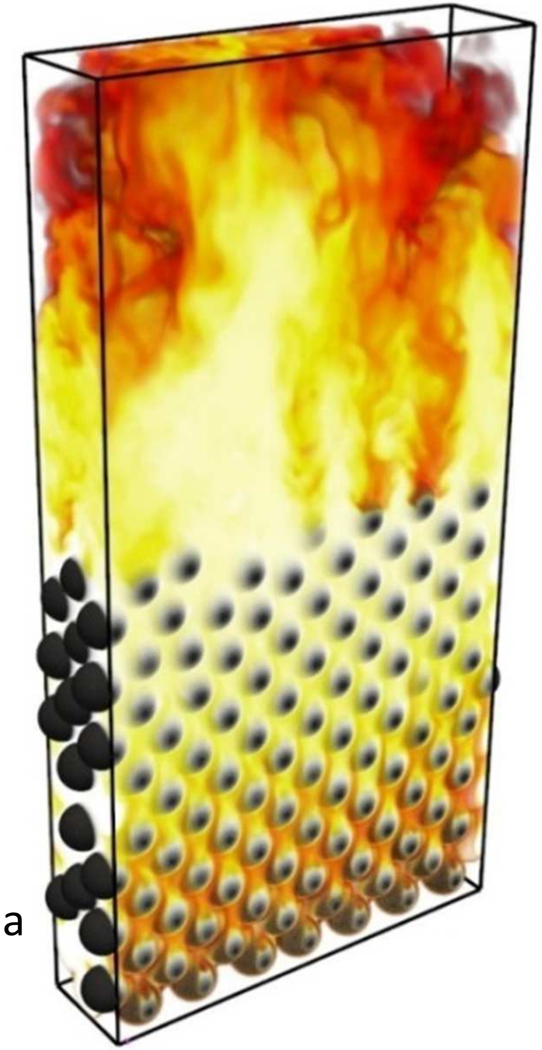
Near-wall effects for momentum, heat and mass transport

in gas-particle suspensions at moderate Reynolds numbers



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Presented at the APS DFD Meeting 2016, Portland, OR

Motivation: engineering models

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Why studying heat and mass transfer in wall bounded gas-particle suspensions ?

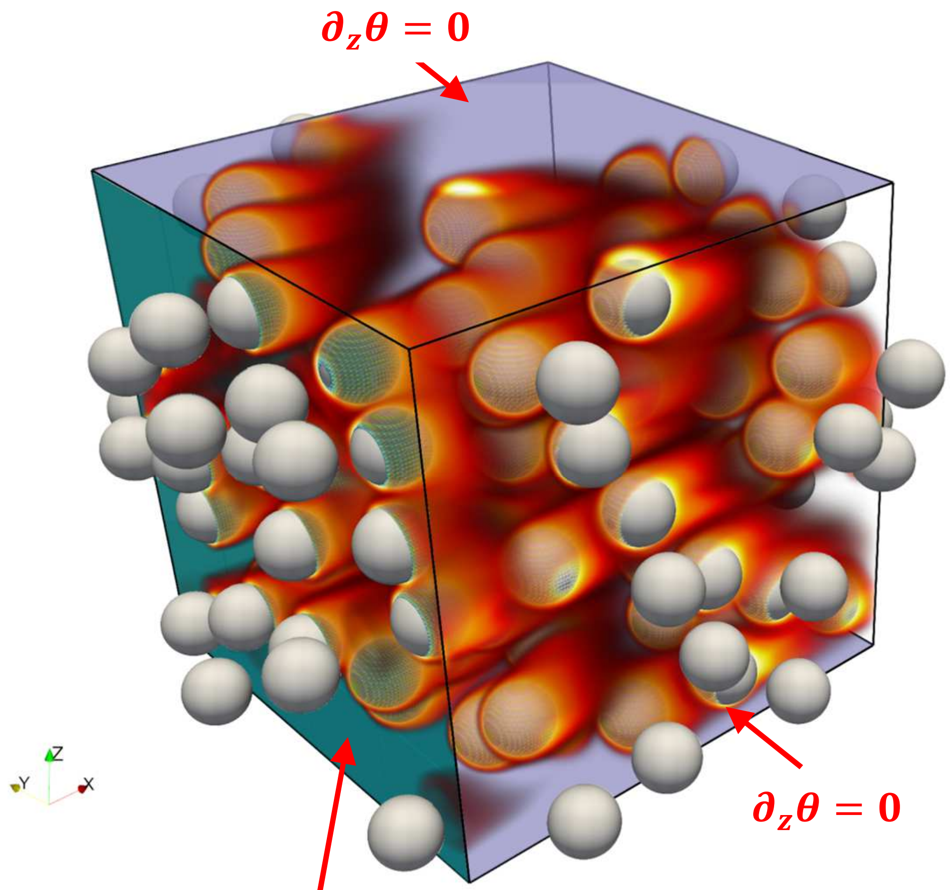
- **Local inhomogeneity of fluid and particle temperature** close to walls can **drastically** affect process performance. This can cause problems in chemical reactors, or heat exchangers (e.g., **local overheating, cool regions near walls**)
- Root cause are perturbations that can happen at small length scales, **below the resolution of classical models for averaged quantities** employed in engineering practice
- We expect that models based on **spatially averaged equations** require **special boundary treatment (closures)**

We use **Particle-Resolved Direct Numerical Simulation (PR-DNS)** to quantify **key effects** to lay the foundation for modeling wall effects

Particle-Resolved DNS

- Particle bed generated via bi-axial **compaction** in the *xy* plane using **LIGGGHTS®**[1]
- Flow and temperature fields are solved in a *xy* **periodic domain**. Particles are isothermal
- **CFDEM®Coupling**[1] to solve the governing equations for the continuum phase
- Particles are represented by forcing terms in the governing equations (solved in a **Cartesian grid**) evaluated using the **HFD-IB**[2] method

Boundary conditions: temperature field



[1]*Kloss et al., Progress in Computational Fluid Dynamics, 12:140–152, 2012*

[2]*Municchi et al., CFDEMCoupling user meeting 2016, Linz*

Current study: parameter space

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- Reynolds number fixed to **100**:

$$Re = \frac{\rho_f (1 - \phi_p)\, u\, d_p}{\nu} = \frac{\rho_f\, U_S\, d_p}{\nu}$$

- Momentum and heat transfer for suspensions characterized by $\boldsymbol{\phi_p = 0.1 - 0.4}$

- Multilple realizations to ensure statistical significance (>2,000 particles considered for each case)
  - $\phi_p = 0.1$: **40 realizations**
  - $\phi_p = 0.2$: **20 realizations**
  - $\phi_p = 0.3$: **20 realizations**
  - $\phi_p = 0.4$: **16 realizations**

ρ_f: fluid phase density
ϕ_p: particle volume fraction
d_p: particle diameter
ν : fluid viscosity
U: reference fluid velocity
U_S: superficial velocity

Particle-based quantities: filtering

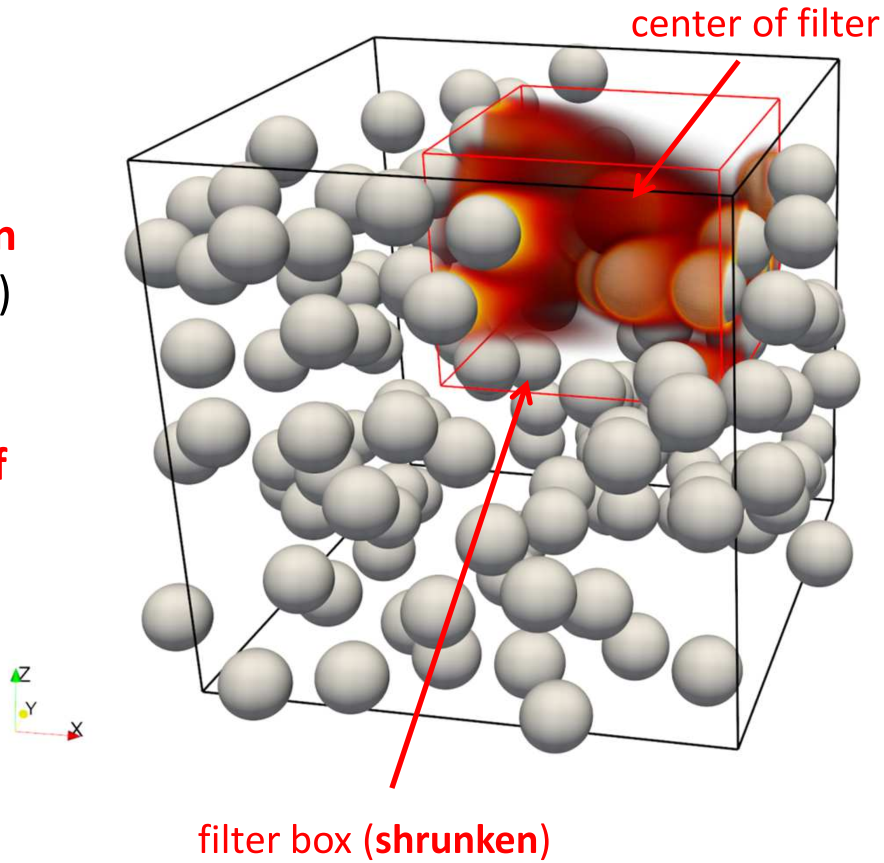
- We make use of the filtering toolbox **CPPPO**[3] to spatially average ("filter") the continuum phase properties around **each particle**

$$\varrho = \frac{L_{filter}}{d_p}$$ Dimensionless filter size

- CPPPO is also employed to draw more "conventional" statistics (e.g., **profiles in wall-normal direction, "pancake filter"**)

- Filter boxes are **shrunk in the vicinity of wall boundaries**, same as done for wall bounded single phase turbulent flow[4]

Lagrangian filtering: wall particles



[3]*Municchi et al., Computer Physics Communications, 2016 207:400-414*

[4]*Sagaut, 2006, Springer*

Particle-based quantities: filtering

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Definitions

$$\mathbf{f}_i^d \equiv \mathbf{f}_i - \mathbf{f}_i^{\nabla p^\varrho}$$

$\mathbf{f}_i$: Total force acting on particle i

$\mathbf{f}_i^d$: Drag force acting on particle i

$\mathbf{f}_i^{\nabla p^\varrho}$: Force due to mean pressure gradient **on particle i**

∇p_i^ϱ : **Mean pressure gradient seen by particle i**

$$F_i \equiv \frac{\mathbf{f}_{i,x}^d}{3\,\pi\,\mu\,d_p\,(1-\phi_i^\varrho)\,\mathbf{u}_{i,x}^\varrho}$$

d_p : Diameter of particles

F_i : Drag coefficient of particle i

ϕ_i^ϱ : Volume fraction of solid phase around particle i.

$\mathbf{u}_{i,x}^\varrho$: Normalized mean **relative velocity seen by particle i**

$$Nu_i \equiv \frac{Q_i^* Pe}{\pi\,(\theta_s - \theta_i^\varrho)}$$

Q_i^* : Normalized heat exchange rate

Pe : Peclet number

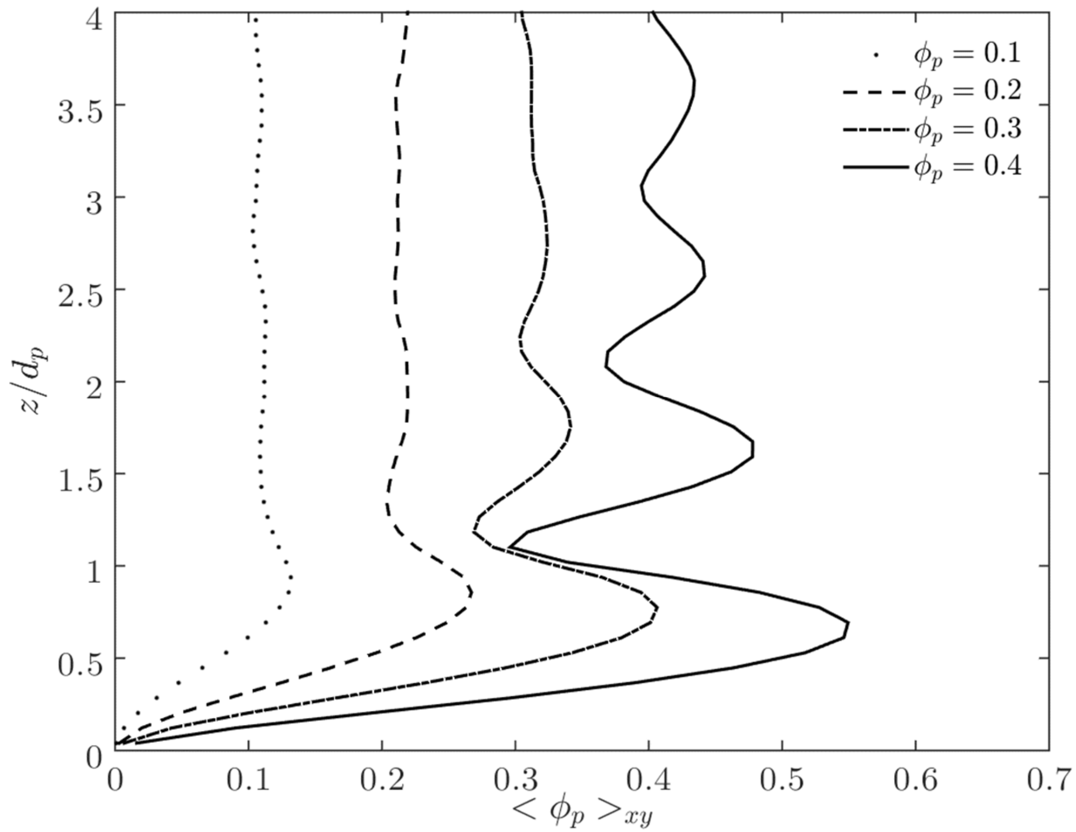
θ_i^ϱ : Fluid **temp. seen by particle i**

θ_s : Surface temperature of particle i

Wall effects: particle distribution

- The particle volume fraction is **inhomogeneous** on the scale of d_p
- This inhomogeneity results also in the continuum phase properties to be inhomogeneous **on the same scale**

"pancake" filter



Wall effects: temperature and velocity

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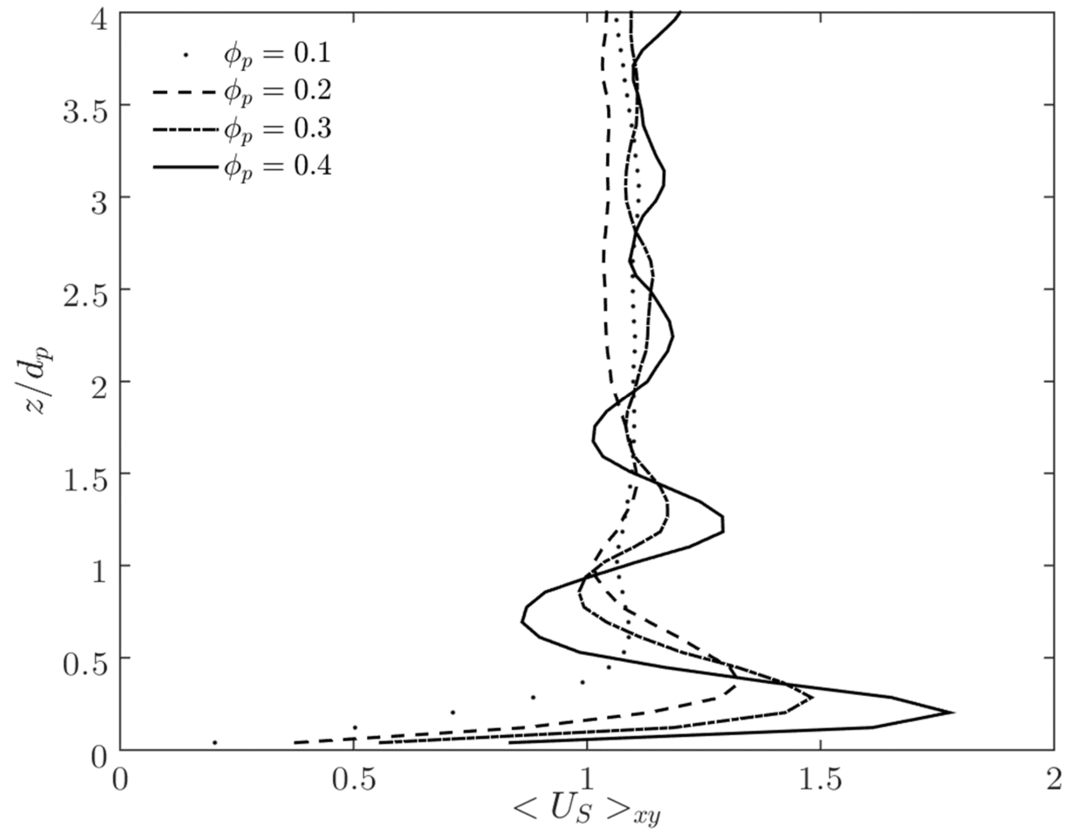
- The temperature profile has a **minimum at the wall** due to the low value of ϕ_p and thus, the reduced exchange surface

- In addition, the exchanged heat is quickly **removed by convection**

- As ϕ_p is **increased** the fluid flows through the path of **minimum resistance: the wall neighborhood**

"pancake" filter



U_S is calculated using the global ϕ_p and the local U.

Wall effects: particle-based Drag

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- **ϕ_p = 0.1**

The drag is **larger at the wall** and **larger for low ϱ**

- **ϕ_p = 0.2**

Oscillations close to the wall and weak dependence on ϱ

- **ϕ_p = 0.3**

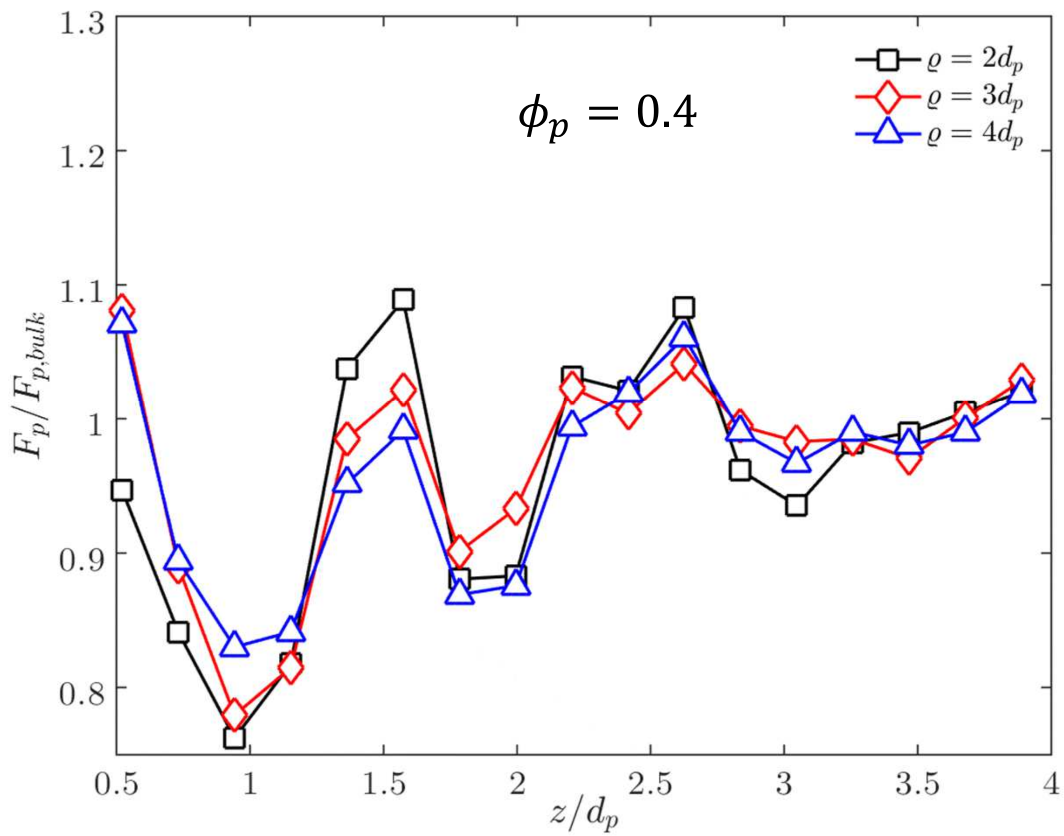
Minimum at $z = d_p$ and **no dependence** on ϱ

- **ϕ_p = 0.4**

The drag is **smaller at the wall** and **smaller for ϱ low**

Oscillations propagate up to $z = 2.5d_p$

"box" filter



The drag coefficient near the wall tends to **decrease with increasing ϕ_p**

Wall effects: particle-based Nusselt number

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"box" filter

- **ϕ_p = 0.1**

No large wall effects

- **ϕ_p = 0.2**

Little changes

- **ϕ_p = 0.3**

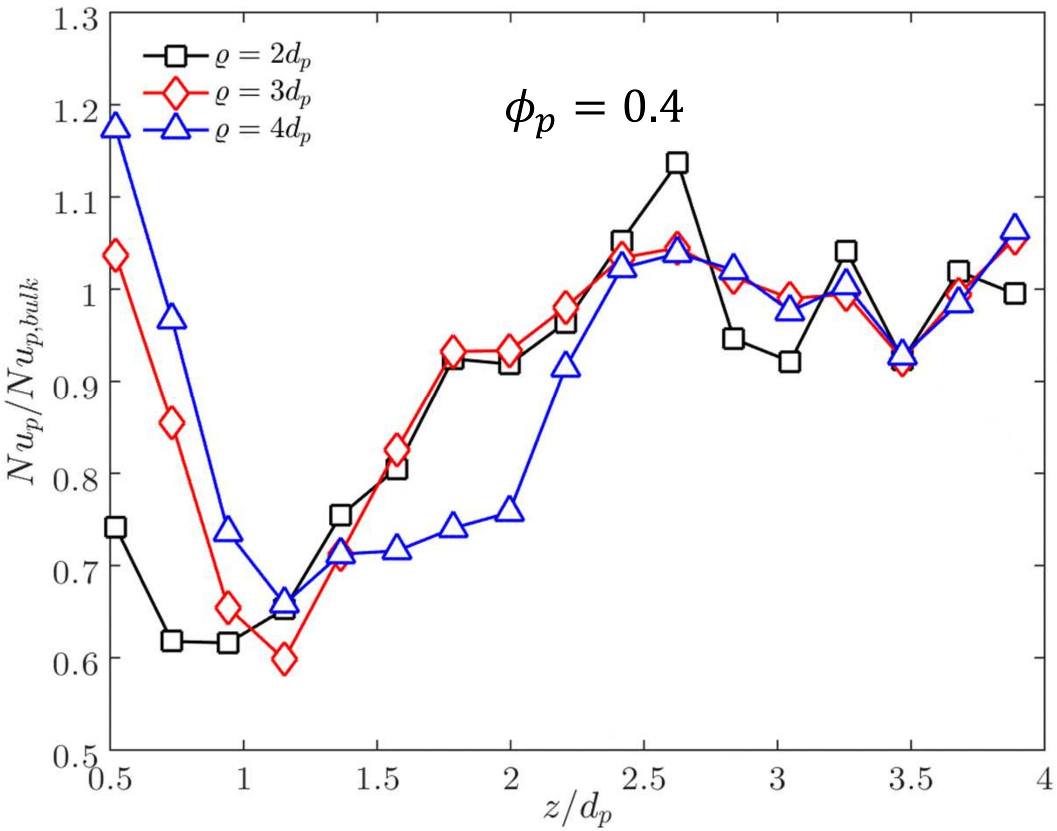
Weak dependency on ϱ

Minimum at $z = d_p$

- **ϕ_p = 0.4**

Marked dependency on ϱ

Stronger minimum and effects up to $z = 2.5d_p$



Similar behavior as for the drag coefficient but increased *Nu* at the wall with increasing ϕ_p

Can we exploit an analogy?

Conclusions

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Which situations are affected by wall effects ?

…for the moderate Reynolds number studied here…

- **Always for the drag coefficient**. Not taking into account wall effects can lead to an error up to $\mathbf{40\%}$. **Wall effects are stronger for increasing values of $\boldsymbol{\phi_p}$**

- In case $\boldsymbol{\phi_p > 0.2}$ **also for the Nusselt number** . The particle-fluid heat transfer does not seem to be significantly affected in dilute suspensions in case of **adiabatic walls.** In dense suspensions we observe **deviations of $\mathbf{-40\%}$ to $\mathbf{+20\%}$** for the per-particle Nusselt number

What is the key consequence of wall effects ?

- Even when using **adiabatic walls, extreme fluid temperature gradients** near the wall are observed

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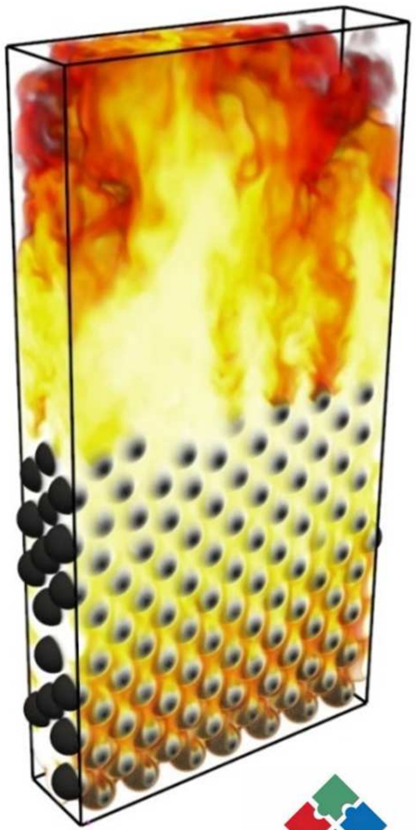

Funding was provided by **EC Grant #604656** (software development), and "**NAWI Graz**" (access to VSC-3 and dcluster.tugraz.at).

Code available via **github.com/CFDEMproject**

For more information search "Radl" on **online.tugraz.at**