Fictitious Domain and Immersed Boundary methods in OpenFOAM: Application to Complex Geometries

Federico Municchi

Stefan Radl

Institute of Process and Particle engineering, TU Graz, Graz

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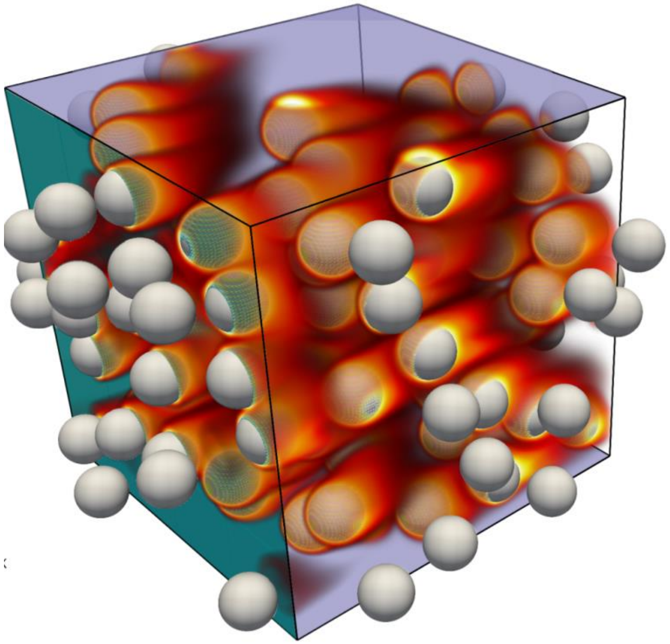


Embedding geometry into the equations

What are Immersed Boundary and Fictitious Domain methods?

- Methods where **the geometry is not resolved explicitly**, but by mean of **additional terms** in the governing equations.
- Allow to use **Cartesian structured grids** even for very complicated geometries.
- Mostly used for **viscous flows**, but can be extended to include wall functions.
- Particularly **effective** when dealing with **moving boundaries**.

Two similar approaches

Our focus

Solving the transport equations in complex domains using a simple cartesian mesh

$$\frac{\partial u_i}{\partial x_i} = 0$$

$$\frac{\partial u_i}{\partial t} + \frac{\partial u_i u_j}{\partial x_j} = -\frac{\partial p}{\partial x_i} + \frac{1}{Re}\frac{\partial^2 u_i}{\partial x_j \partial x_j} + f_i^{IB}$$

$$\frac{\partial \theta}{\partial t} + \frac{\partial u_i \theta}{\partial x_i} = \frac{1}{Pe}\frac{\partial^2 \theta}{\partial x_i \partial x_i} + Q^{IB}$$

And boundary conditions...

Take into account the presence of rigid bodies inside the fluid domain

Immersed Boundary

The forcing term imposes the Dirichlet boundary condition at the immersed body surface*.

Fictitious Domain

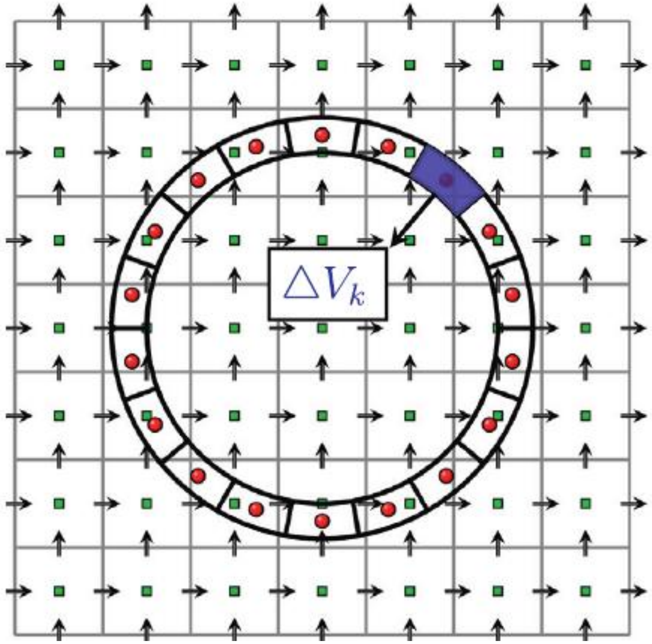
The forcing term a imposes a rigidity condition inside the immersed body**.

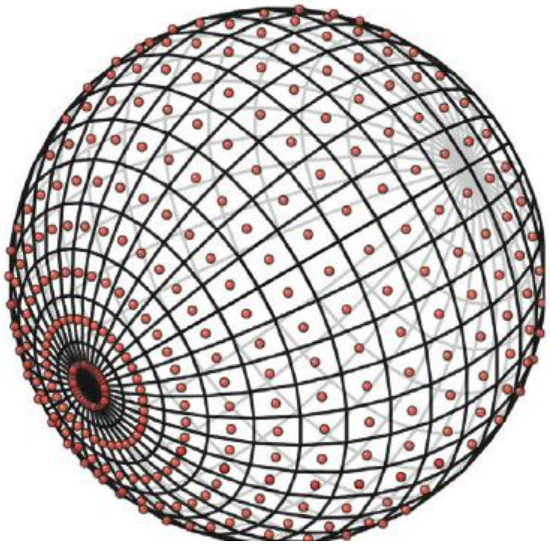
**Peskin C. , Flow patterns around heart valves: a numerical method, Journal of computational physics ,1971*

***Smagulov S. , Fictitious domain method for the Navier-Stokes equations (in russian), Preprint CS SO USSR, N 68, 1979*

Two similar approaches

A closer look – immersed boundary





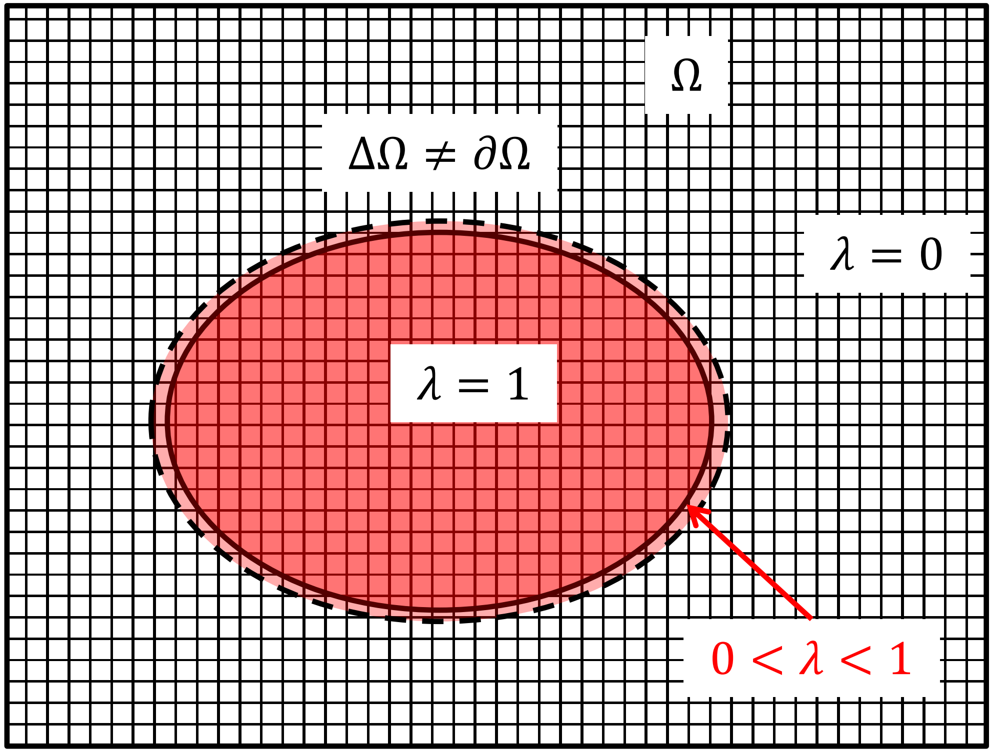
Additional discretization for the immersed surface

Tavassoli et al., 2013

- Forcing terms are evaluated calculated at the boundary nodes and subsequantly estrapolated to the fluid nodes.
- **Not convergent.**

Two similar approaches

A closer look – fictitious domain



- A penalty field λ represents the solid volume fraction at each cell.
- The solid boundary is **diffused**.
- Fields are calculated as weighted sums of solid and fluid phase: $\theta = \lambda\theta_s + (1 - \lambda)\theta_f$
- **This method is convergent**,

A hybrid approach

One can use a **fictitious domain approach for the interior** of the immersed body and a **correction for surface cells**. Thus:

- Imposing the **body field** at **cells completely inside the body.**
- Imposing a value at the **partially covered cells** that ensure the **boundary condition is respected at the immersed surface.**

This requires a term in the Navier-Stokes equation that is able to impose the required field values.

May also require a source term in the continuity equation to balance the fluxes inside the immersed body (we neglect this term).

These terms must return the limit of fictitious domain when the grid size tends to zero

A hybrid approach

Forcing term for Navier-Stokes:

$$f_i^{IB} = \Psi(\boldsymbol{x}, t)\left(\frac{\partial u_i}{\partial t} + \frac{\partial u_i u_j}{\partial x_j} + \frac{\partial p}{\partial x_i} - \frac{1}{Re}\frac{\partial^2 u_i}{\partial x_j \partial x_j} + u_i^{IB} - u_i\right)$$

$\Psi(\boldsymbol{x}, t)$ is the indicator function (tells where the term is active)

u_i^{IB} is the imposed velocity

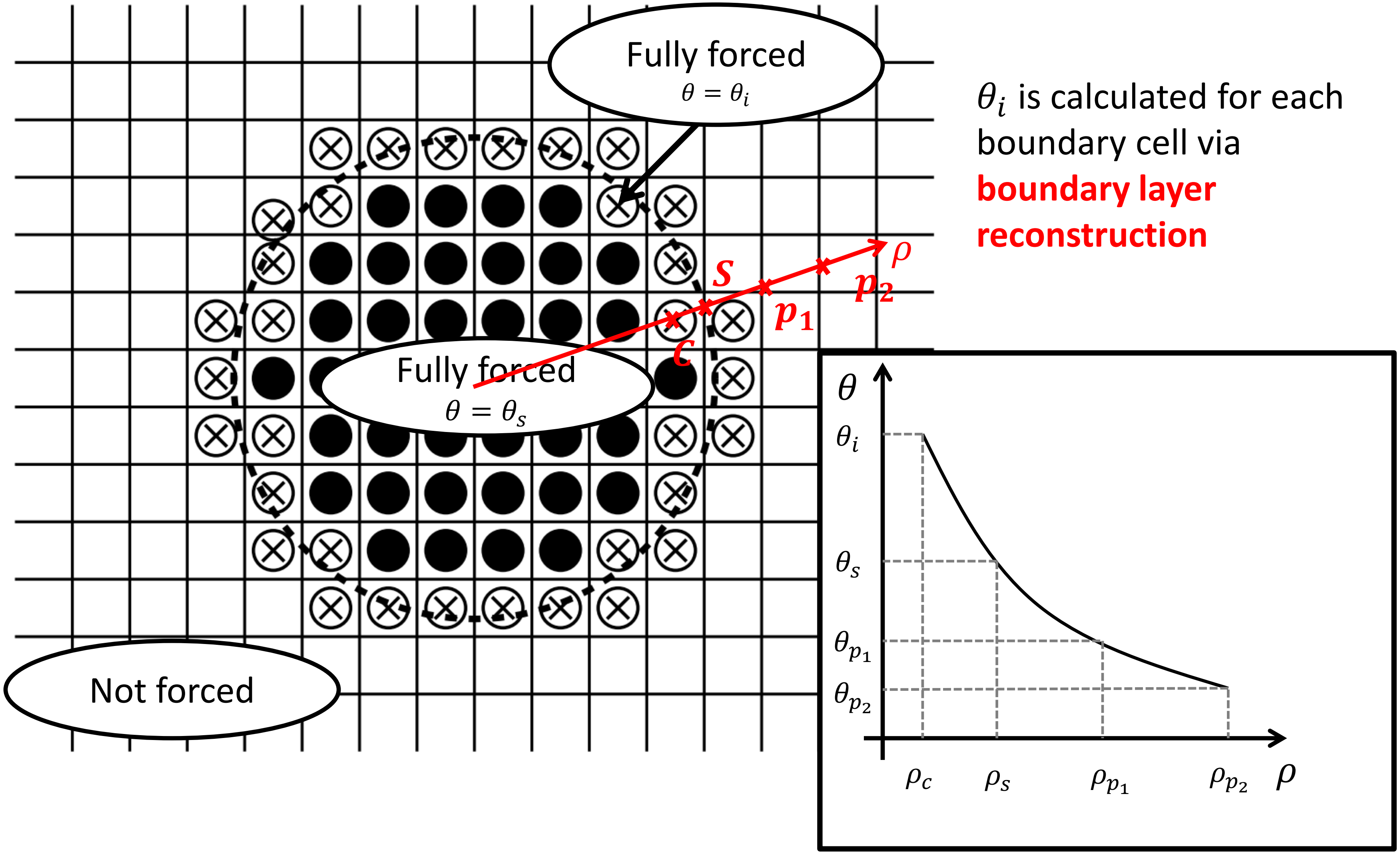
u_i^{IB} is the body velocity inside the body. At surface cells, we can express it in Taylor series:

$$u_i^{IB} = u_i^s + \left.\frac{\partial u_i}{\partial n}\right|_s \Delta s + \frac{1}{2}\left.\frac{\partial^2 u_i}{\partial n^2}\right|_s \Delta s^2$$

u_i^s is the velocity at the particle surface (calculated)
n indicates the direction normal to the surface
Δs is the distance between the surface cell and the particle surface over $\hat{n}$

Second order boundary layer reconstruction

A hybrid approach



θ_i is calculated for each boundary cell via **boundary layer reconstruction**

HFDIB-where to find it

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Practical implementation in OpenFOAM

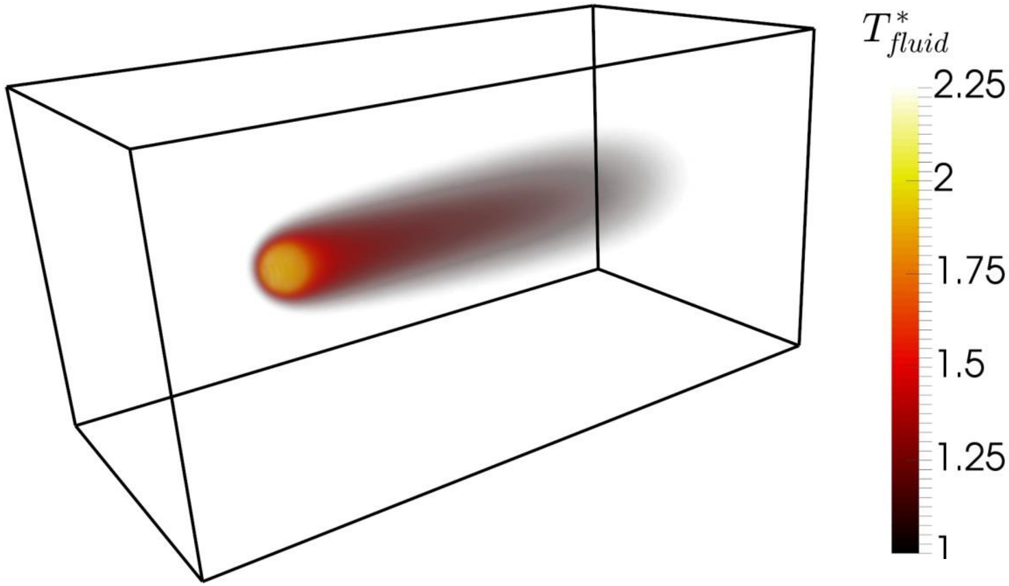
The code is available in:

- CFDEMCoupling®
- openHFDIB (https://github.com/fmuni/openHFDIB my repo)

openHFDIB

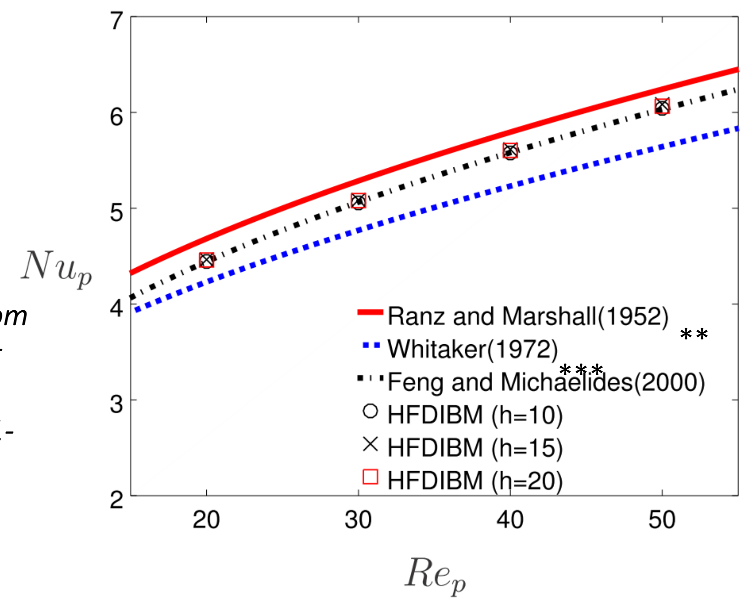
- Able to read any geometry from stl files
- Currently only for flow field
- Allows definition of rotating objects
- Stable but somehow less accurate implementation
- Small piece of code and anyone can contribute

HFDIB-accuracy



Forced convection past a steady sphere

Agreement with existing correlations, in particular with the latest work of **Feng and Michaelides***



**Feng Z. , Michaelides E. A numerical study on the transient heat transfer from a sphere at high Reynolds and Peclet numbers, International Journal of Heat and Mass transfer, 2000*

***Ranz W. , Marshall W. , Evaporation from drops, Chem. Eng. Prog., 48, 141-146, 1952*

**** Whitaker S. , Forced convection heat transfer correlations for flows in pipes, past flat plates, single cylinders, single spheres and for flow in packed beds and tube bundles, AICHE J., 1972*

HFDIB-accuracy

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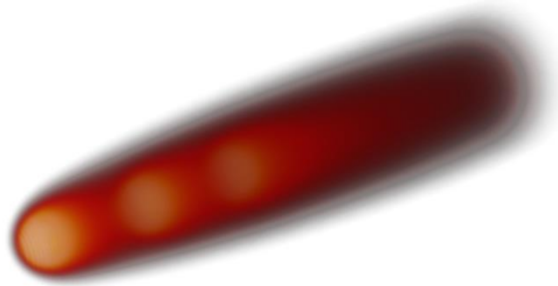


Forced convection past a chain of three spheres

Deviations from literature are comparable (or even lower) to the deviations obtained by Tavassoli et al.***

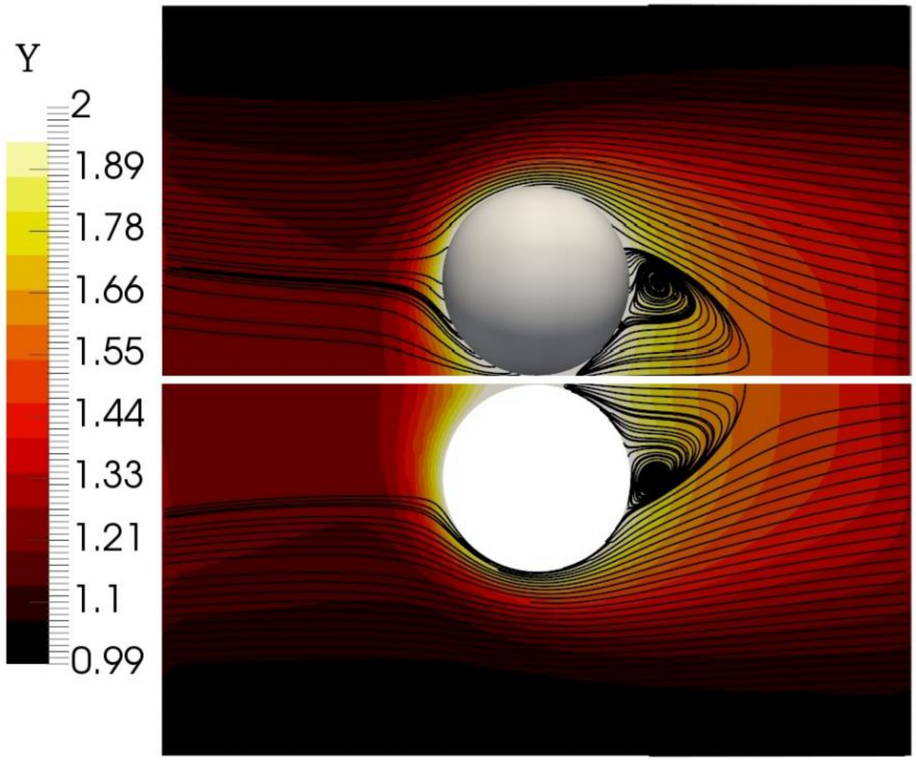
	HFDIBM Maheshwari*	HFDIBM Ramachandran**	Tavassoli Maheshwari	Tavassoli Ramachandran
Sph. 1 d=2	**0.35%**	2.1%	**4.1%**	2.5%
Sph. 2 d=4	**6.8%**	**6.8%**	**8.3%**	7.2%
Sph. 3 d=4	6.7%	**7.4%**	6.7%	**7.5%**

*Mashewari A. ,Chhabra R., Biswas G. , Effect of blockage on drag and heat transfer fom a single sphere and an in-line array of three spheres, powder technology, 168, 74-83, 2006

**Rachmadran R., Kleinstreurer C., Wang T., Forced convection heat transfer of interacting spheres, Numerical Heat Transfer, 15°, 471-487, 1989

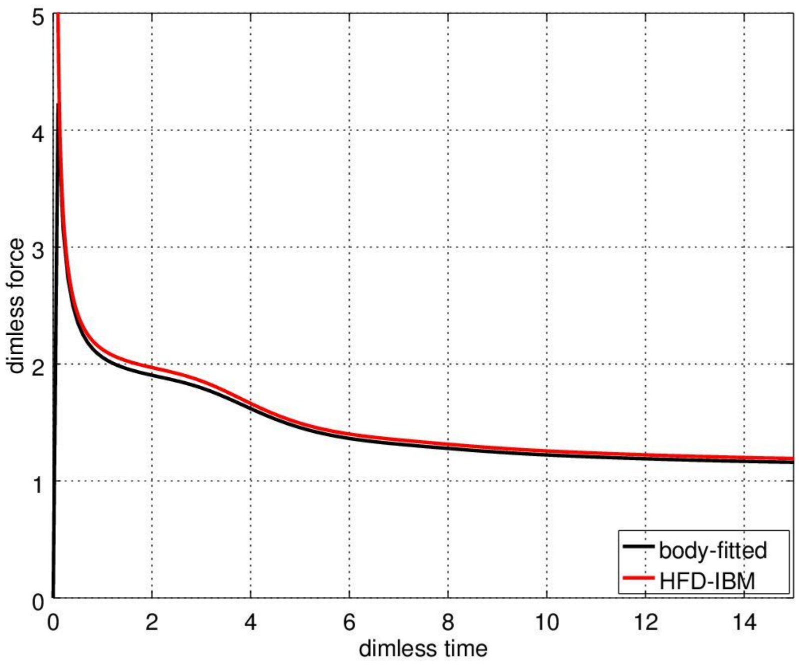
*** Tavassoli H. , Kriebitzsch S., Vand der Hoef M, Kuipers J.A.M , Direct numerical simulation of particulate flow with heat transfer, International journal of multiphase flow 57, 29-37, 2013

HFDIB-accuracy



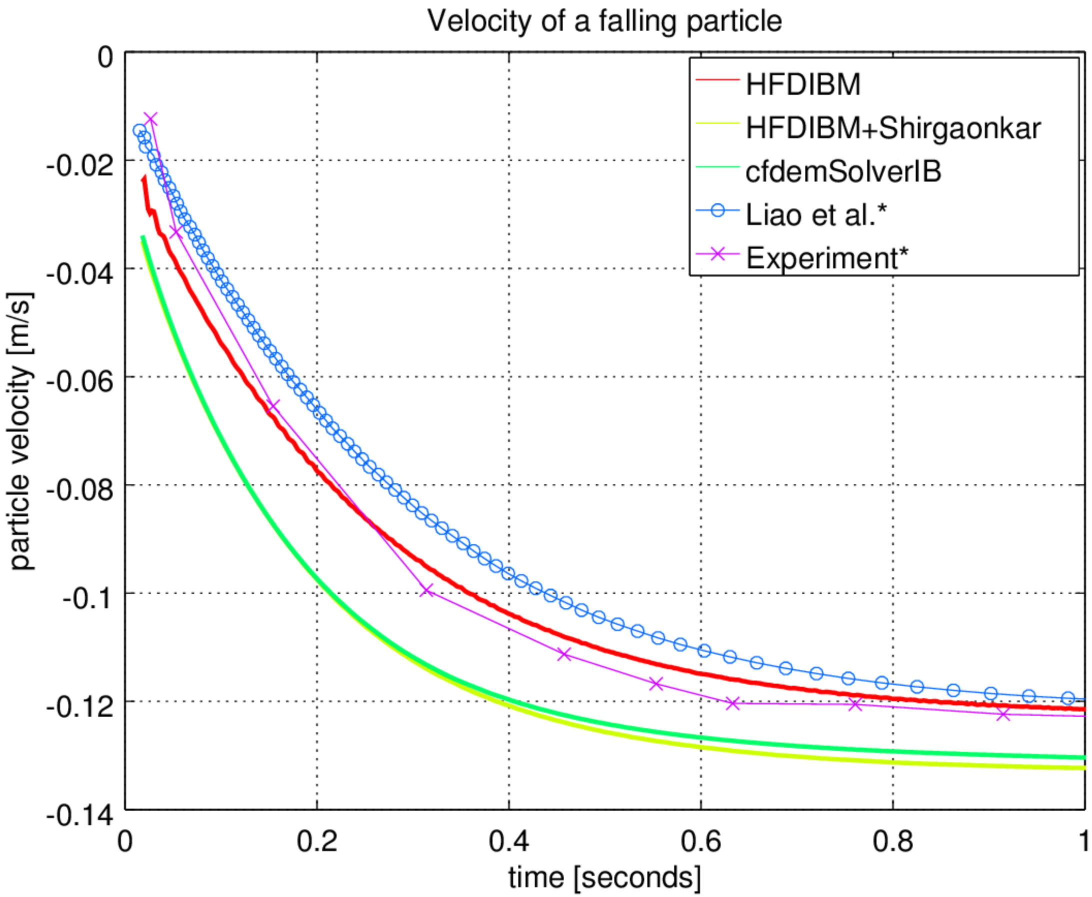
Two close spheres – direct comparison with body fitted DNS

The Nusselt number differs by less than 3%



Slight overprediction of the dimensionless force but similar trend

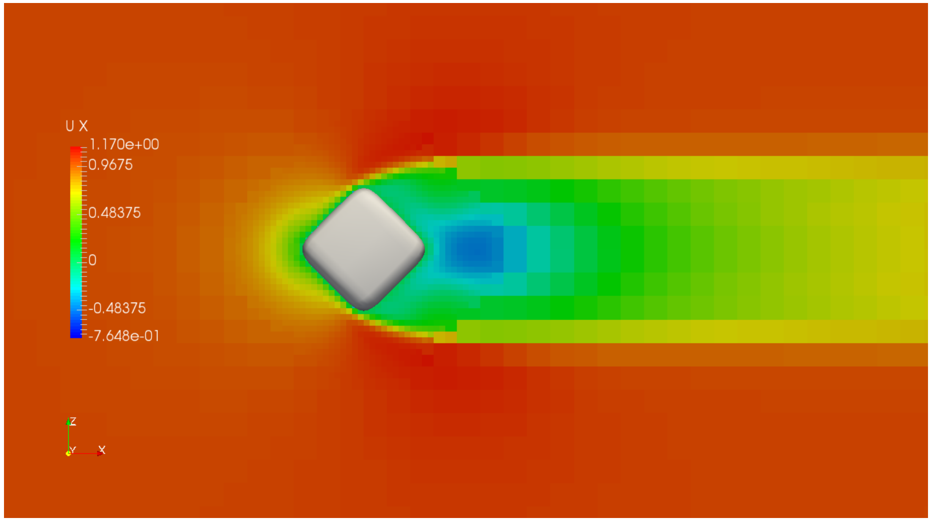
HFDIB-accuracy

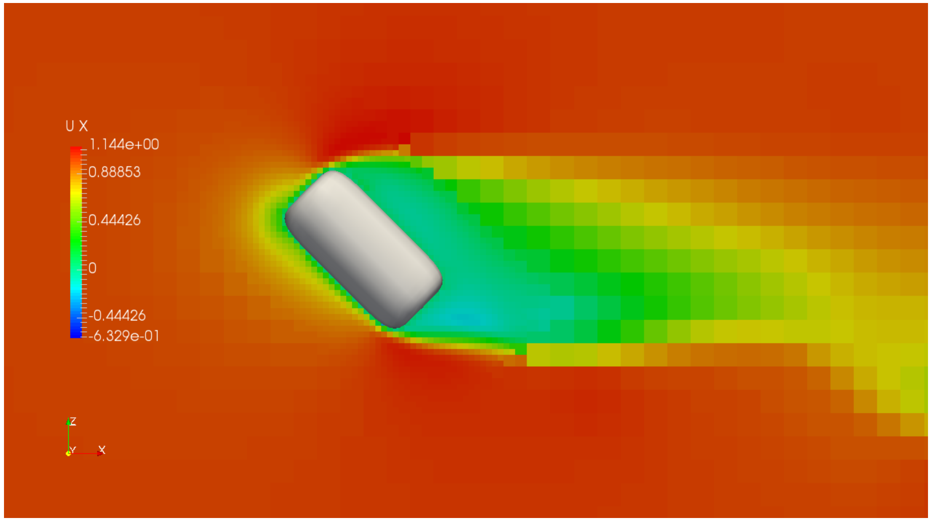


Podlozhnyuk et al., 11th OpenFOAM Workshop 2016

HFDIB in very good agreement with experiments for a free falling particle

HFDIB-applications



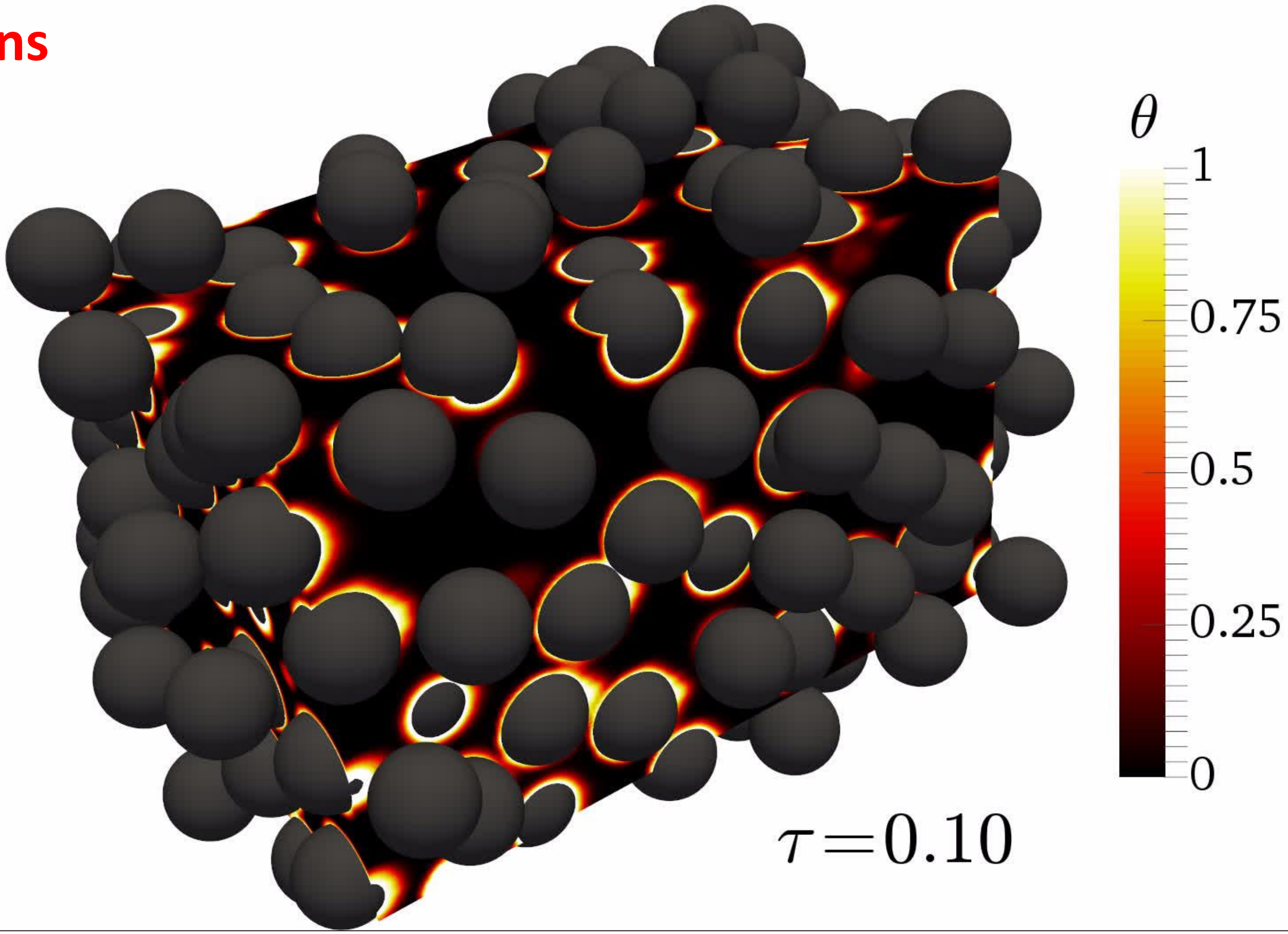


Tested for superquadric particles in CFDEMCoupling®

Podlozhnyuk et al., 11th OpenFOAM Workshop 2016

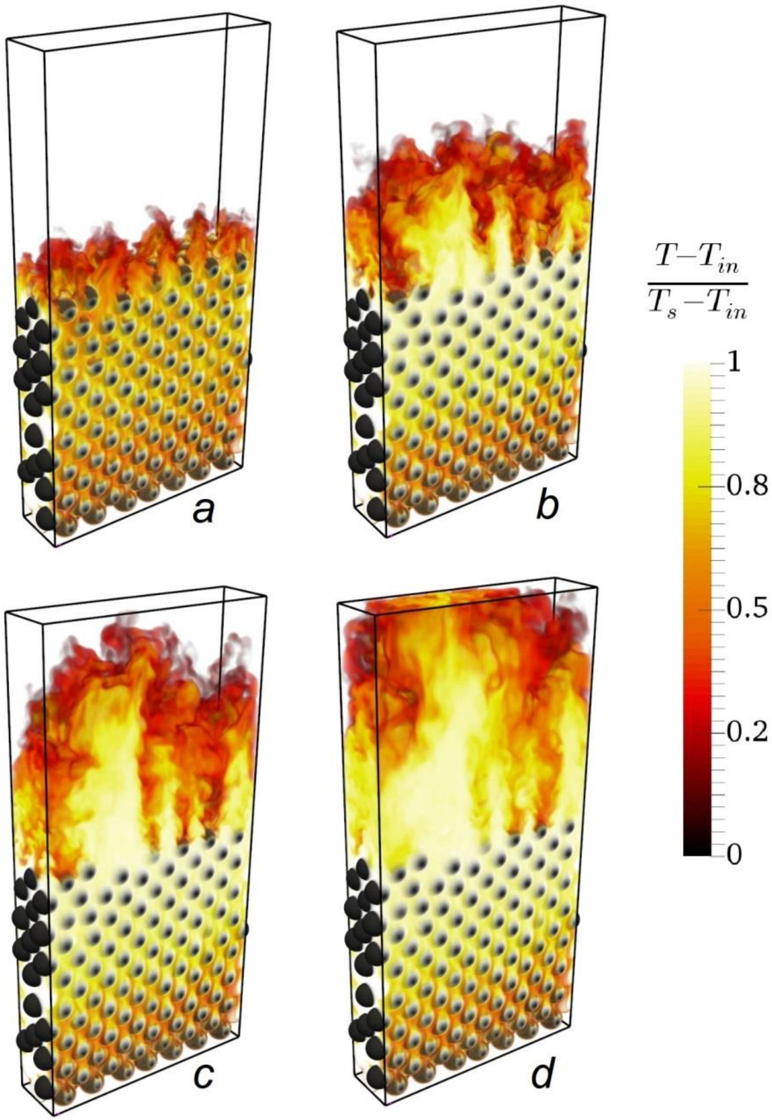
HFDIB-applications

Heat and mass transfer in poly-disperse gas-particle suspensions



HFDIB-applications

Heat and mass transfer in wall bounded particle beds



- Fully resolved PR-DNS.
- Working with periodic and wall boundary conditions.
- Highly parallelizable

HFDIB-conclusions

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- The HFDIB is robust and accurate both for static and moving objects.
- Can deal with momentum and energy/species transport.
- Can be adapted to any gemetry.
- Code can be found in CFDEMCoupling® or:
- Dedicated repository for OpenFOAM (https://github.com/fmuni/openHFDIB)

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