Filtered Two-Fluid Model for Gas-Particle Suspension flow

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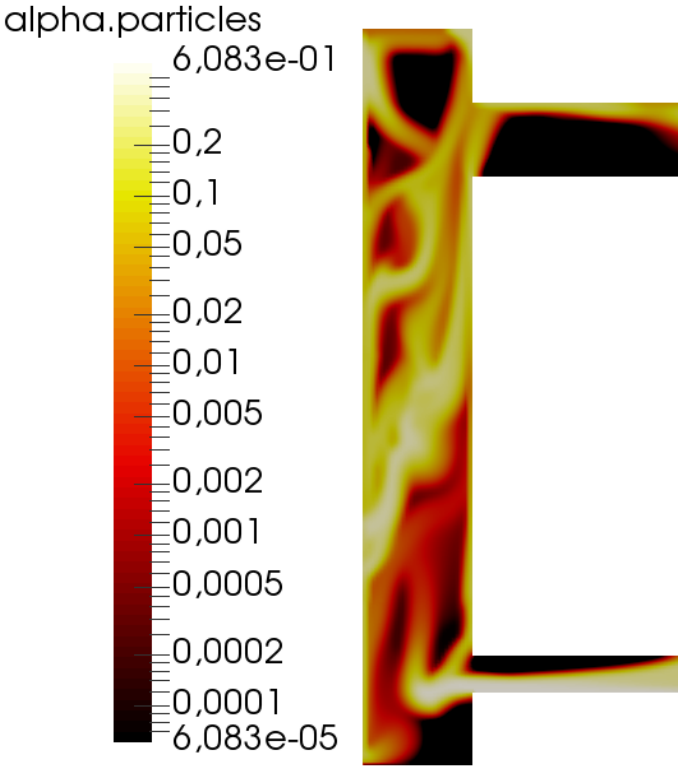
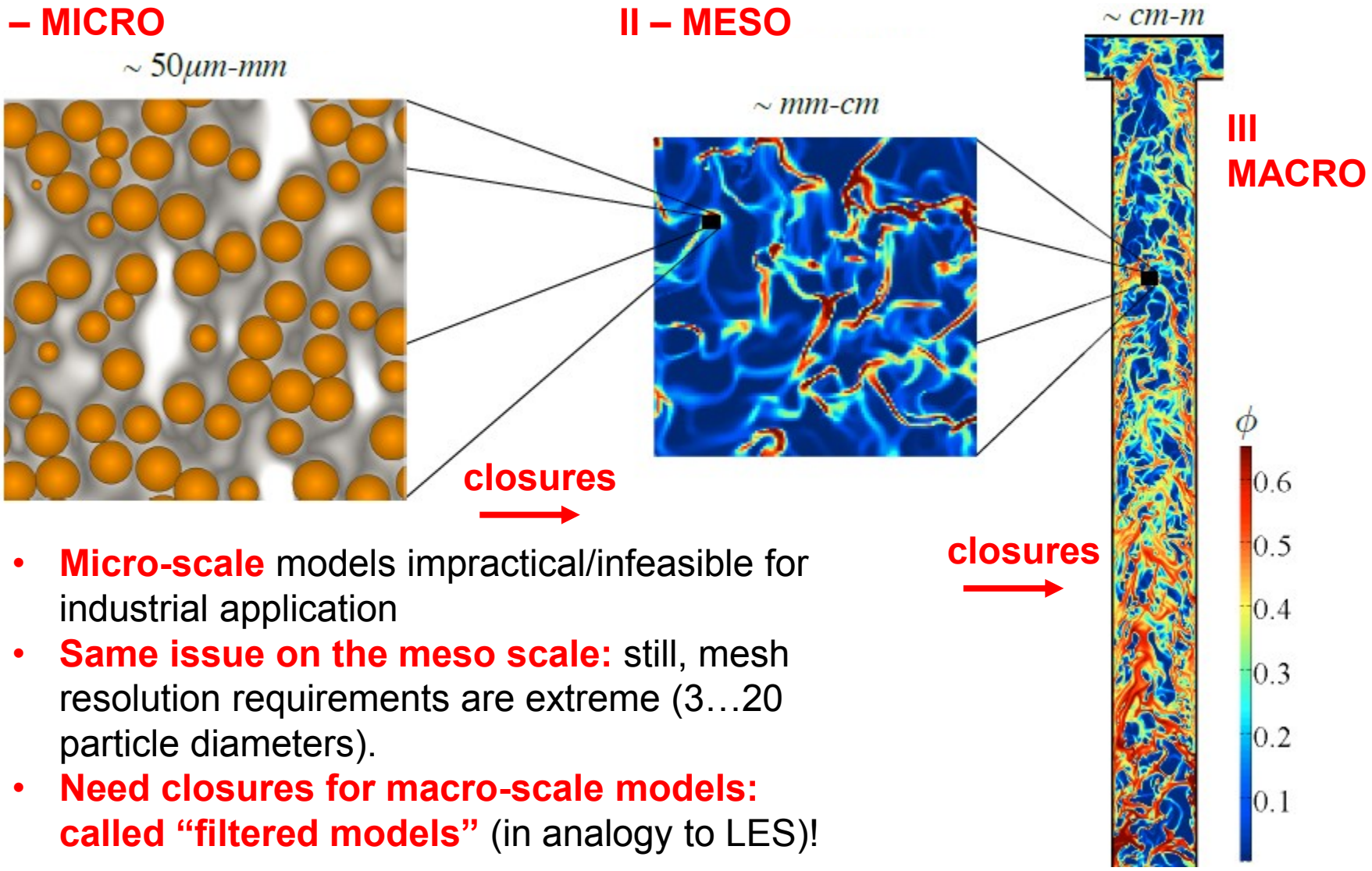


SEVENTH FRAMEWORK PROGRAMME

NanoSim

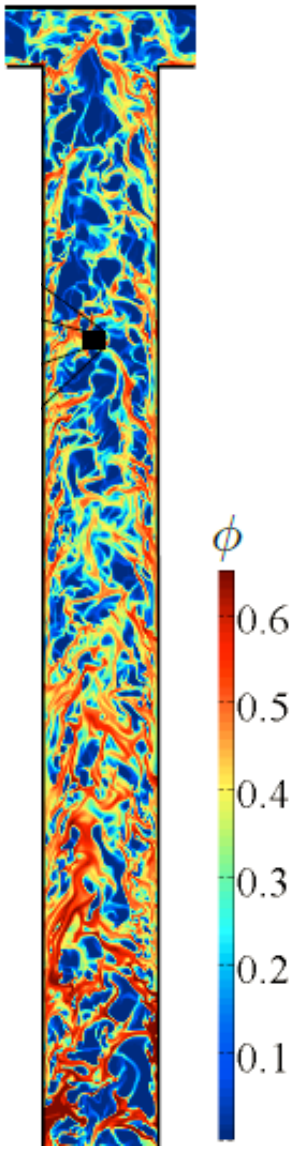
Motivation



- **Micro-scale** models impractical/infeasible for industrial application
- **Same issue on the meso scale:** still, mesh resolution requirements are extreme (3…20 particle diameters).
- **Need closures for macro-scale models: called "filtered models"** (in analogy to LES)!

[1] W. Holloway, PhD Thesis, 2012.

Idea



- Heavily modified **OpenFOAM solver "eulerianFilteredTFM" to simulate an FTFM**
- **new 'eulerianFilteredTFM' library with the following functionality**
  - "Meso-scale" correction to **drag and heat exchange coefficients** (accounting for filter size, voidfraction, voidfraction variance, slip velocity, shear rate, wall-normal distance)
  - **Stress models**
  - **Dispersion models (for scalars)**
  - **Dynamic parameter adjustment based on re-filtered fields** (Ozel et al., AIChE meeting 2016) to close voidfraction variance. Allow future extension to refined scalar variance model (e.g., via transport eqn.)
  - **Future**: boundary conditions for stress

Governing Equations

Particle phase

$$\frac{\partial}{\partial t}\left(\rho_{\mathrm{s}}\overline{\phi}_{\mathrm{s}}\right)+\boldsymbol{\nabla}\cdot\left(\rho_{\mathrm{s}}\overline{\phi}_{\mathrm{s}}\widetilde{\boldsymbol{u}}_{\mathrm{s}}\right)=0$$

$$\frac{\partial}{\partial t}\left(\rho_{\mathrm{s}}\overline{\phi}_{\mathrm{s}}\widetilde{\boldsymbol{u}}_{\mathrm{s}}\right)+\boldsymbol{\nabla}\cdot\left(\rho_{\mathrm{s}}\overline{\phi}_{\mathrm{s}}\widetilde{\boldsymbol{u}}_{\mathrm{s}}\widetilde{\boldsymbol{u}}_{\mathrm{s}}\right)=-\boldsymbol{\nabla}\overline{p}-\boldsymbol{\nabla}\cdot\left(\overline{\boldsymbol{\Sigma}_{\mathrm{s}}^{\mathrm{ms}}}+\overline{\boldsymbol{\Sigma}_{\mathrm{s}}^{\mathrm{fr}}}+\overline{\boldsymbol{\Sigma}_{\mathrm{s}}^{\mathrm{kc}}}\right)$$
$$+\left(\widetilde{\boldsymbol{f}_{gs}}-\overline{\phi_{\mathrm{s}}'\boldsymbol{\nabla}\cdot\boldsymbol{\sigma}_{\mathrm{g}}'}\right)+\rho_{\mathrm{s}}\overline{\phi}_{\mathrm{s}}\mathbf{g}$$

3 regimes to model:
(i) meso-scopic,
(ii) frictional, and
(iii) kinetic theory-based stress

"Heterogeneous" drag laws

Fluid phase

$$\frac{\partial}{\partial t}\left(\rho_{\mathrm{g}}\overline{\phi}_{\mathrm{g}}\right)+\boldsymbol{\nabla}\cdot\left(\rho_{\mathrm{g}}\overline{\phi}_{\mathrm{g}}\widetilde{\boldsymbol{u}}_{\mathrm{g}}\right)=0$$

$$\frac{\partial}{\partial t}\left(\rho_{\mathrm{g}}\overline{\phi}_{\mathrm{g}}\widetilde{\boldsymbol{u}}_{\mathrm{g}}\right)+\boldsymbol{\nabla}\cdot\left(\rho_{\mathrm{g}}\overline{\phi}_{\mathrm{g}}\widetilde{\boldsymbol{u}}_{\mathrm{g}}\widetilde{\boldsymbol{u}}_{\mathrm{g}}\right)=-\boldsymbol{\nabla}\overline{p}-\boldsymbol{\nabla}\cdot\overline{\boldsymbol{\Sigma}_{\mathrm{s}}^{\mathrm{ms}}}$$
$$-\left(\widetilde{\boldsymbol{f}_{gs}}-\overline{\phi_{\mathrm{s}}'\boldsymbol{\nabla}\cdot\boldsymbol{\sigma}_{\mathrm{g}}'}\right)+\rho_{\mathrm{g}}\overline{\phi}_{\mathrm{g}}\mathbf{g}$$

2 regimes to model:
(i) molecular and
(ii) meso-scopic stress

Closures

Common structure for closures (drag)

$$\left(\widetilde{\boldsymbol{f}_{\mathrm{gs}}} - \overline{\phi'_{\mathrm{s}} \boldsymbol{\nabla} \cdot \boldsymbol{\sigma}'_{\mathrm{g}}}\right) = \widetilde{\beta}(\widetilde{\boldsymbol{u}}_{\mathrm{g}} - \widetilde{\boldsymbol{u}}_{\mathrm{s}}) - \overline{\beta(\boldsymbol{u}_{\mathrm{g}} - \boldsymbol{u}_{\mathrm{s}})}$$

$$\overline{\beta(\boldsymbol{u}_{\mathrm{g}} - \boldsymbol{u}_{\mathrm{s}})} = (\mathbf{I} - \boldsymbol{H_D}) \cdot \widetilde{\beta}(\widetilde{\boldsymbol{u}}_{\mathrm{g}} - \widetilde{\boldsymbol{u}}_{\mathrm{s}})$$

Required:

- Closures for microscopic drag coefficient (standard)
- Closure data type for the heterogeneity factor ***H_D* is a tensor.**

Closures

Common structure for closures (stress)

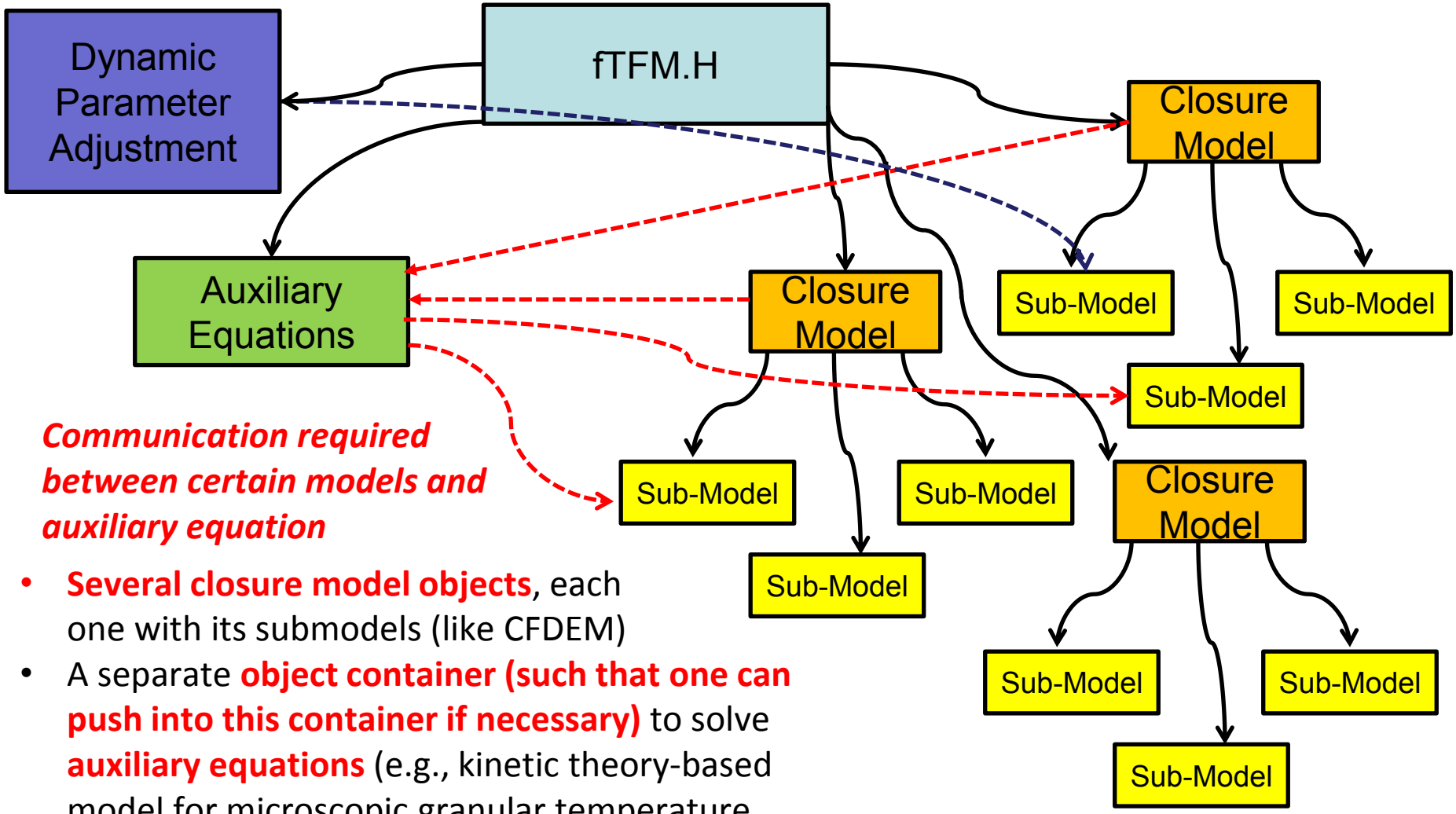
$$\overline{\mathbf{\Sigma}_{\mathrm{q}}^{\mathrm{i}}} = \left[p_{\mathrm{q}}^{\mathrm{i}} - \lambda_{\mathrm{q}}^{\mathrm{i}} \mathrm{tr}\left(\mathbf{D}_{\mathrm{q}}\right)\right] \mathbf{I} - 2\mu_{\mathrm{q}}^{\mathrm{i}} \mathrm{dev}\left(\mathbf{D}_{\mathrm{s}}\right) + \overline{\boldsymbol{\sigma}}_{q,a}^{i}$$

Required:

- Pressure
- Bulk viscosity λ_q (often disregarded)
- Viscosity μ_q
- Residual anisotropic stress tensor contribution $\sigma_{q,a}$ (symmetric tensor)

Stress model classes provide those 4 quantities!

Library Structure



Communication required between certain models and auxiliary equation

- **Several closure model objects**, each one with its submodels (like CFDEM)
- A separate **object container (such that one can push into this container if necessary)** to solve **auxiliary equations** (e.g., kinetic theory-based model for microscopic granular temperature, filtered granular temperature)

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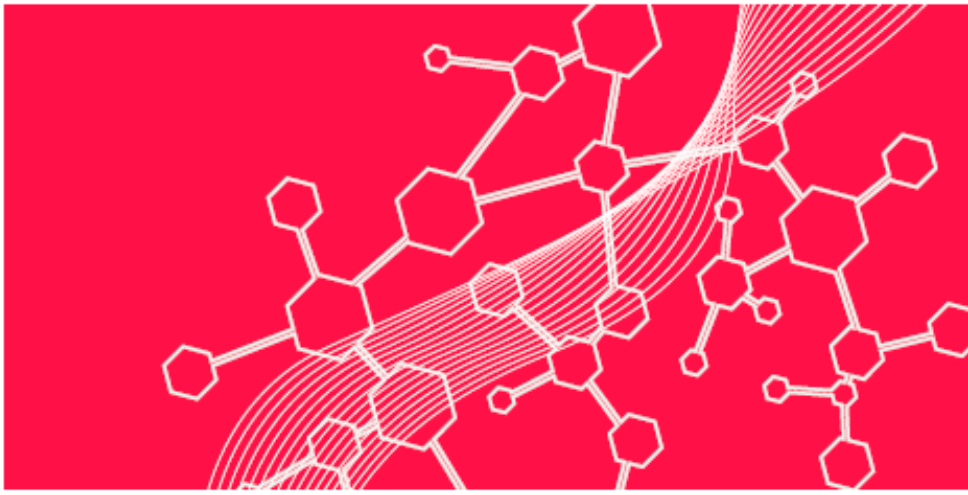

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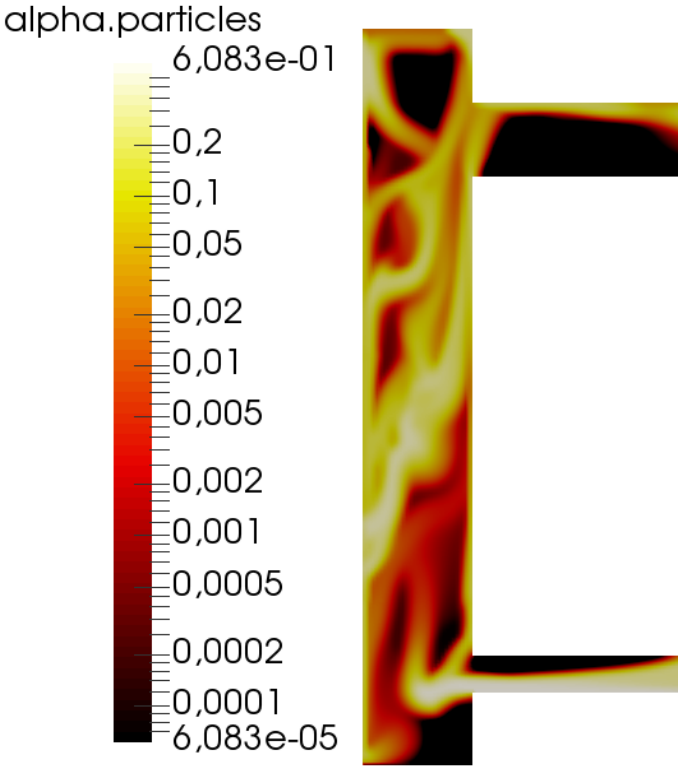
Expected Public Release Date: End of November 2017 via https://github.com/CFDEMproject



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