widetilde{T_s} - \widetilde{\boldsymbol{v}_{s_x} T_s}\right)}{\frac{\partial \widetilde{T_s}}{\partial x}}$$

$$\frac{\alpha_{s_{filt}}}{\left(v_t^3/g\right)}$$

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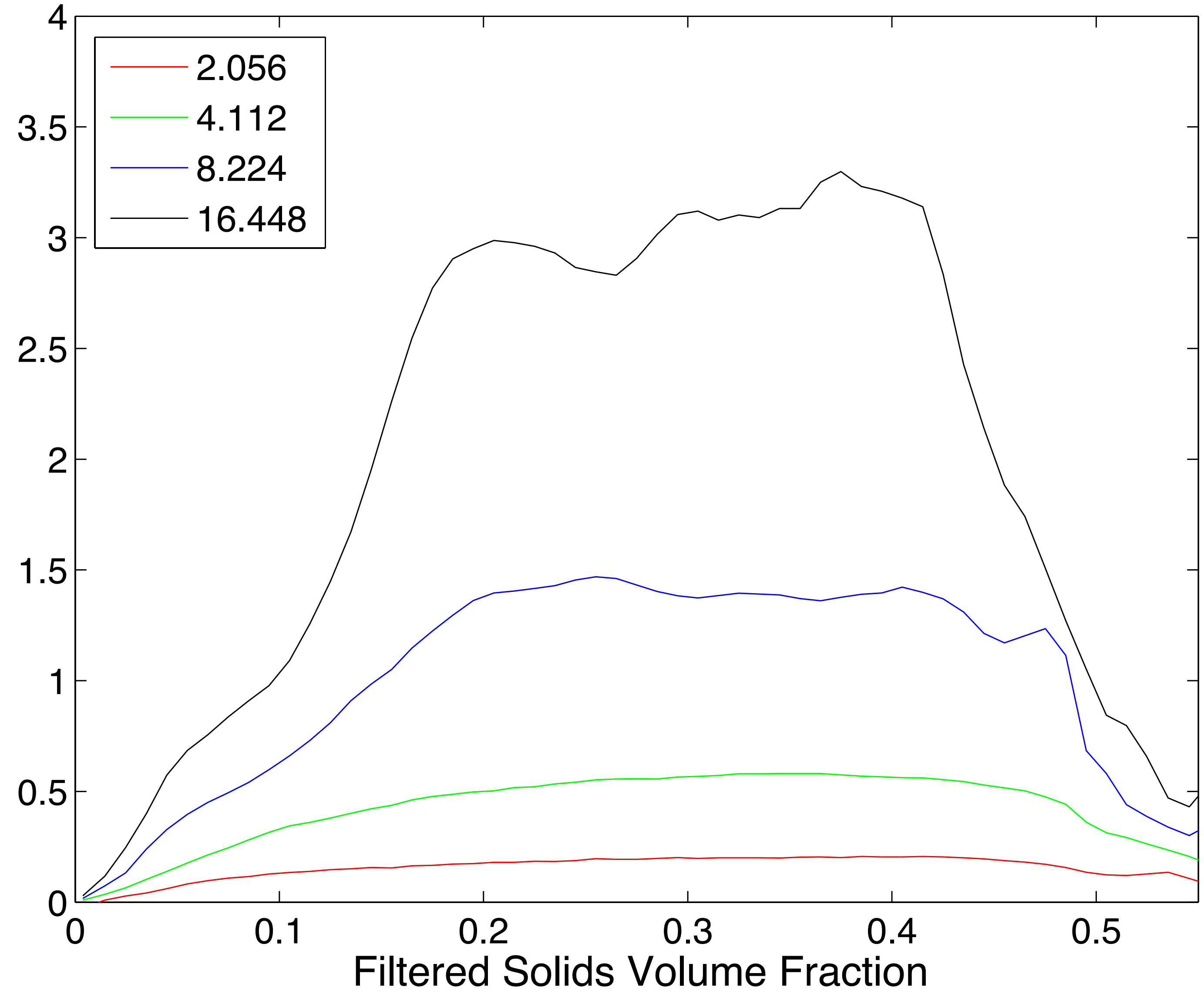


Curves correspond to different filter sizes.

Dimensionless filter size shown in legend $\dfrac{\Delta}{v_t^2/g}$

$(Fr_\Delta)^{-1}$

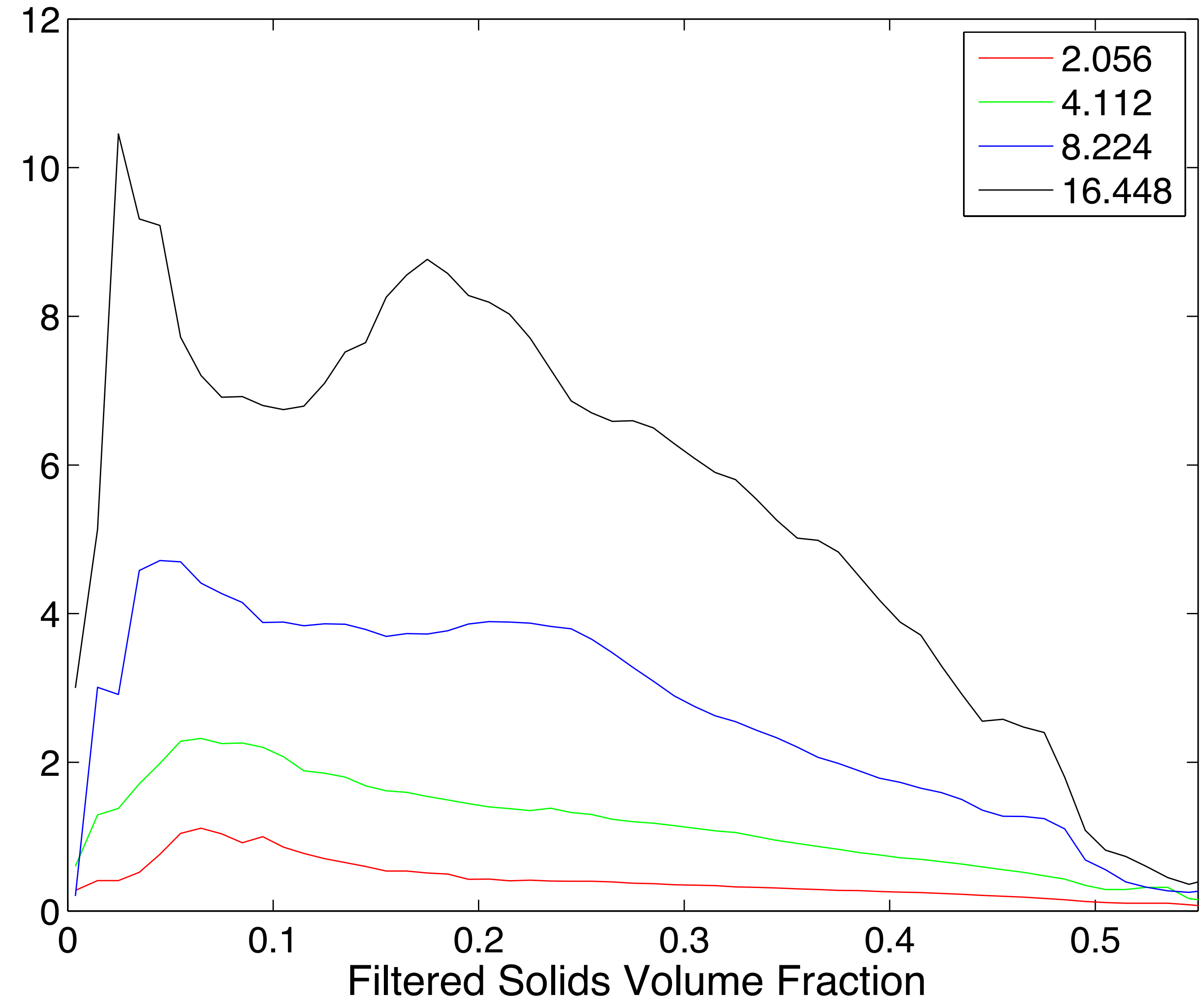
FCC particles in air

Dimensionless filter size of 2.056 corresponds to 1cm.

Filtered Gas Thermal Dispersion

$$\alpha_{g_{filt}} = \frac{k_{g_{filt}}}{\rho_g C_{p_g}} = \frac{\overline{\phi_g}\left(\widetilde{\boldsymbol{v}_{g_x} T_g} - \widetilde{\boldsymbol{v}_{g_x}}\widetilde{T_g}\right)}{\frac{\partial \widetilde{T_g}}{\partial x}}$$

$$\frac{\alpha_{g_{filt}}}{(v_t^3/g)}$$



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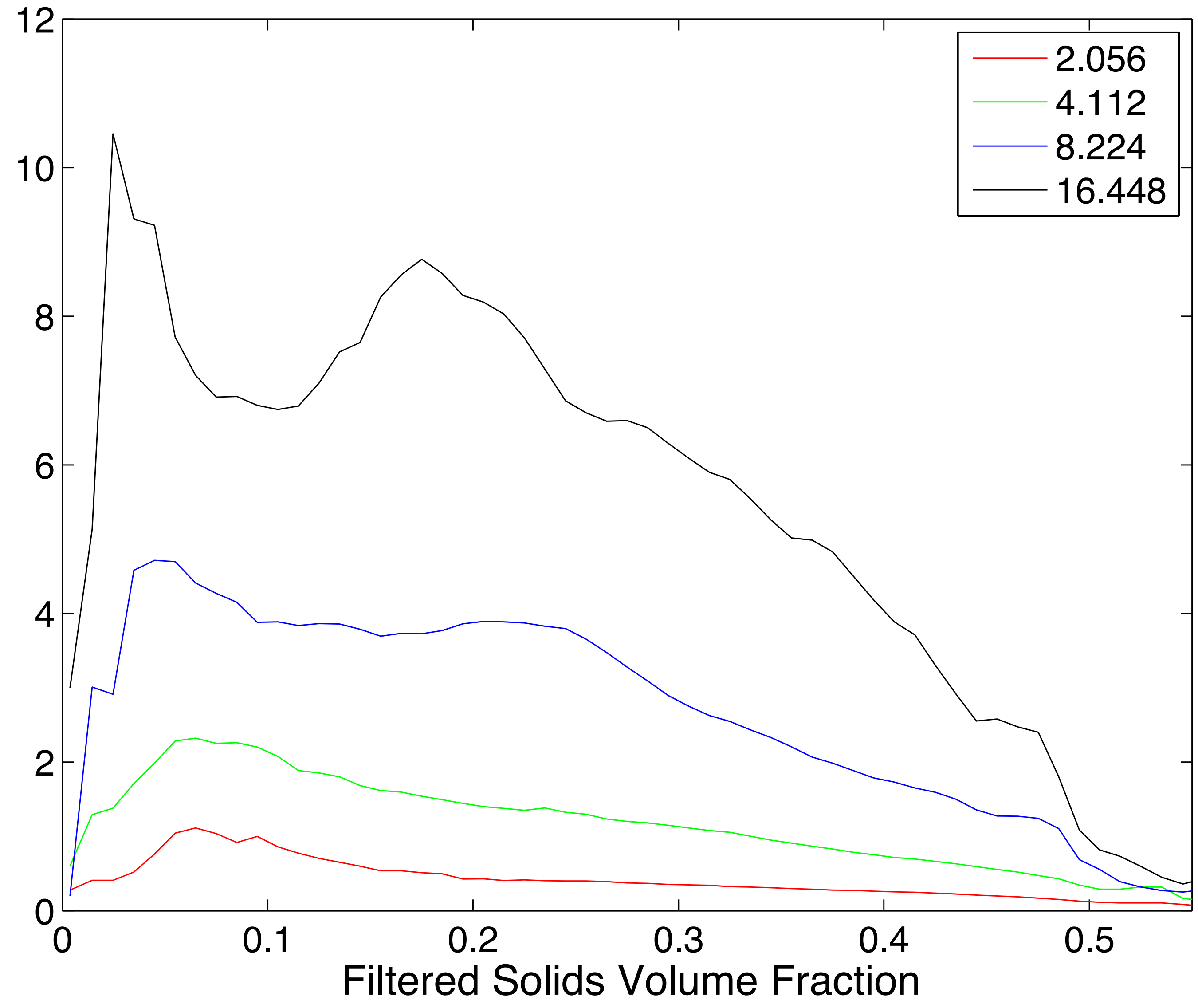

Scaled Filtered Solids Thermal Dispersion

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$$\widehat{\alpha}_{s_{filt}} = \frac{\alpha_{s_{filt}}}{(v_t^3/g)}$$

$$\frac{\widehat{\alpha}_{s_{filt}}}{\widehat{\Delta}^2 \widehat{|\widetilde{S_s}|}}$$

Dimensionless Filtered Solids Shear Rate

$$\widetilde{S_s} = \frac{1}{2}\left(\nabla \widetilde{v_s} + \nabla \widetilde{v_s}^T\right) - \frac{1}{3}\left(\nabla \cdot \widetilde{v_s}\right) \boldsymbol{I}$$

$$|\widetilde{S_s}| = \sqrt{2\widetilde{S_s} : \widetilde{S_s}}$$

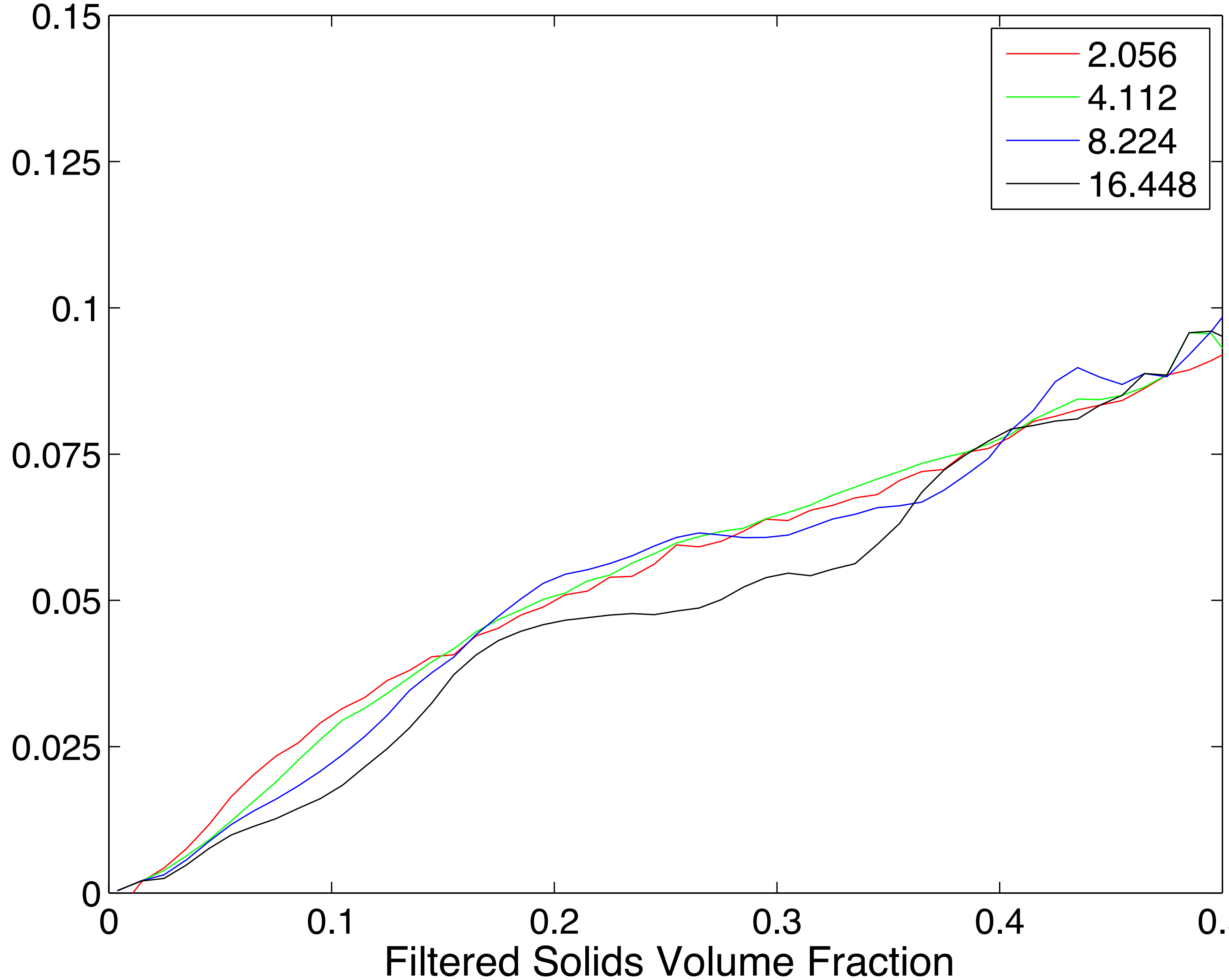
Scaled Filtered Solids Thermal Dispersion

$$\widehat{\alpha}_{s_{filt}} = \frac{\alpha_{s_{filt}}}{(v_t^3/g)}$$

$$\frac{\widehat{\alpha}_{s_{filt}}}{\widehat{\Delta}^2 |\widehat{\widetilde{S}_s}|}$$

$$\frac{\widehat{\alpha}_{s_{filt}}}{\widehat{\Delta}^2 |\widehat{\widetilde{S}_s}|} \sim 0.2\overline{\phi_s}$$

Smagorinsky type model



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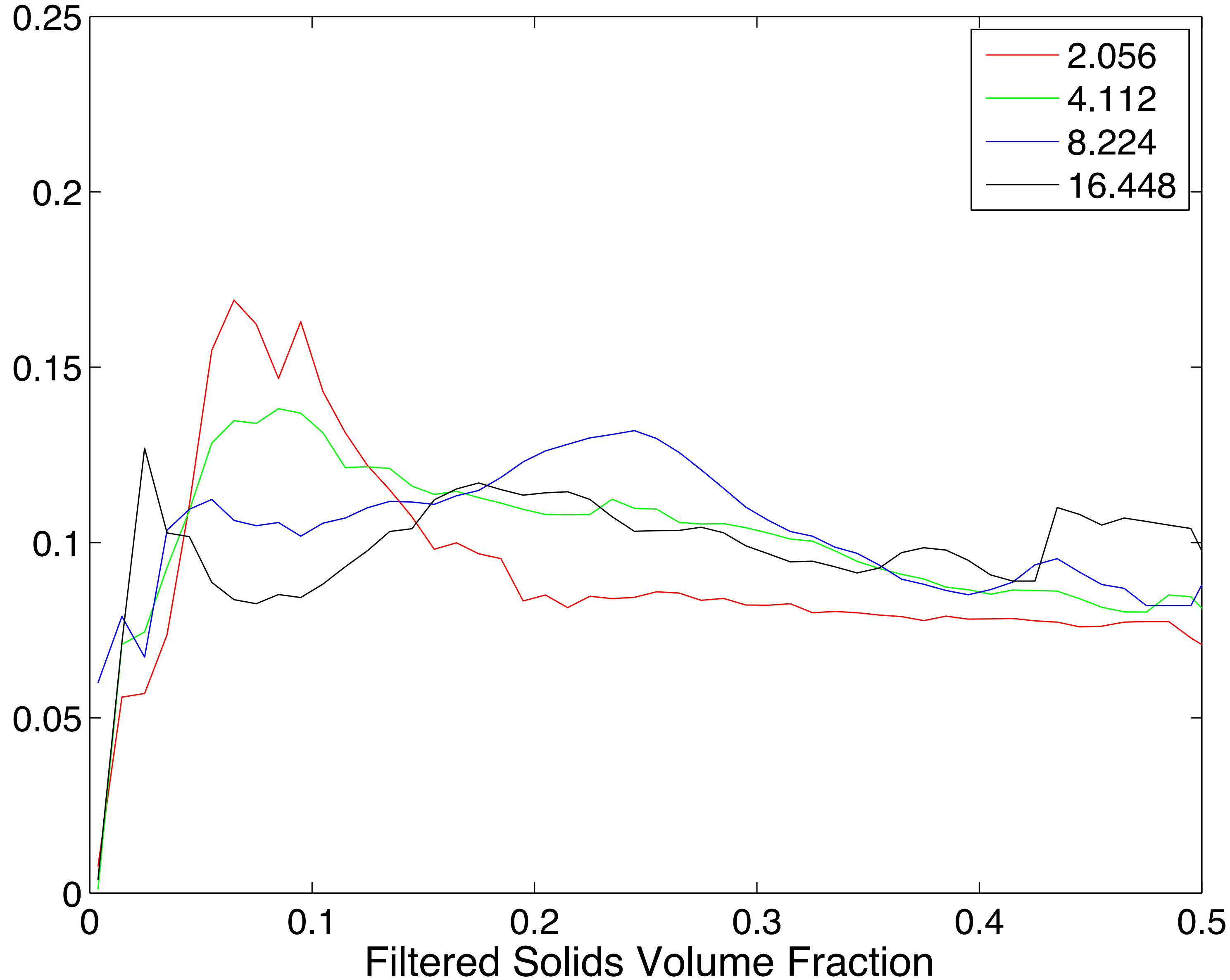
$$\frac{\widehat{\alpha}_{g_{filt}}}{\widehat{\Delta}^2 |\widehat{\widetilde{S}_g}|} \sim 0.1(1 - e^{-60\overline{\phi_s}})$$

Smagorinsky type model



Connection to Momentum Transfer

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- For gas-solid flows we may define a filtered Prandtl number for each phase.

- Based on earlier studies of turbulent momentum transfer in gas-solid flows we find[1,2]

$$\overline{Pr}_s \sim 0.5$$

$$\overline{Pr}_g \sim 1$$

[1,2] Igci et. al. (2011)/Milioli et. al (in preparation)

Filtered Interphase Heat Transfer Coefficient

$$\frac{\gamma_{filt}}{\gamma(\overline{\phi_s}, \widetilde{\boldsymbol{v}}_{slip})}$$

$$\gamma_{filt} = \frac{\overline{\gamma(T_s - T_g)}}{(\widetilde{T_s} - \widetilde{T_g})}$$

- Look for the form

$$\frac{\gamma_{filt}}{\gamma(\overline{\phi_s}, \widetilde{\boldsymbol{v}}_{slip})} = f\left(\overline{\phi_s}, \widetilde{\boldsymbol{v}}_{slip}, \Delta\right)$$

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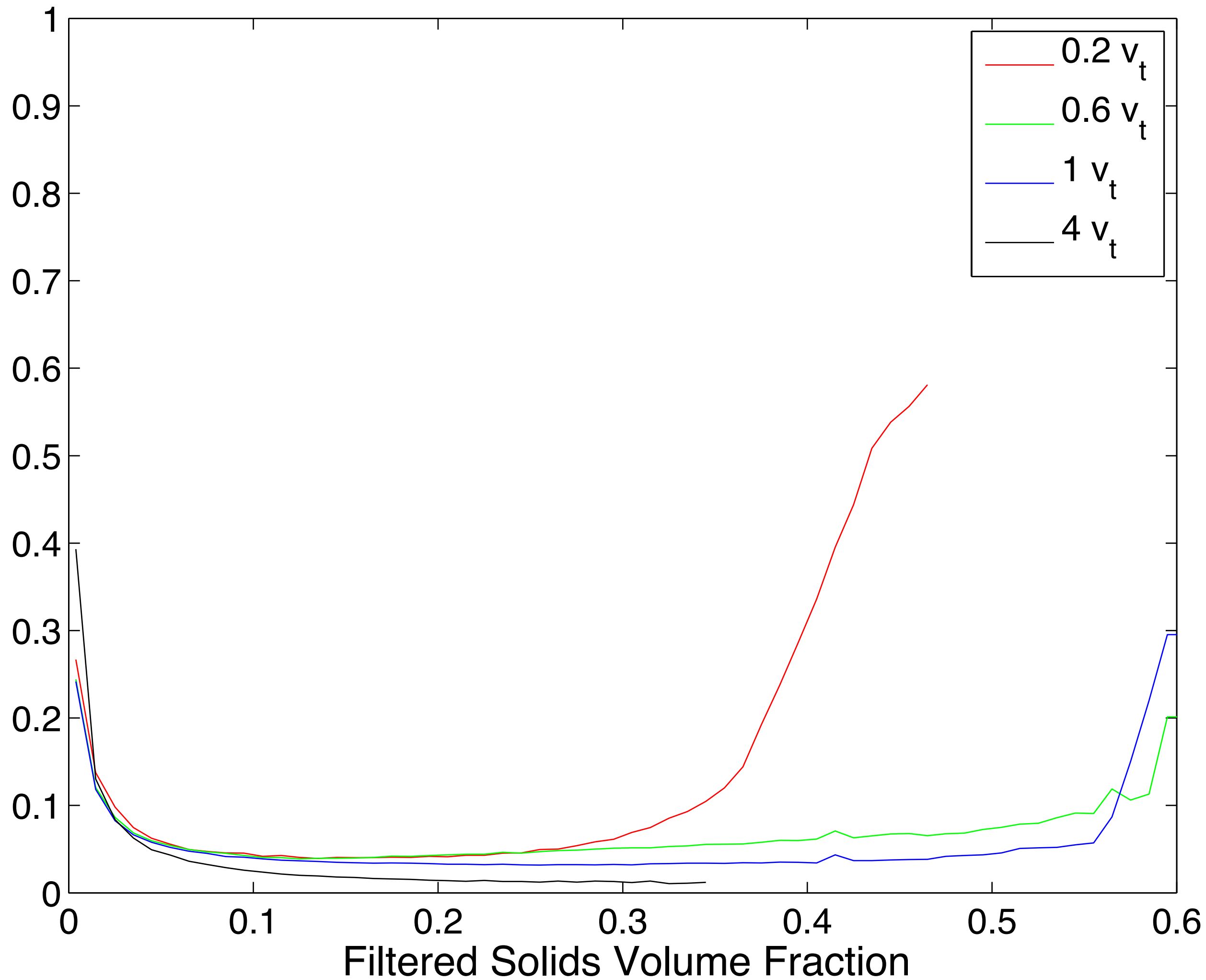


Dimensionless filter size of 2.056 (1cm).

- Look for the form

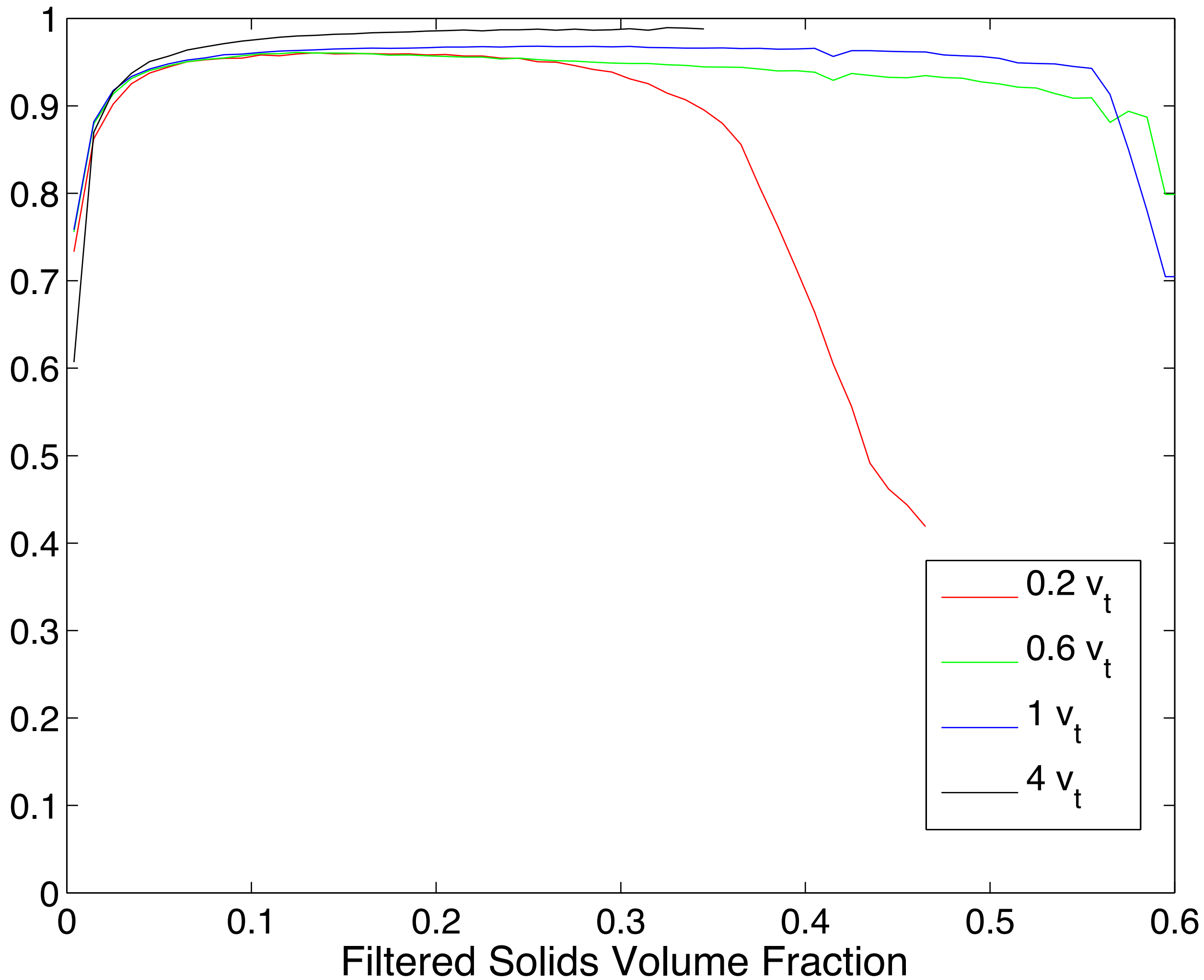
$$\frac{\gamma_{filt}}{\gamma(\overline{\phi_s}, \widetilde{\boldsymbol{v}}_{slip})} = f\left(\overline{\phi_s}, \widetilde{\boldsymbol{v}}_{slip}, \Delta\right)$$

- Reduction in heat transfer coefficient ~ 2-3 orders of magnitude.

Breault (2006); Dong et. al (2008); Kashyap & Gidaspow (2010,2011)

Filtered Interphase Heat Transfer Coefficient

$$1 - \frac{\gamma_{filt}}{\gamma(\overline{\phi_s}, \widetilde{\boldsymbol{v}}_{slip})}$$



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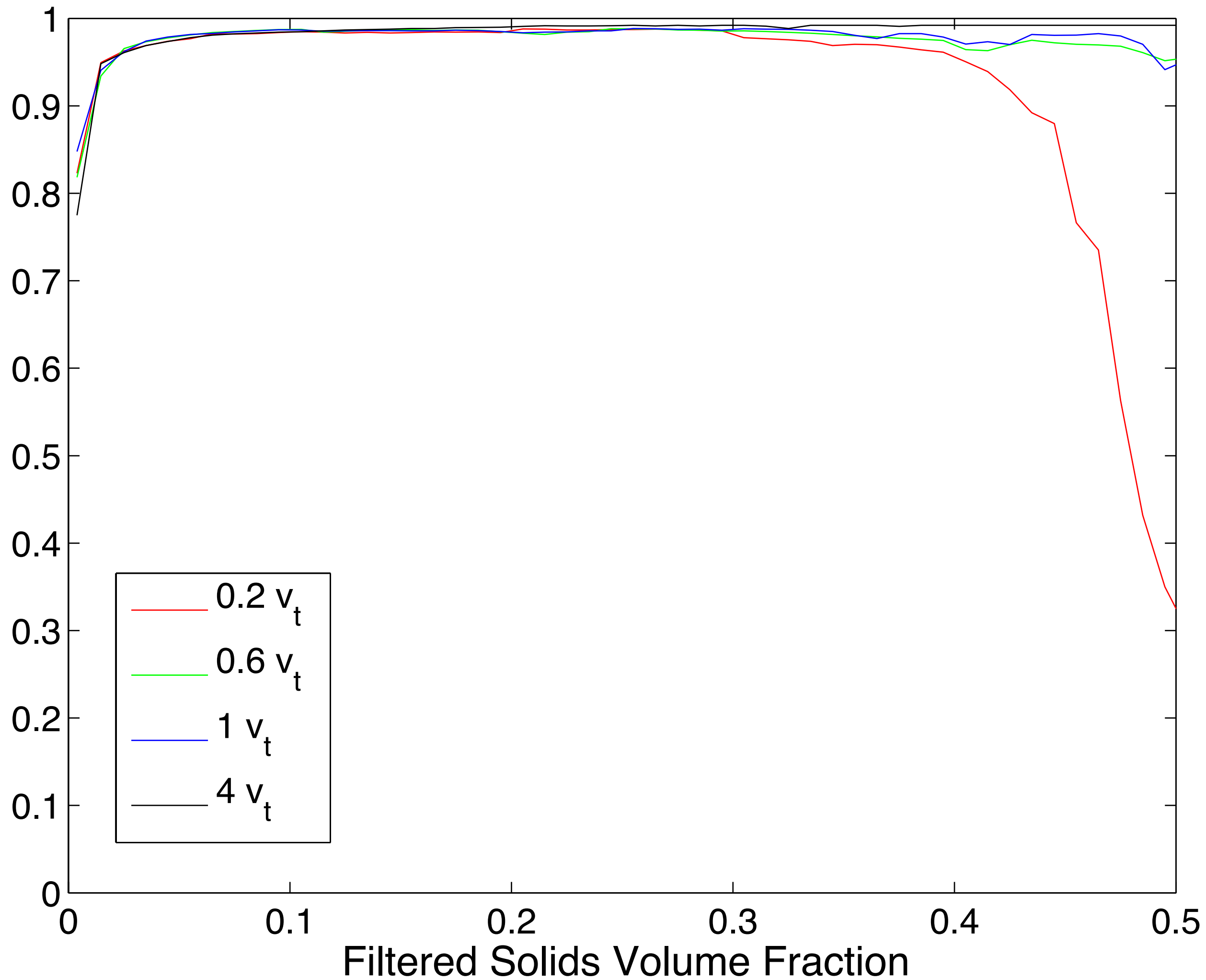

Dimensionless filter size of 8.224 (4cm).

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- Reduction in heat transfer coefficient ~ 2-3 orders of magnitude.
- Weak function of filter size/slip velocity at larger slip velocities.
- Most realizations with lows slip velocities occur in regions of high solids concentration.
- Behavior similar to filtered interphase drag coefficient, but the effect is more pronounced.

Filtered Interphase Heat Transfer Coefficient

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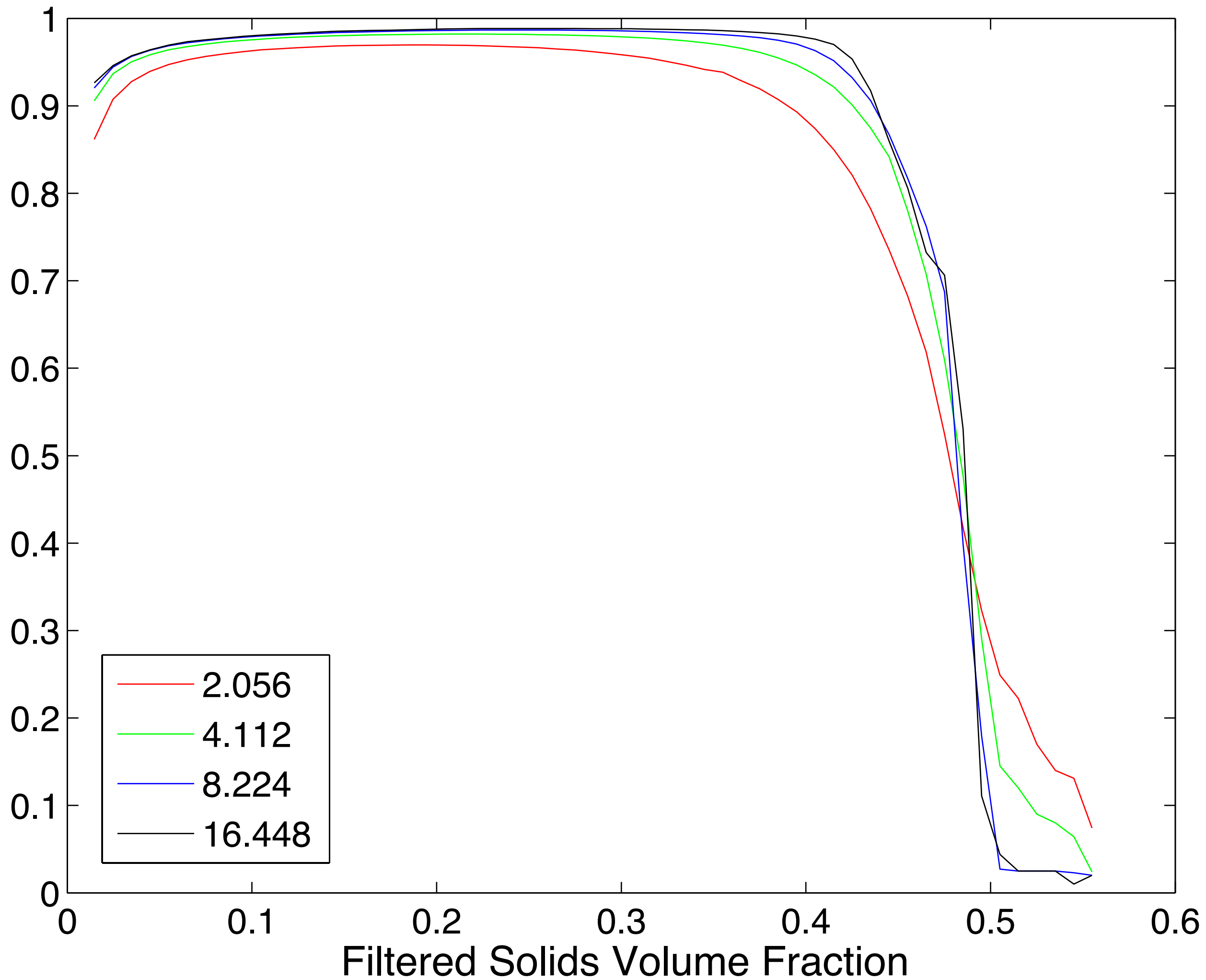

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- Weak function of filter size/slip velocity at larger slip velocities.
- Most realizations with lows slip velocities occur in regions of high solids concentration.
- Behavior similar to filtered interphase drag coefficient, but the effect is more pronounced.
- In practice for large filter size we may employ

$$\frac{\gamma_{filt}}{\gamma(\overline{\phi_s}, \widetilde{\boldsymbol{v}}_{slip})} \sim f\left(\overline{\phi_s}\right)$$

Summary

- Smagorinsky type model for filtered dispersion coefficient

$$\frac{\widehat{\alpha}_{g_{filt}}}{\widehat{\Delta}^2 |\widehat{\widetilde{S_g}}|} = h(\overline{\phi_s}) \qquad \frac{\widehat{\alpha}_{s_{filt}}}{\widehat{\Delta}^2 |\widehat{\widetilde{S_s}}|} = g(\overline{\phi_s})$$

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- Filtered Prandtl Numbers $$\overline{Pr}_s \sim 0.5 \qquad \overline{Pr}_g \sim 1$$
- Filtered interphase heat transfer coefficient $$\frac{\gamma_{filt}}{\gamma(\overline{\phi_s}, \widetilde{\boldsymbol{v}}_{slip})} \sim f(\overline{\phi_s}) << 1$$

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- Results carry over to mass transfer and tracer dispersion

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Further areas for investigation

- Impact of going from 2-D to 3-D
  - Results for hydrodynamics suggest the effect is small (*Igci et. al, 2011*)

Acknowledgements

Disclaimer

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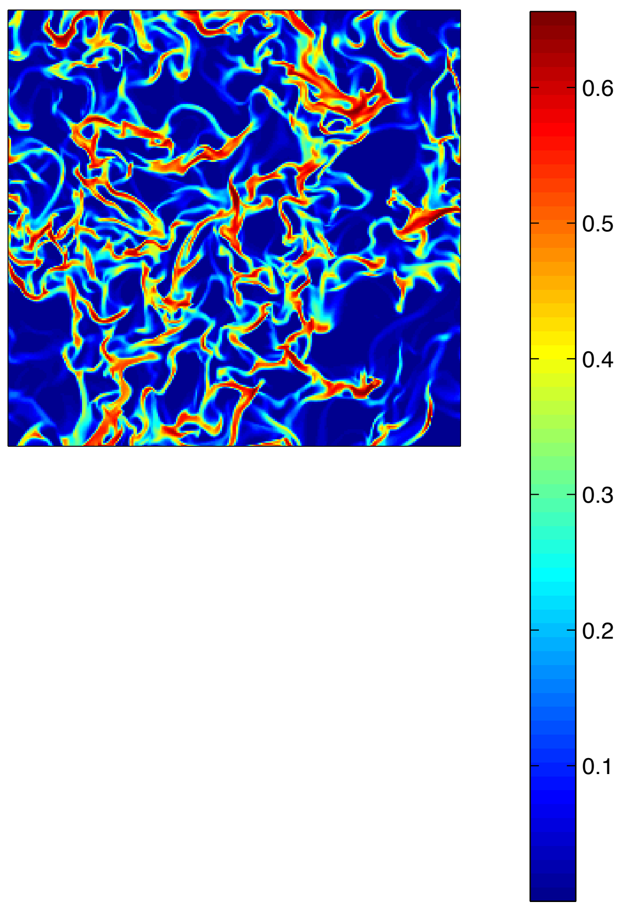
Filtered Interphase Heat Transfer Coefficient: A Preview

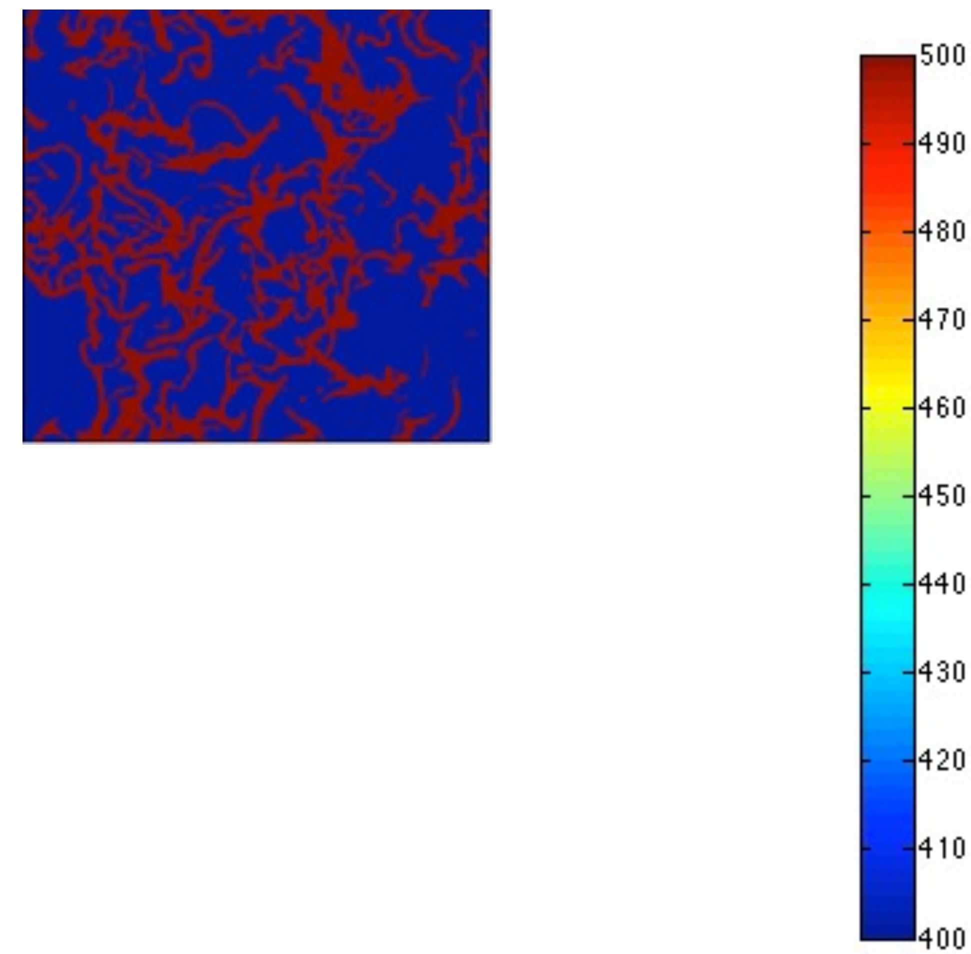
Solids Volume Fraction Field

ϕ_s



Temperature Field

T_s, T_g

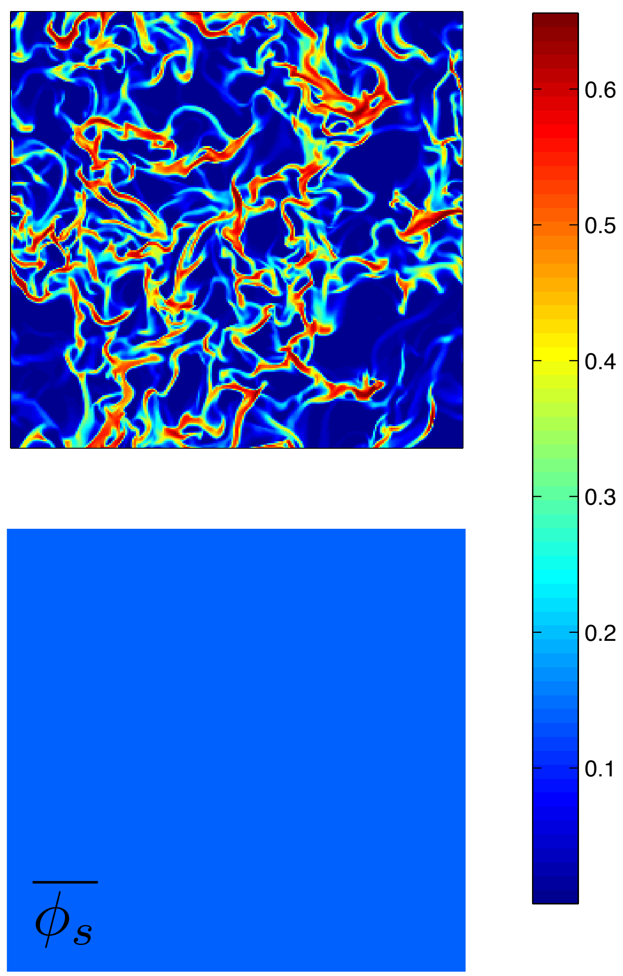


Filtered Interphase Heat Transfer Coefficient: A Preview

Solids Volume Fraction Field

ϕ_s

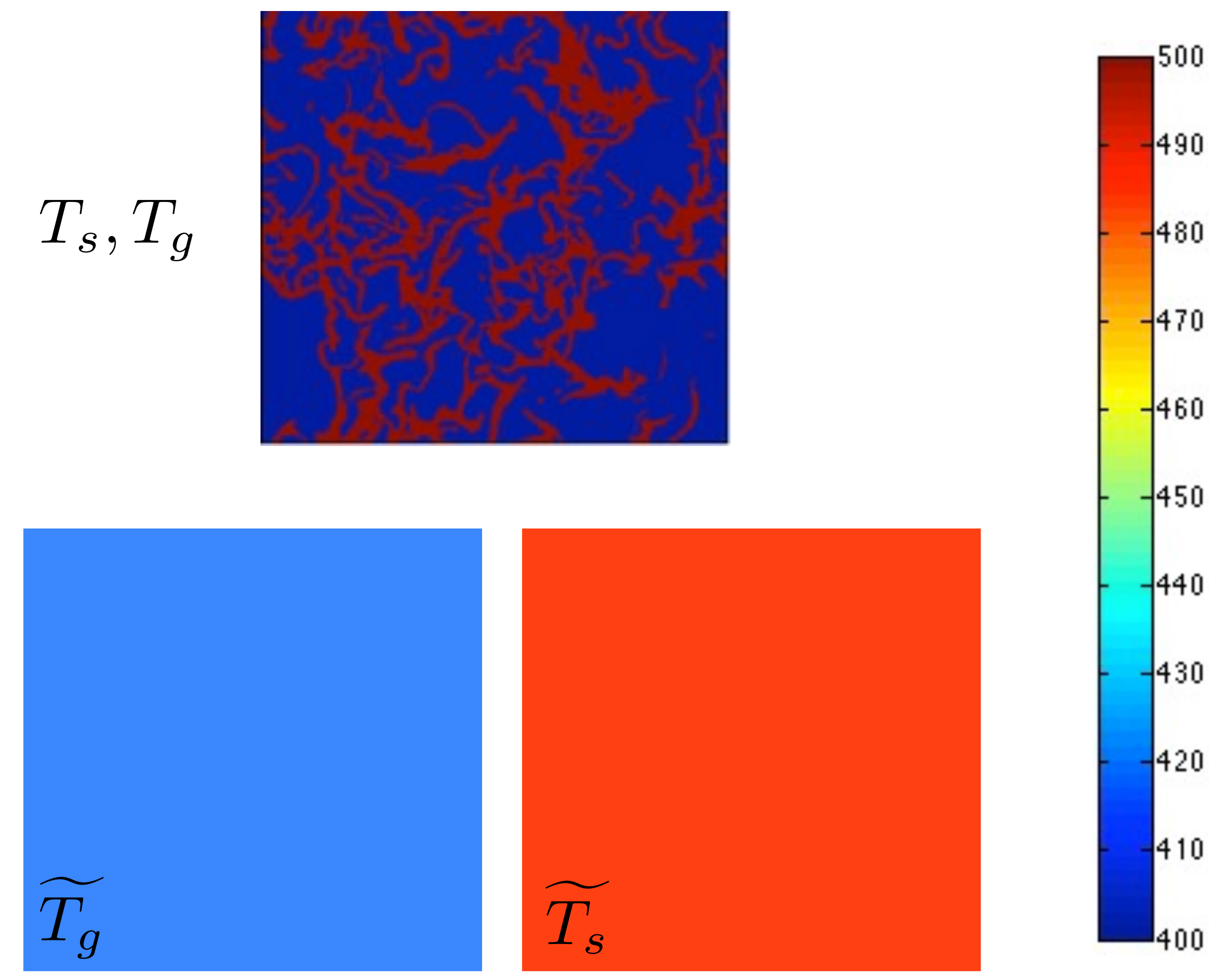
Filtered



Temperature Field

T_s, T_g

Filtered

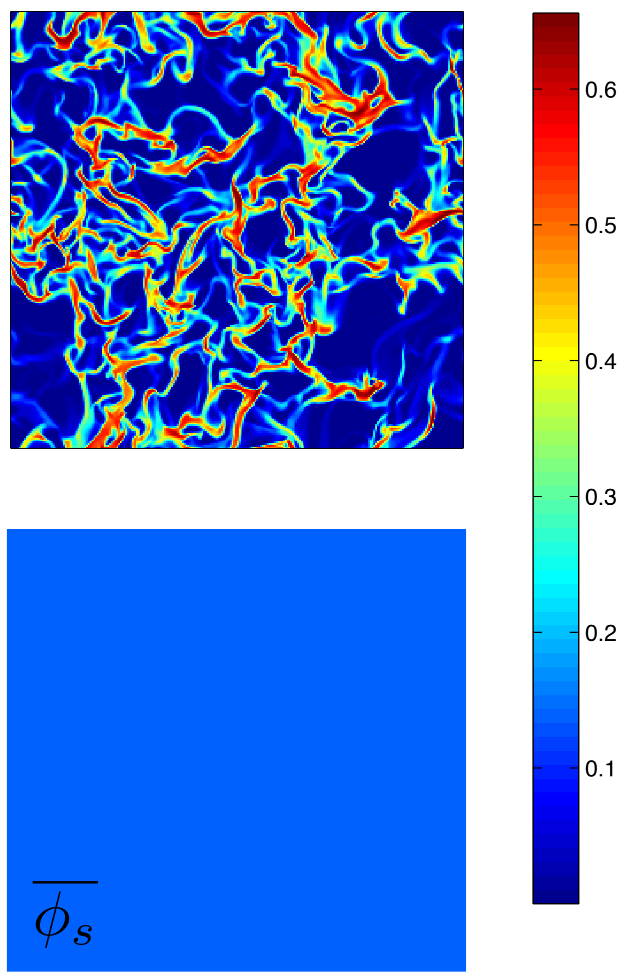


Filtered Interphase Heat Transfer Coefficient: A Preview

Solids Volume
Fraction Field

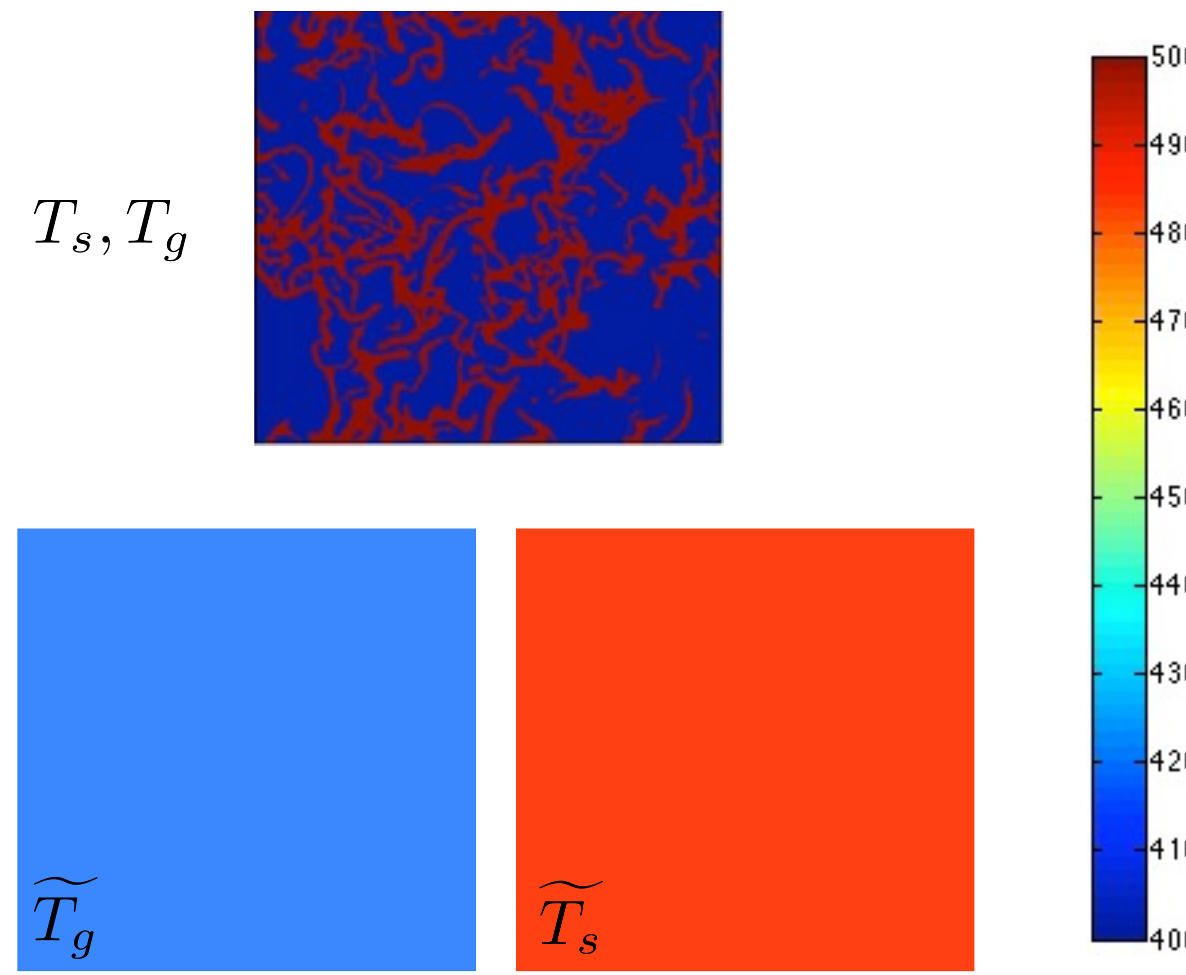
ϕ_s

Filtered



Temperature
Field

Filtered



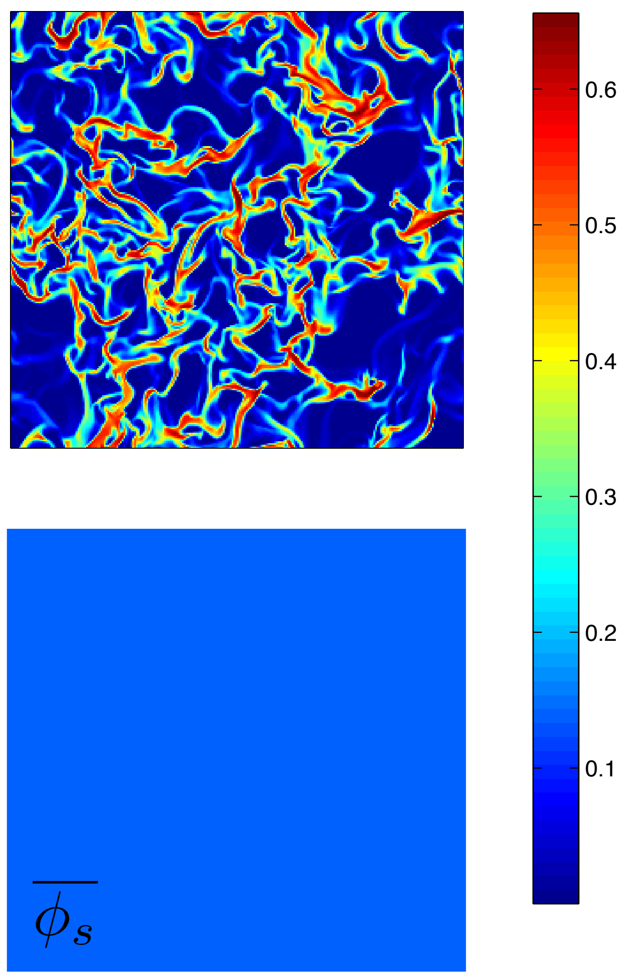
$$(\widetilde{T_s} - \widetilde{T_g}) >> (T_s - T_g)$$

Filtered Interphase Heat Transfer Coefficient: A Preview

Solids Volume Fraction Field

ϕ_s

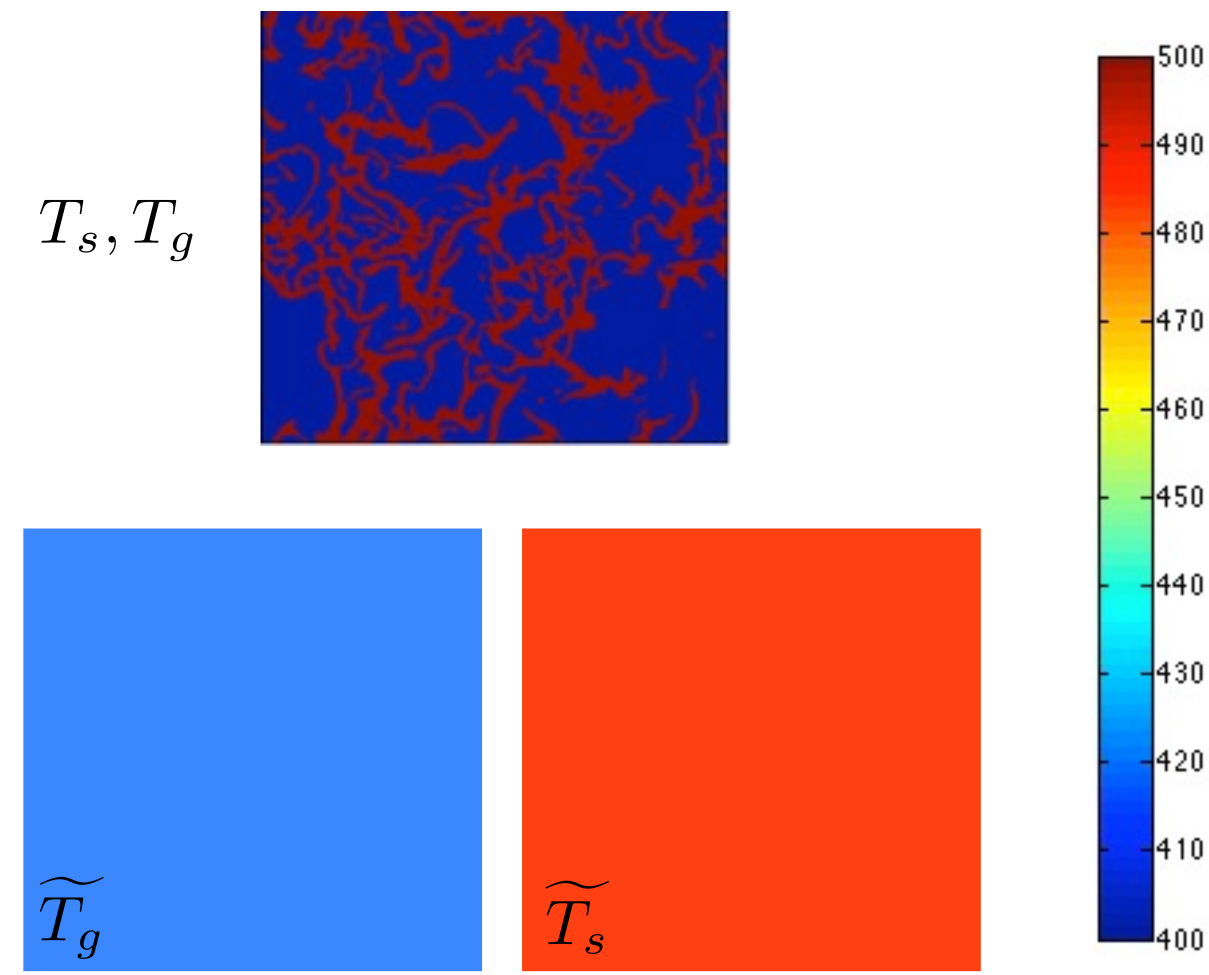
Filtered



Temperature Field

T_s, T_g

Filtered

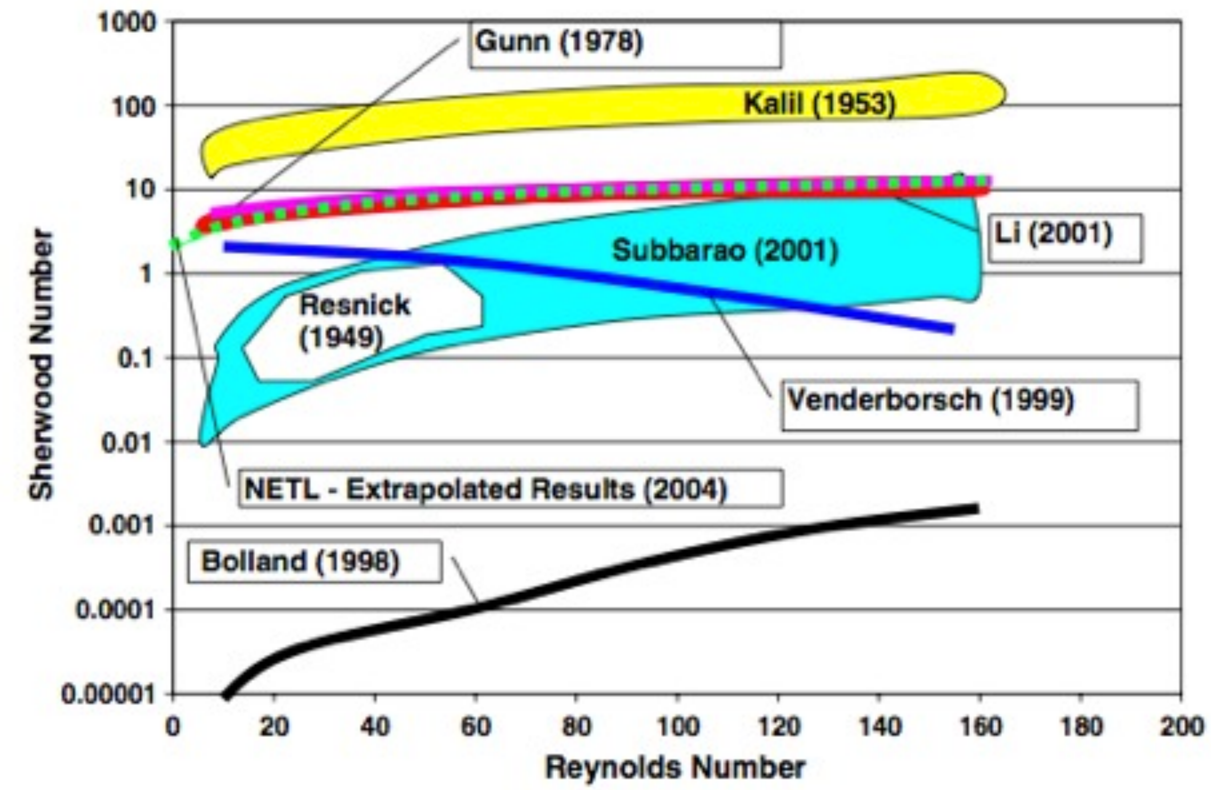


$$(\widetilde{T_s} - \widetilde{T_g}) >> (T_s - T_g)$$

$$\frac{\gamma_{filt}}{\gamma(\overline{\phi_s}, \widetilde{\boldsymbol{v}}_{slip})} << 1$$

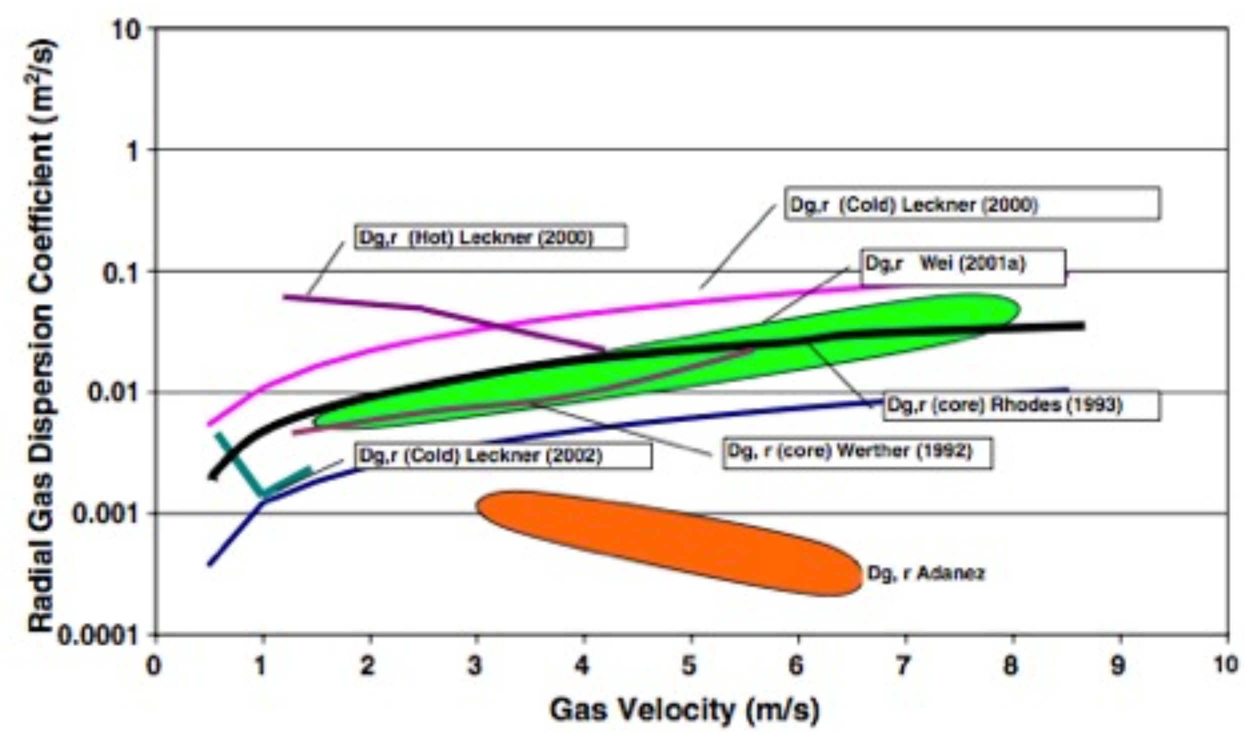
Mass Transfer & Dispersion Coefficients In the Literature

Experimental Data in the literature show considerable variation



Mass transfer coefficients differ by several orders of magnitude

Dispersion coefficients differ by several orders of magnitude



Modeling efforts suggest origins of variance related to inadequate representation of meso-scale structures (clusters/bubbles)

R.W. Breault / Powder Technology (2006)

Interphase Heat Transfer Correlation

$$Nu = (7 - 10\phi_g + 5\phi_g^2)(1 + 0.7Re_p^{0.2}Pr^{1/3}) + (1.33 - 2.4\phi_g + 1.2\phi_g^2)Re_p^{0.7}Pr^{1/3}$$

$$\gamma = \frac{6k_g Nu}{d_p^2}$$

Filtered Transport Properties

Filtered Interphase Heat Transfer Coefficient

$$\gamma_{filt} = \frac{\overline{\gamma(T_s - T_g)}}{(\widetilde{T_s} - \widetilde{T_g})}$$

Filtered Transport Properties

Filtered Interphase Heat Transfer Coefficient

$$\gamma_{filt} = \frac{\overline{\gamma(T_s - T_g)}}{(\widetilde{T_s} - \widetilde{T_g})}$$

Filtered Thermal Dispersion Coefficient

$$\alpha_{filt} = \frac{k_{filt}}{\rho_s C_{p_s}} = \frac{\overline{\phi_s}\left(\widetilde{\boldsymbol{v}_{s_x}}\widetilde{T_s} - \widetilde{\boldsymbol{v}_{s_x} T_s}\right)}{\dfrac{\partial \widetilde{T_s}}{\partial x}}$$

Filtered Transport Properties

Filtered Interphase Heat Transfer Coefficient

$$\gamma_{filt} = \frac{\overline{\gamma(T_s - T_g)}}{(\widetilde{T_s} - \widetilde{T_g})}$$

Filtered Thermal Dispersion Coefficient

$$\alpha_{filt} = \frac{k_{filt}}{\rho_s C_{p_s}} = \frac{\overline{\phi_s}\left(\widetilde{\boldsymbol{v}_{s_x}}\widetilde{T_s} - \widetilde{\boldsymbol{v}_{s_x} T_s}\right)}{\frac{\partial \widetilde{T_s}}{\partial x}}$$

Calculated in Simulations as follows:

$$\gamma_{filt} = \frac{\left\langle \overline{\gamma(T_s - T_g)} \right\rangle}{\left\langle (\widetilde{T_s} - \widetilde{T_g}) \right\rangle} \qquad \alpha_{filt} = \frac{\left\langle \overline{\phi_s}\left(\widetilde{\boldsymbol{v}_{s_x}}\widetilde{T_s} - \widetilde{\boldsymbol{v}_{s_x} T_s}\right) \right\rangle}{\left\langle \frac{\partial \widetilde{T_s}}{\partial x} \right\rangle} \qquad \left\langle \frac{\partial \widetilde{T_s}}{\partial x} \right\rangle = \chi$$