2021 Workshop on Multiphase Flow Science
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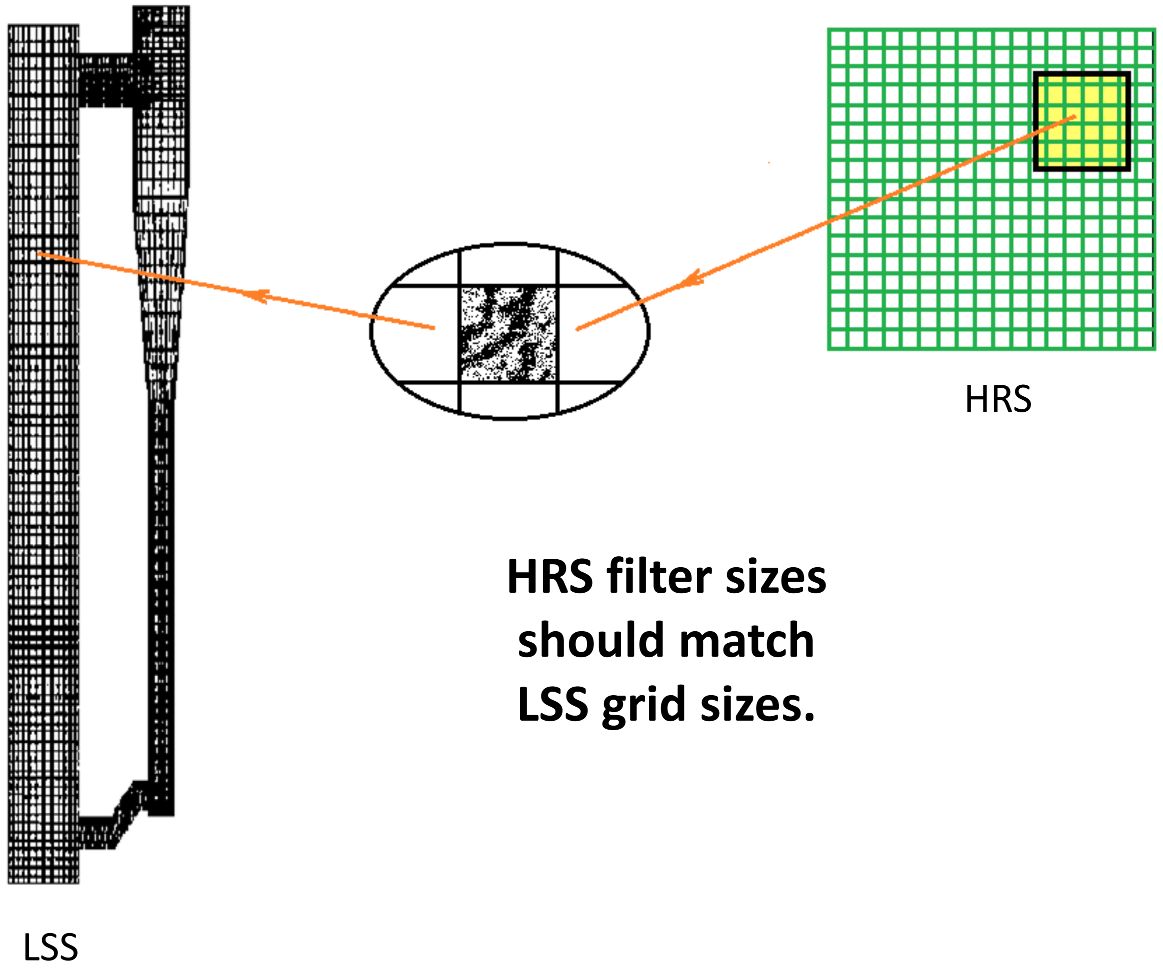
On the effect of particle Froude number in sub-grid modeling of gas-solid fluidized flows

Chris C Milioli
Fernando E Milioli
University of São Paulo - Brazil

Our ultimate objective
(constitutive modeling through HRS)



HRS filter sizes should match LSS grid sizes.

At left a numerical mesh of a Large Scale Simulation (LSS), highliting a grid cell over which the inside meso-scale flow is dissipated and turned homogeneous.

At right a numerical mesh of a Highly Resolved Simulation (HRS) applying fine grids thereby allowing the capture of meso-scale flow heterogeneities, also showing a space filter applied over the grids so as to recover effects of flow heterogeneities to be provided to the Large Scale Simulations as constitutive models.

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Microscopic two-fluid model

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

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

$$\frac{\partial}{\partial t}(\rho_g \phi_g \boldsymbol{v}_g) + \nabla \cdot (\rho_g \phi_g \boldsymbol{v}_g \boldsymbol{v}_g) = -\phi_g \nabla \cdot \boldsymbol{\sigma}_g - \boldsymbol{M}_{\boldsymbol{l}} + \rho_g \phi_g \boldsymbol{g}$$

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

$$\phi_{\boldsymbol{g}} + \phi_{\boldsymbol{s}} = 1$$

Closures

$$\frac{3}{2}\left[\frac{\partial}{\partial t}(\rho_s\phi_s\theta)+\nabla\cdot(\rho_s\phi_s\boldsymbol{v}_s\theta)\right]=-\boldsymbol{\sigma}_s:\nabla\boldsymbol{v}_s+\nabla\cdot(k_s\theta)+\Gamma_{slip}-J_{coll}-J_{vis}$$

$$\boldsymbol{M_I}=\beta(\boldsymbol{v}_g-\boldsymbol{v}_s) \qquad \beta=\frac{3}{4}C_D\frac{\rho_s\phi_s\phi_g|\boldsymbol{v}_g-\boldsymbol{v}_s|}{d_p}(\phi_g)^{-2.65}$$

$$C_D=\begin{cases}\frac{24}{Re_p}\left(1.0+0.15\,Re_p{}^{0.687}\right) & for\ Re_p<1000\\ 0.44 & for\ Re_p\geq 1000\end{cases}$$

$$Re_p=\frac{|\boldsymbol{v}_g-\boldsymbol{v}_s|d_p\rho_g\phi_g}{\mu_g}$$

Filtered parameters

$$H = 1 - \frac{\beta_{eff}}{\bar{\beta}}$$

$$\beta_{eff} = \frac{\overline{\beta(\boldsymbol{v}_g - \boldsymbol{v}_s)}}{(\tilde{\boldsymbol{v}}_g - \tilde{\boldsymbol{v}}_s)} - \frac{[\overline{\phi_s \nabla P_g} - \bar{\phi}_s \nabla \tilde{P}_g]}{(\tilde{\boldsymbol{v}}_g - \tilde{\boldsymbol{v}}_s)}$$

$$P_{fill,s} = \bar{P}_s - \overline{\left(\lambda_s + \frac{2}{3}\mu_s\right)(\nabla \cdot \boldsymbol{v}_s)}$$

$$\mu_{fill,s} = \bar{\mu}_s$$

Residual parameters

$$P_{res,l} = \frac{1}{3}\, tr(\boldsymbol{\tau}_l^{'})$$

$$\mu_{res,l} = \frac{\left|\boldsymbol{\tau}_{shear,l}^{'}\right|}{2\left|\tilde{S}_{shear,l}^{'}\right|}$$

HRS simulations

Simulations were performed with the microscopic two-fluid model of MFIX, for:

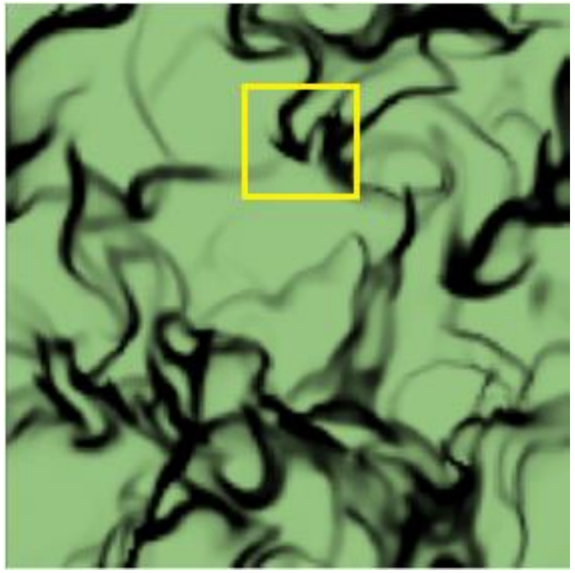
- **low Reynolds number suspensions**
- **15% domain average solid volume fraction**
- **particulates of 40, 75, 150, 300 μm (Fr_{dp}= 12.21, 64.95, 286.69, 799.26)**
- **all periodic boundaries**
- **16 x 16 cm domain**
- **128 x 128 grids (1.25 x 1.25 mm grid cells)**

Particulate and gas properties:

$\rho_s = 1500\ \mathrm{kg/m^3}$ $\quad e = 0.9$

$\rho_g = 1.3\ \mathrm{kg/m^3}$ $\quad \mu_g = 1.8\times10^{-5}\ \mathrm{kg/(m\,s)}$

Filtering HRS data



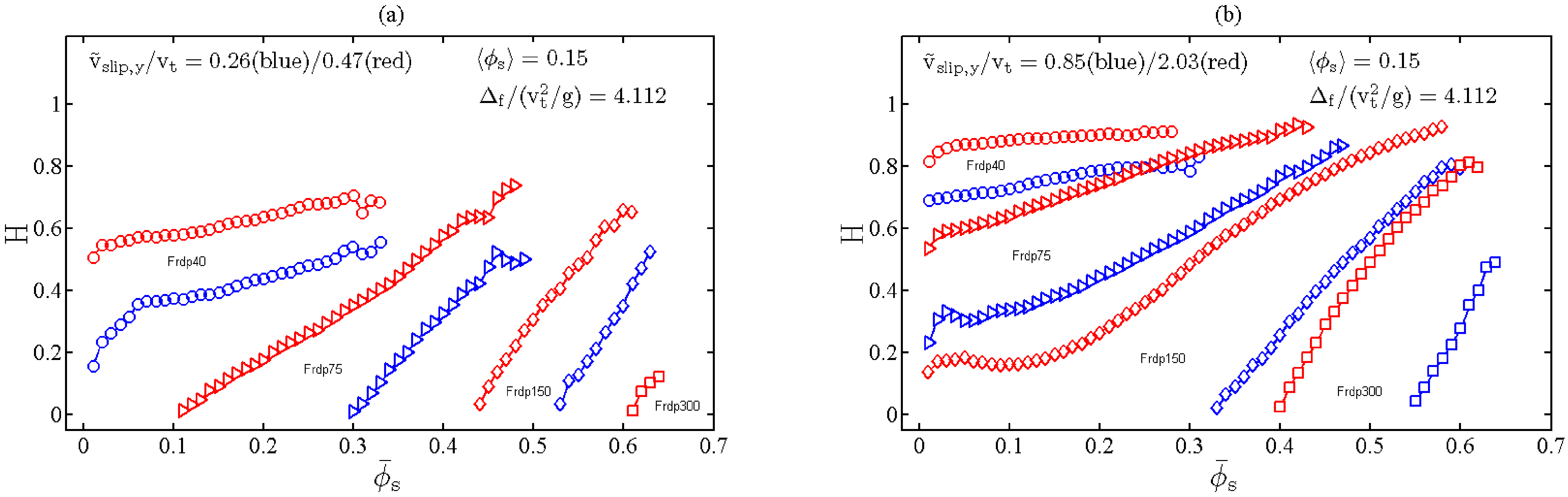
HRS snapshot (grayscale plot of solid volume fraction)

- A square filter box is defined embracing a number of HRS grid cells, which is made to sweep all over the domain while calculating inside averages (i.e. filtered data).
- Filtered data are classified while statistically averaged for ranges of suitable markers (binning).

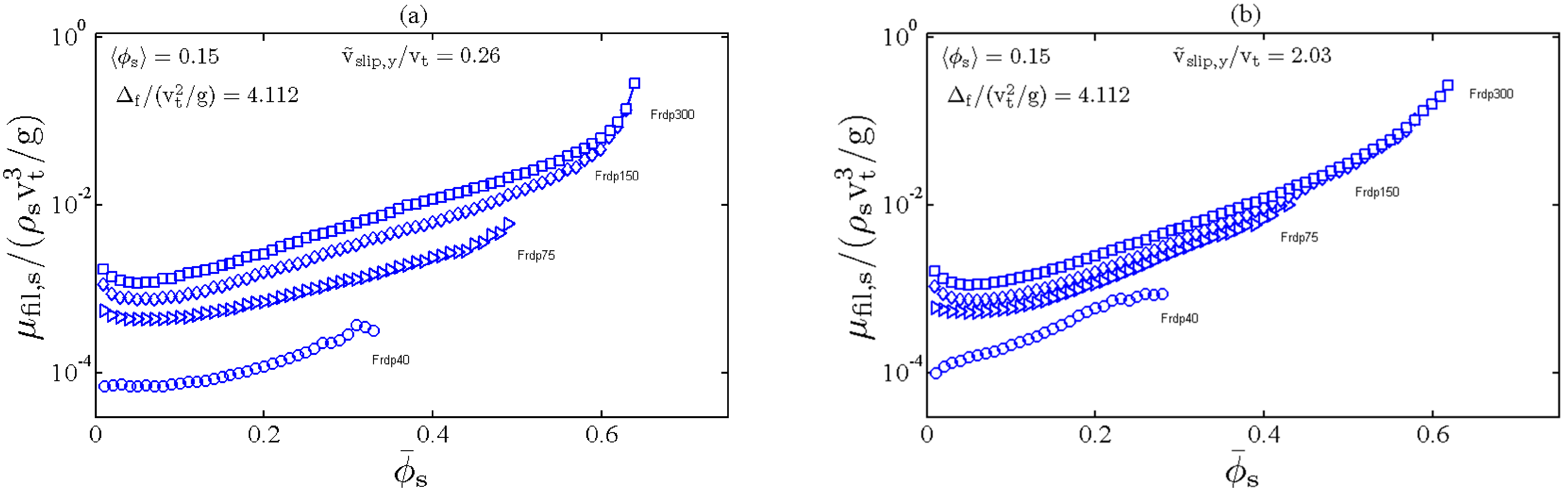
Our markers: $\overline{\phi}_s$, $\tilde{V}_{slip,y}$

Some results

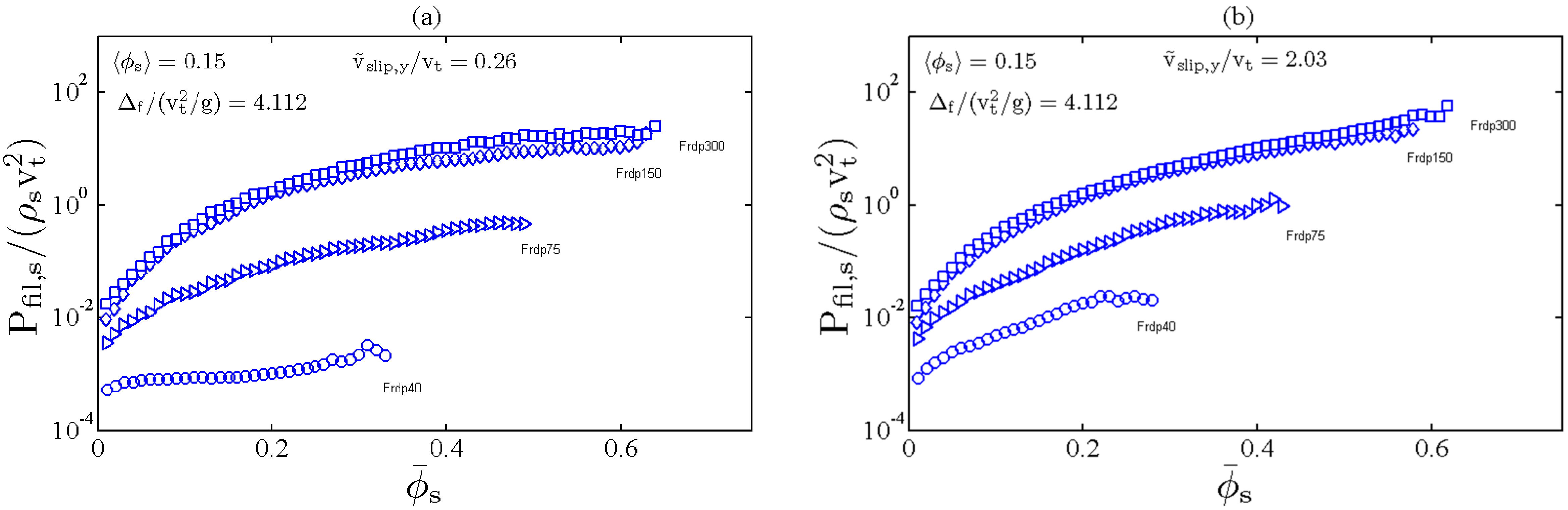
Drag coeficiente correction factor



Filtered solid viscosity



Filtered solid pressure



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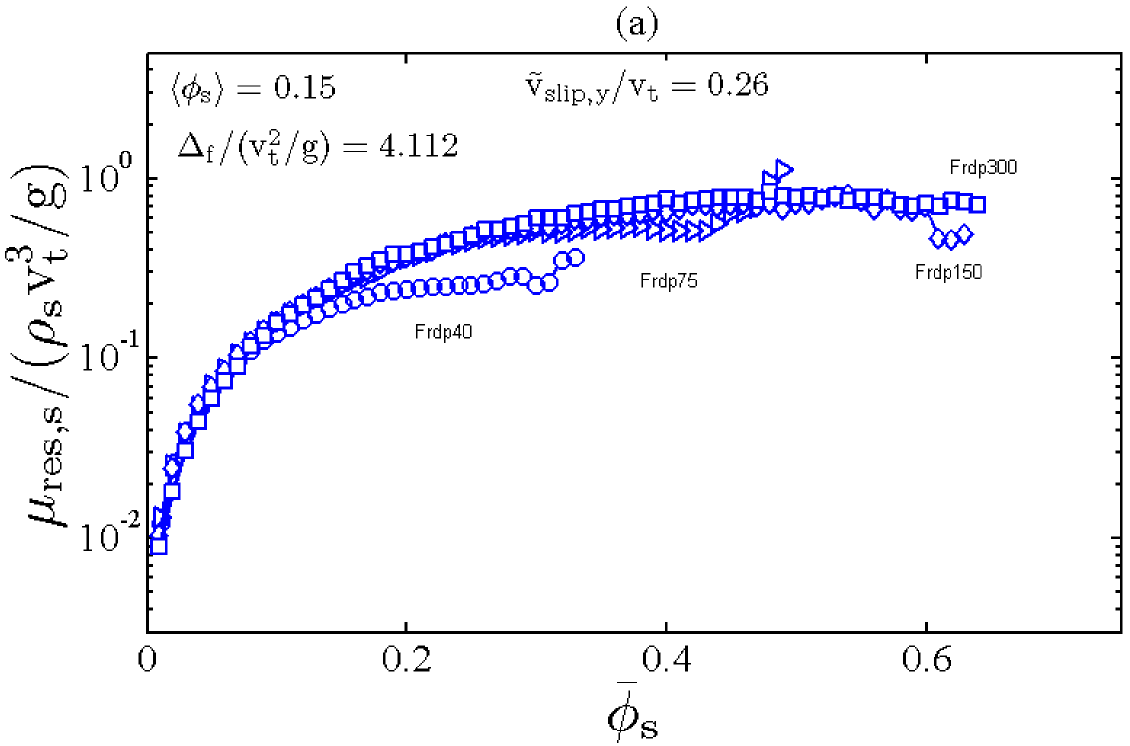
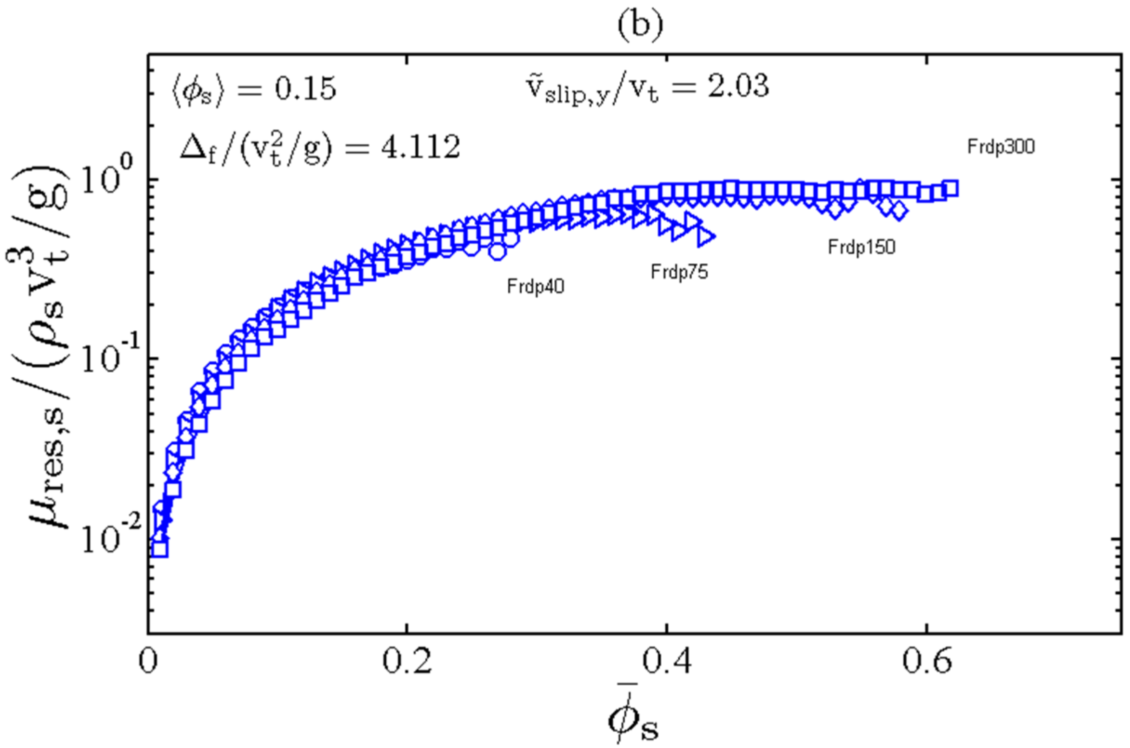
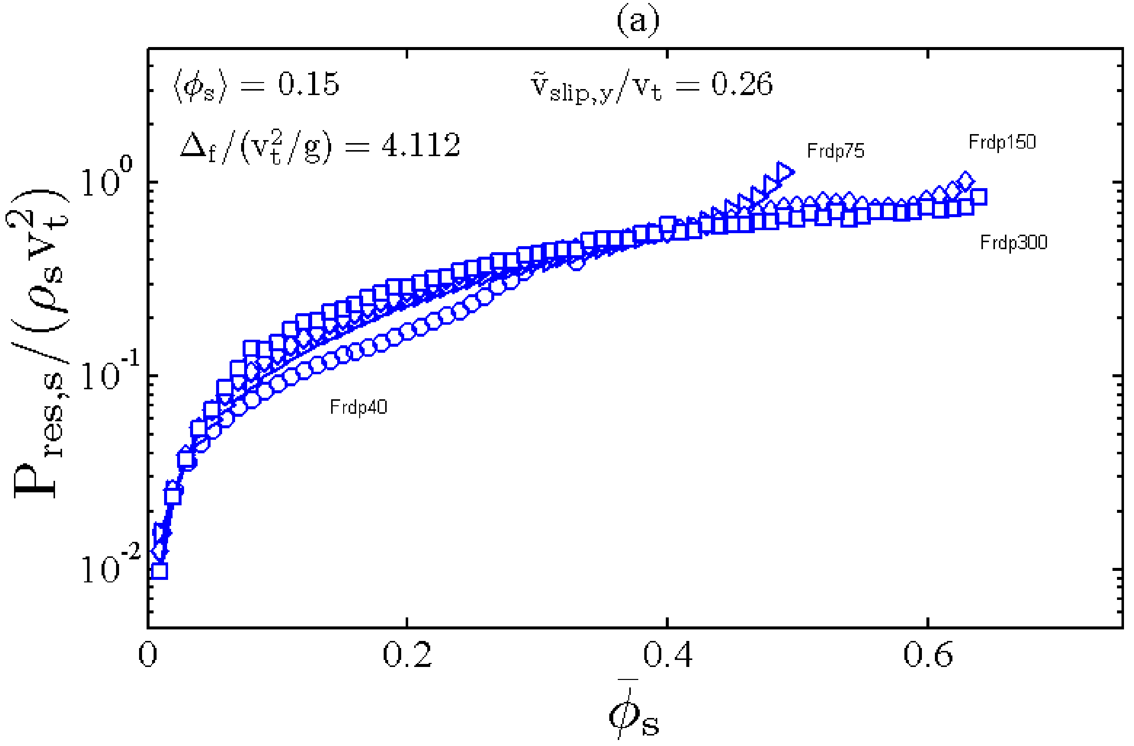
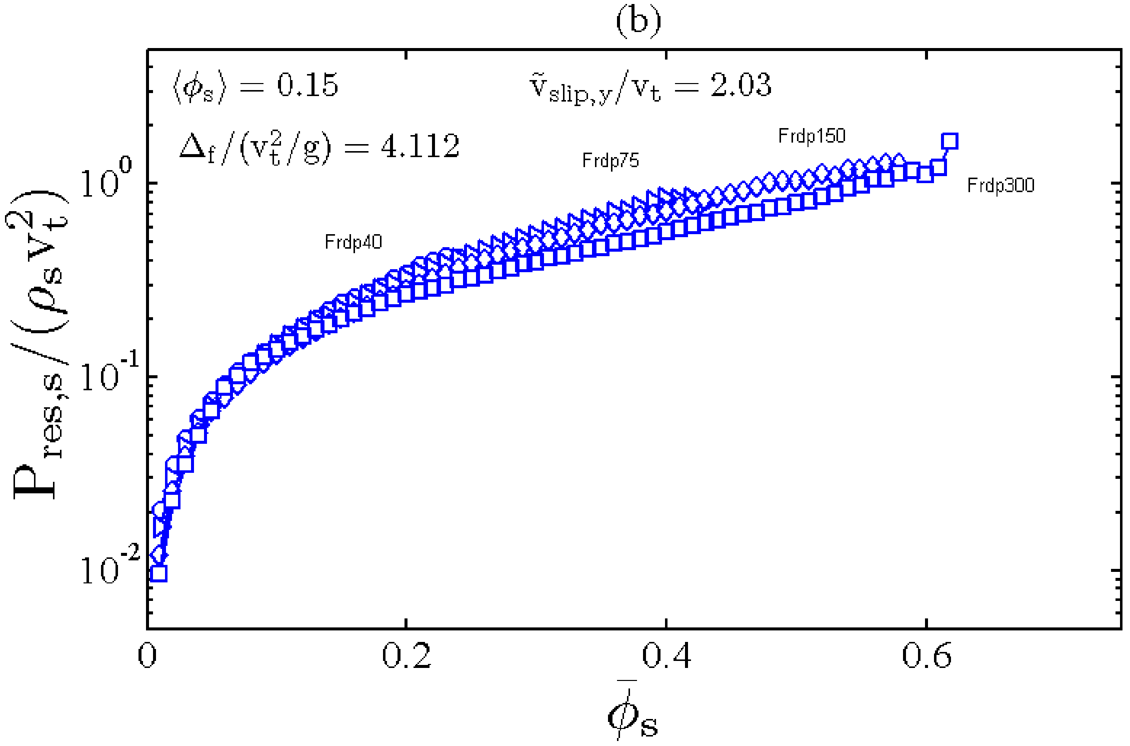
Residual solid viscosity





Residual solid pressure





Main conclusion and future work

- The filtered parameters of concern were affected by particle Froude number at different extents, indicating that future constitutive models must account for particle Froude number.

- Before new constitutive models can be derived accounting for particle Froude number, further work is required to account for:

  # higher domain average gas Reynolds numbers

  # a variety of domain average solid volume fractions

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Thank you very much!