Analysis of Heat Transfer in Dense Suspensions by Particle Resolved Numerical Simulations

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Outline

Context and Reviews

- Forced convection around isolated particle
- Non-isothermal flows through Static Array of particles

Numerical method and code validation

- Tensorial penalty method
- Validation test cases

Analysis of heat transfer in dense Suspension

- Calculation of heat transfer coefficient
- Result compared to correlations

Random mobile Suspension

- Suspended Particle
- Heat transfer in fluidized bed

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Non-isothermal particle laden flows in dense regime

Particle-particle interaction, Particle-wall interactions

Heat exchange

- Between phases
- Between phases and wall
- Nusselt number, function of
  - Solid fraction
  - Structure of the suspension
  - ....

Industrial Applications

- Chemical Looping Combustion
- CO_2 Capture
- Carbon neutral-energy
  - Generation
  - Transformation

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Industrial Applications

- Chemical Looping Combustion
- CO_2 Capture
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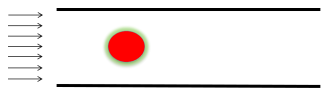
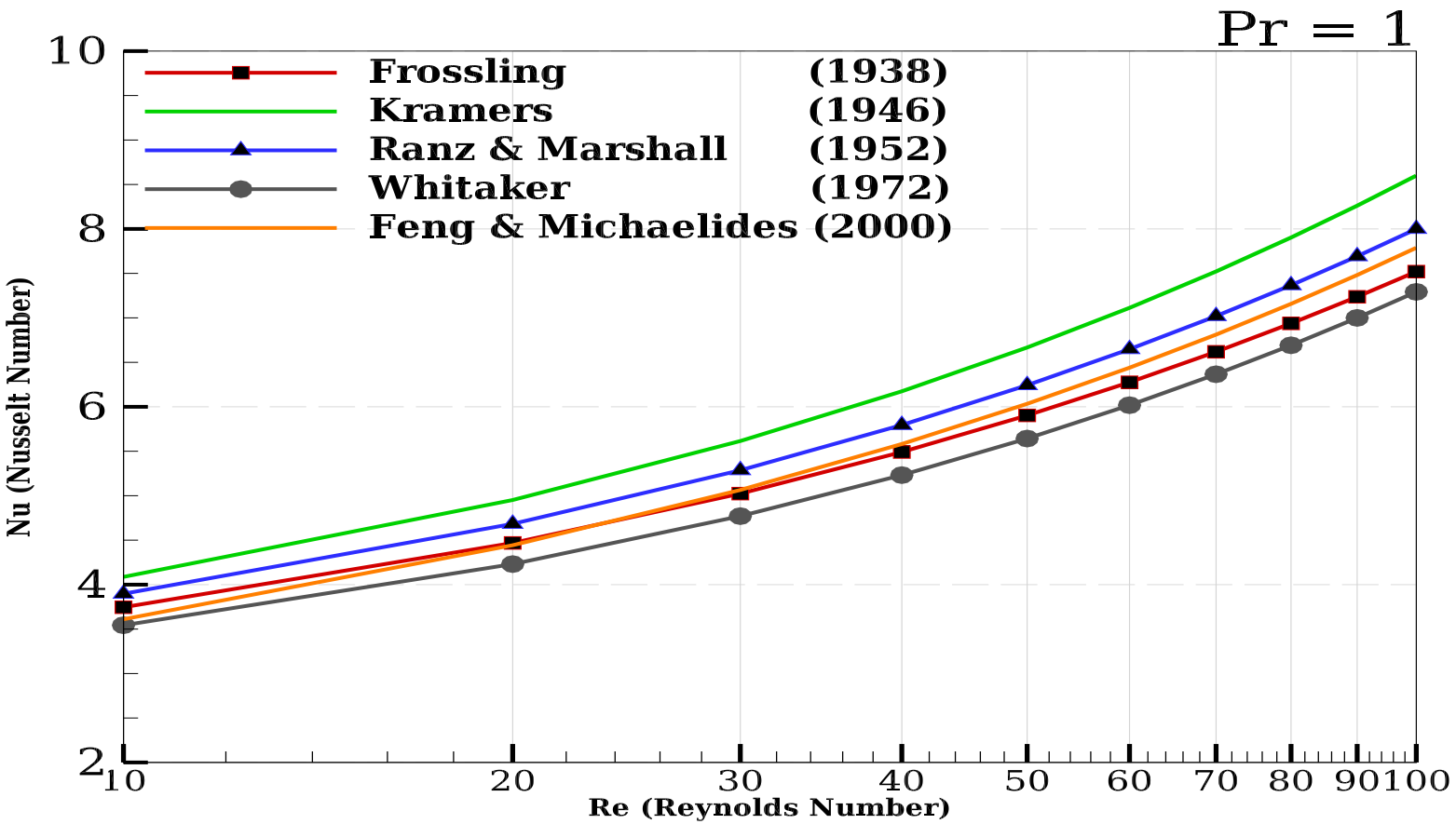
  - Generation
  - Transformation

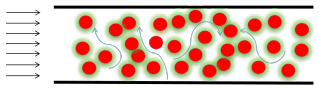
- Cases of validation for Single particle
- Fluid-particle heat transfer coefficient
  - Fixed assembly of particles, mobile suspension

$$Nu \sim= f(R_e, Pr)$$

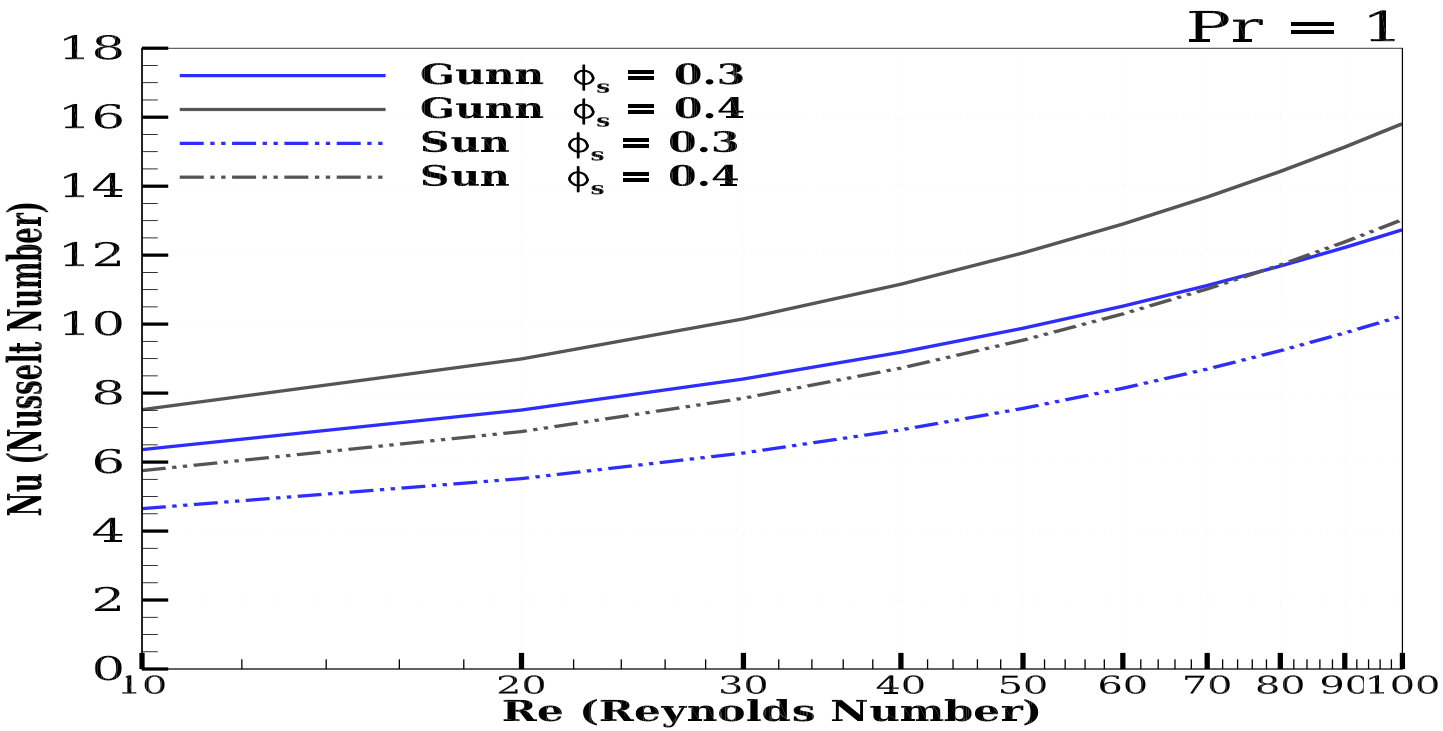



Pr = 1
Frossling (1938)
Kramers (1946)
Ranz & Marshall (1952)
Whitaker (1972)
Feng & Michaelides (2000)
Nu (Nusselt Number)
Re (Reynolds Number)
10
8
6
4
2
10
20
30
40
50
60
70
80
90
100

$$Nu \sim= f(R_e, Pr, \phi_s)$$



- Gunn (Int. J. Heat and Mass Transfer 1977)
- Sun & al (Int. J. Heat and Mass Transfer 2015)



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$$\nabla \cdot \mathbf{u} = 0$$

$$\rho \left(\frac{\partial \mathbf{u}}{\partial t} + (\mathbf{u} \cdot \nabla)\, \mathbf{u} \right) = -\nabla p + \rho \mathbf{g} + \underbrace{\nabla \cdot \left(\mu \left(\nabla \mathbf{u} + \nabla^t \mathbf{u} \right) \right)} + \mathbf{F}_{si}$$

$$\frac{\partial \mathbf{C}}{\partial t} + \mathbf{u} \cdot \nabla \mathbf{C} = 0$$

$$\rho C_p \left(\frac{\partial T}{\partial t} + u \cdot \nabla T \right) + \ell T = \nabla \cdot (\lambda \nabla T) + S.$$

$$\nabla \cdot \mathbf{u} = 0$$

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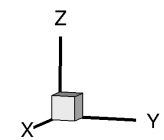
- Tensorial Penalty Method (Vincent & Caltagirone J. Comput Phys 2011)

$$\nabla \cdot \left(\mu \left(\nabla \mathbf{u} + \nabla^t \mathbf{u} \right) \right) = \nabla \cdot [\kappa \Lambda((\mathbf{u})] + [\zeta \Theta((\mathbf{u})] + [\eta \Gamma((\mathbf{u})]$$

  Solid behaviour , $\mathbf{C} = 1 :: \eta \gg 1,\ \zeta = \kappa = 2\eta$

- Darcy Penalty Method (Kadra & al. Int. J. Numer Meth Fluids 1999)
- Constant temperature in the solid particle : ℓT, S

Conduction

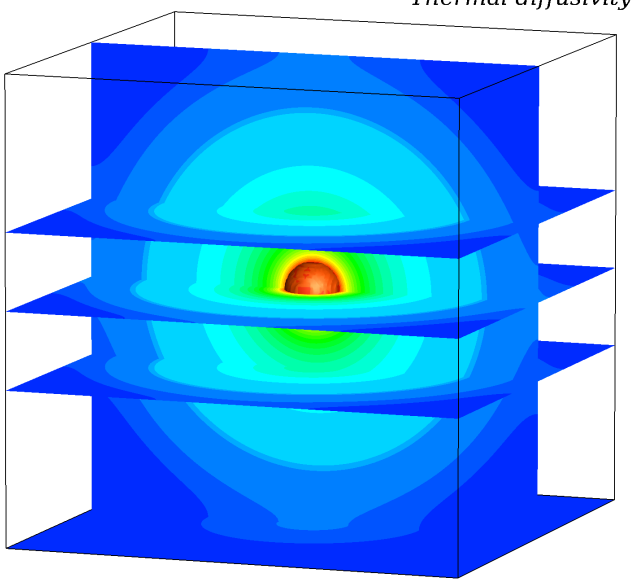


Cubic Domain : $L = 8D_p$

Constant Temperature in the spherical particle

Periodic Bounbary Condition for the temperature

Thermal diffusivity : $\alpha = 10^{-6}\ m^2/s$



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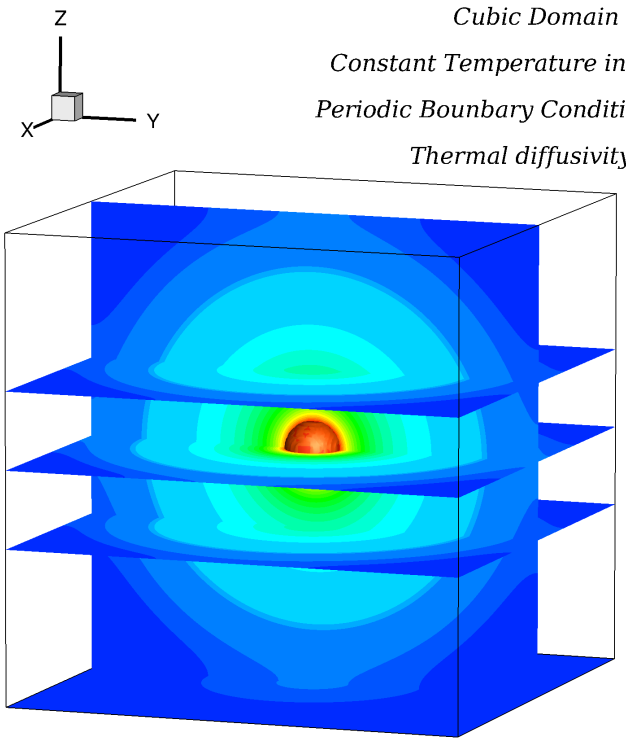


$$\frac{T(r,t)-T_\infty}{(T_s-T_\infty)} = \left(\frac{R}{r}\left(1-\frac{2}{\sqrt{\pi}}\int_0^\eta e^{-\xi^2}d\xi\right)\right)$$

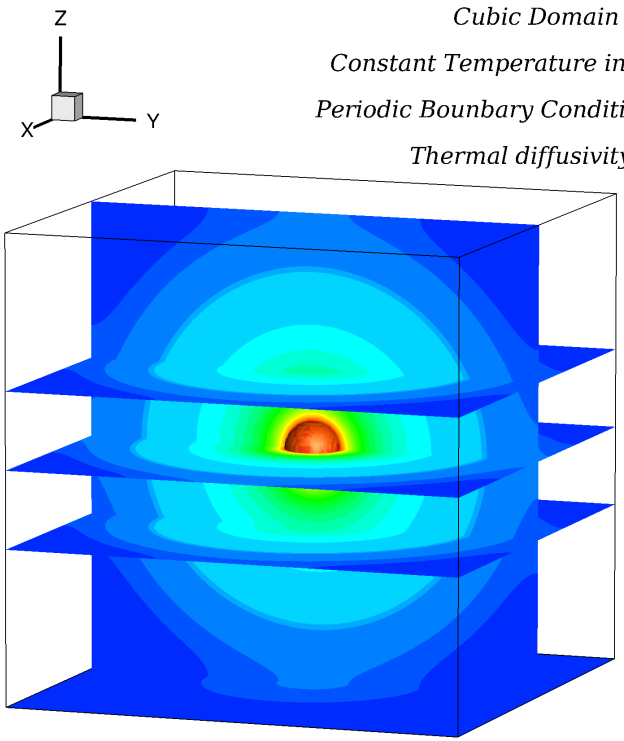
$$r \geq R, \quad \eta = \frac{r-R}{\sqrt{4\alpha t}}$$

$$Nu_a(t) = 2 + \frac{2R}{\sqrt{\pi\alpha t}}$$

$$Nu_s(t) = \frac{\Phi D_p}{4\pi R^2 (T_s - T_\infty) k_f}$$

$$E_r(\%) = 100\frac{|Nu_a(t) - Nu_s(t)|}{|Nu_a(t)|}$$

Conduction



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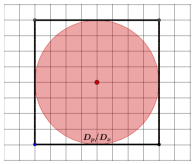
$$\Phi = \iint_{S_\nabla} -k_f \vec{\nabla} T(x_b, y_b, z_b) \cdot \vec{n}_\nabla \, dS_\nabla$$

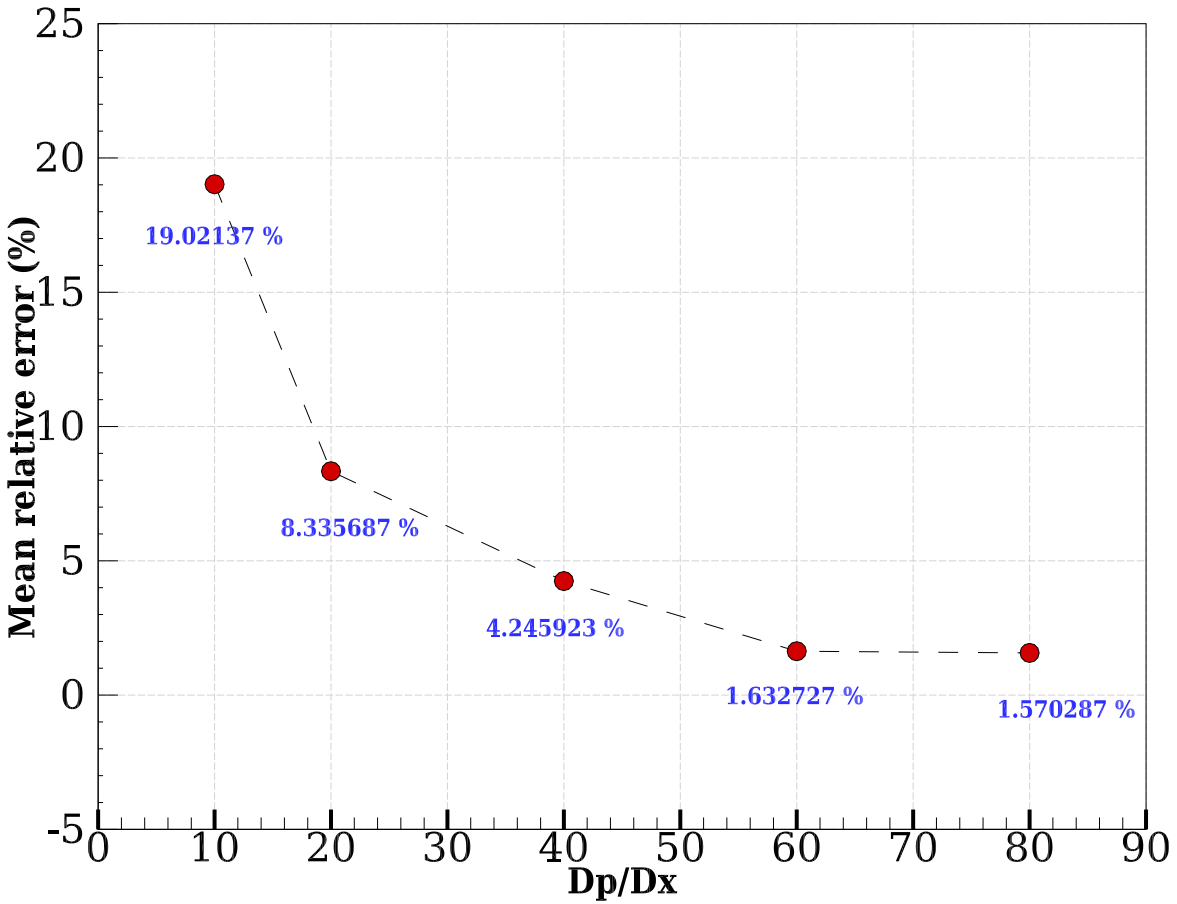
Spherical particle surface is approximated by triangular elements and the flux is computed as :

- $\Phi = \sum -k_f \vec{\nabla} T(x_b, y_b, z_b) \cdot \vec{n}_\triangledown \, dS_\triangledown$
- (x_b, y_b, z_b) barycenter of each triangle
- $\vec{n}_\triangledown$ normal vector of each surface element
- $dS_\triangledown$ surface of each triangle

$$\left.\frac{dT}{dx}\right|_i = \frac{-T_{i+2} + 8(T_{i+1} - T_{i-1}) + T_{i+2}}{12Dx} + \mathcal{O}(h^4)$$

Mean relative error Nu, $f(\frac{D_p}{D_x})$



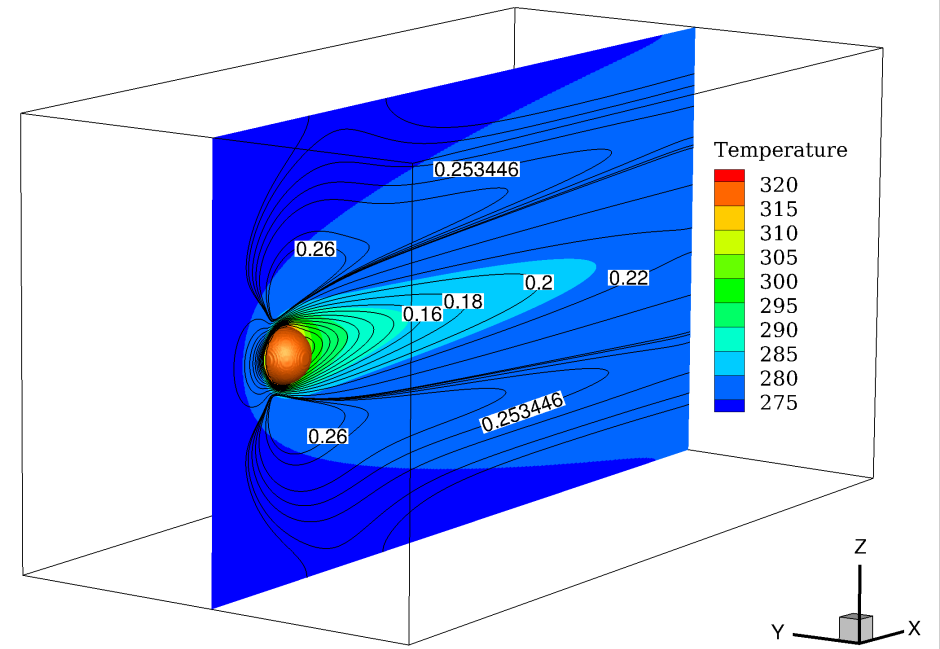


Forced Convection

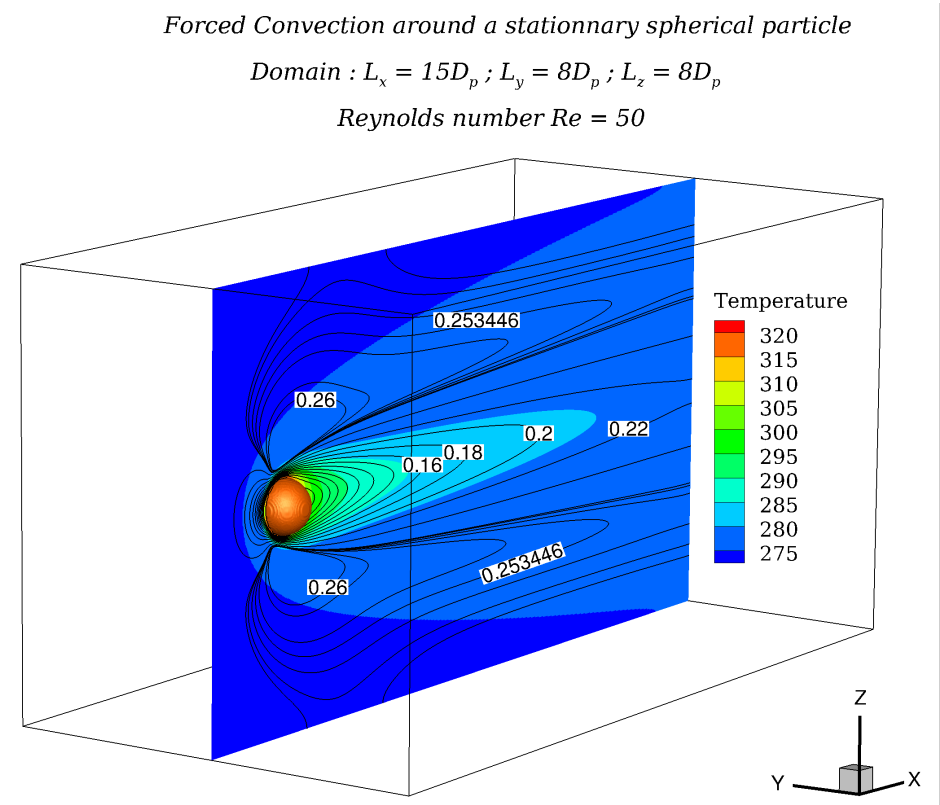
Forced Convection around a stationnary spherical particle

Domain : $L_x = 15D_p$; $L_y = 8D_p$; $L_z = 8D_p$

Reynolds number Re = 50



Forced Convection



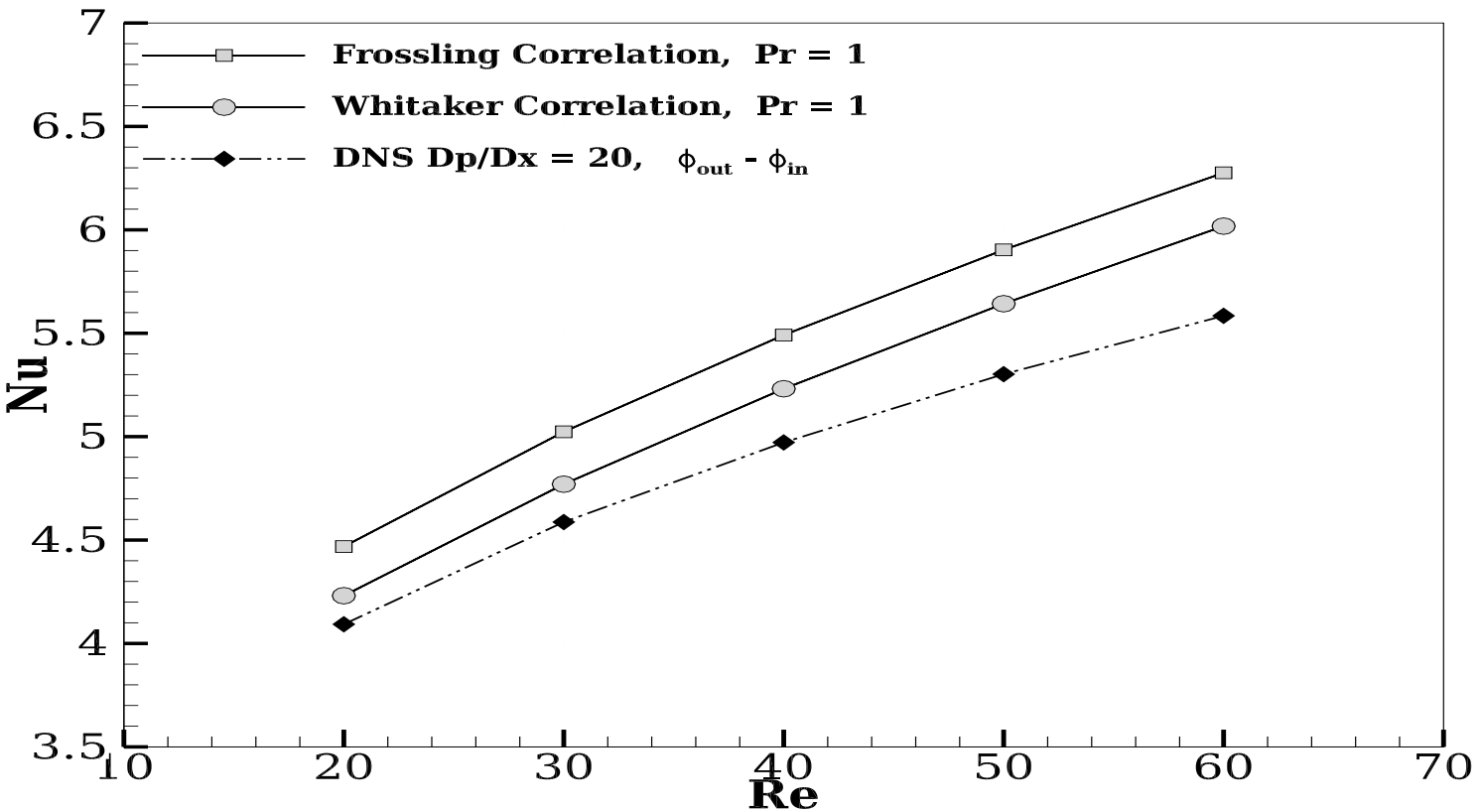
- Darcy Penalty Method (DPM)
- $R_e = 10 \cdots 60, \;\; P_r = 1$

$$N_u = \frac{h_f D_p}{k_f}$$

$$h_f = \frac{\Phi}{\Delta T (4\pi R^2)}$$

$$\Phi = \Phi_{out} - \Phi_{in}.$$

$$\Phi = \rho_f C_p \iint_{S_{out}} U_x(L_x, y, z)\, T(L_x, y, z)\, dydz - \rho_f C_p \iint_{S_{in}} U_x(0, y, z)\, T(0, y, z)\, dydz$$



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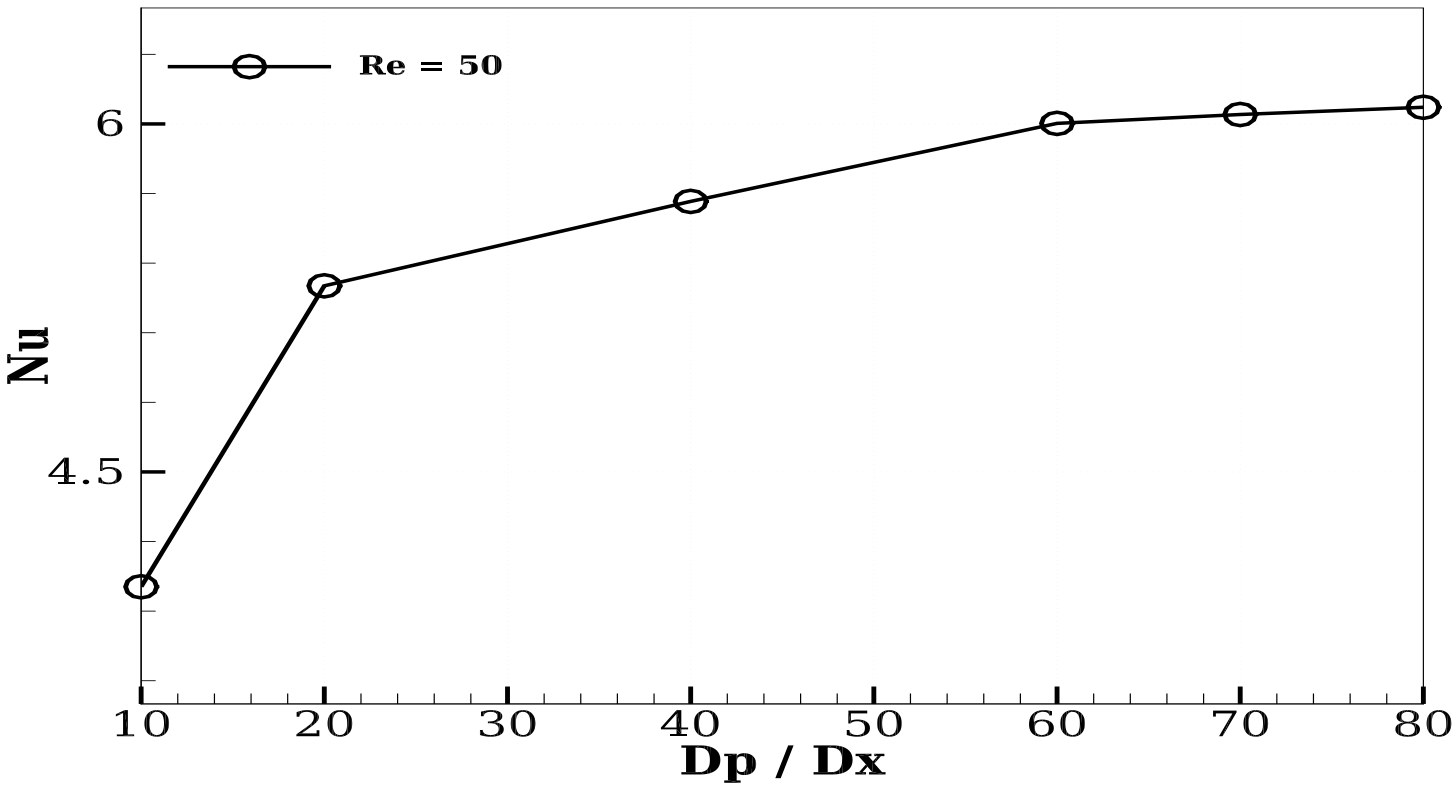

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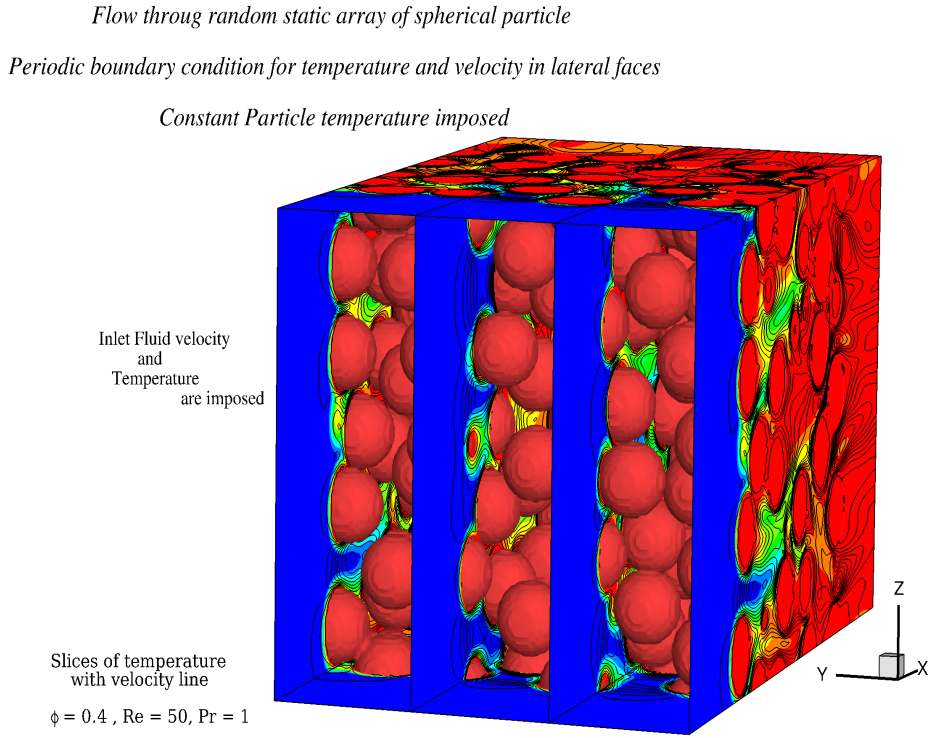
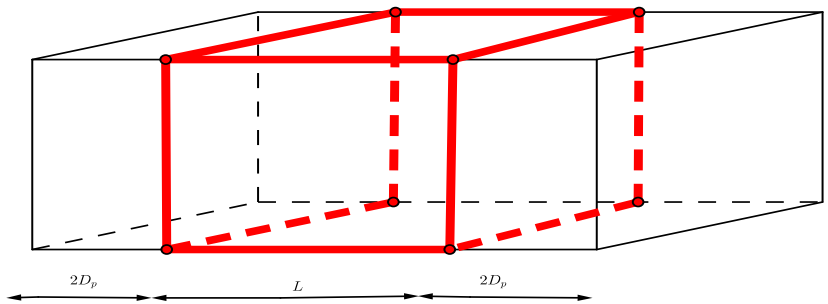




- Darcy Penalty Method (DPM)
- Imposed Inlet (T,V)
- Randomly distributed particle
- $\phi_s = 0.1,\ 0.2,\ 0.3,\ 0.4$
- $R_e = 10,\ 50,\ 100\ ;\ P_r = 1$

- $\chi(x,y,z) = 1 - \mathbf{C}(x,y,z)$ Phase Function
- T_b Cup-mixing bulk temperature

$$T_b(x) = \frac{\iint\limits_{A_c} \chi(x,y,z)\, U_x(x,y,z)\, T(x,y,z)\, dydz}{\iint\limits_{A_c} \chi(x,y,z)\, U_x(x,y,z)\, dydz}$$

- Total convective heat flux

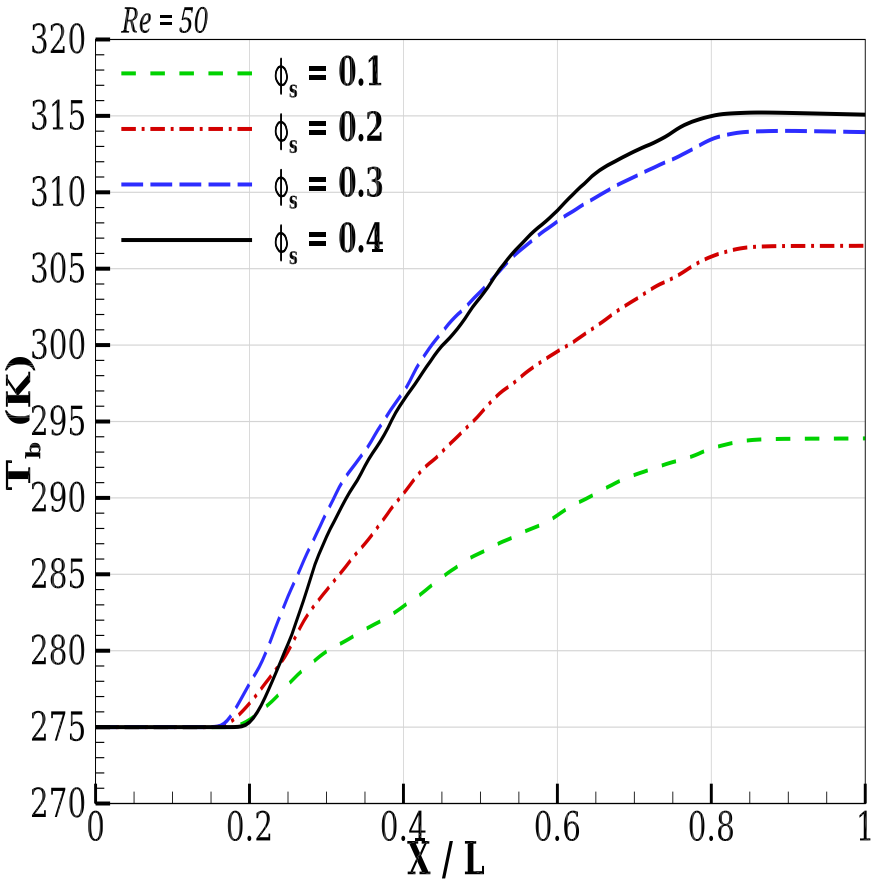
  (Deen & al Chem. Eng. Sci 2012; Tavassoli & al Int. J. Multiph. Flow 2013)

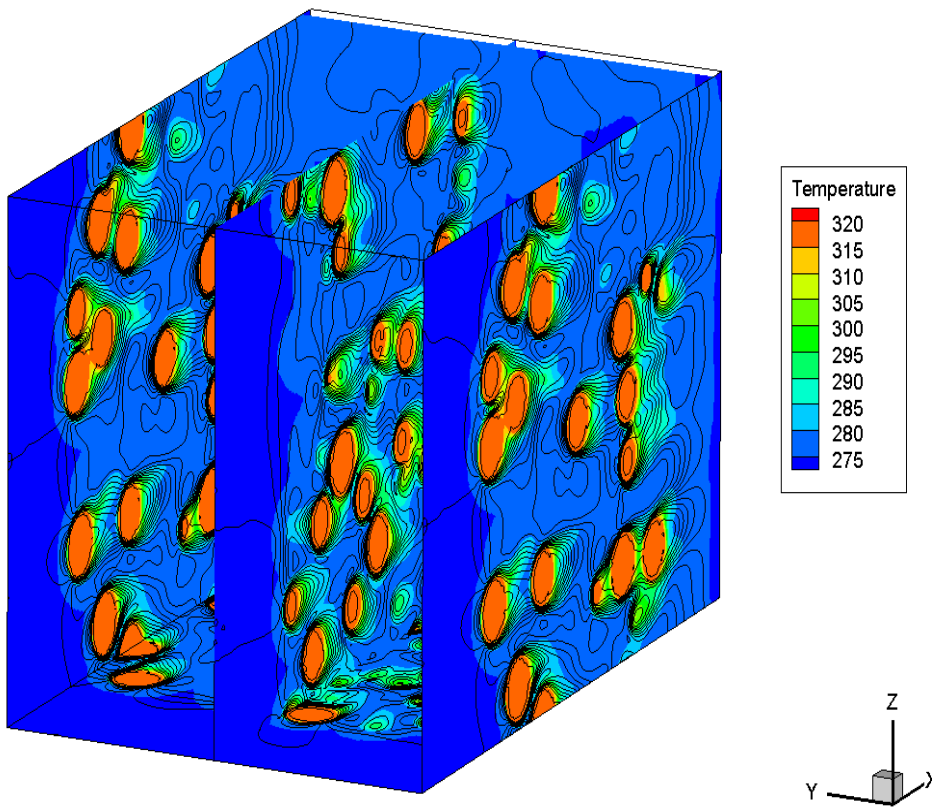
$$Q = U_\infty \rho_f C_p \frac{dT_b(x)}{dx} = h_f \frac{6\phi_s}{D_p} \left(T_s - T_b(x)\right).$$

- The heat transfer coefficient assumed to be constant

$$h_f = -\ln\left(\frac{T_s - T_{b_{out}}}{T_s - T_{b_{in}}}\right)\left(\frac{U_\infty \rho_f C_p}{\frac{6\phi_s}{D_p} L}\right)$$

Bulk temperature





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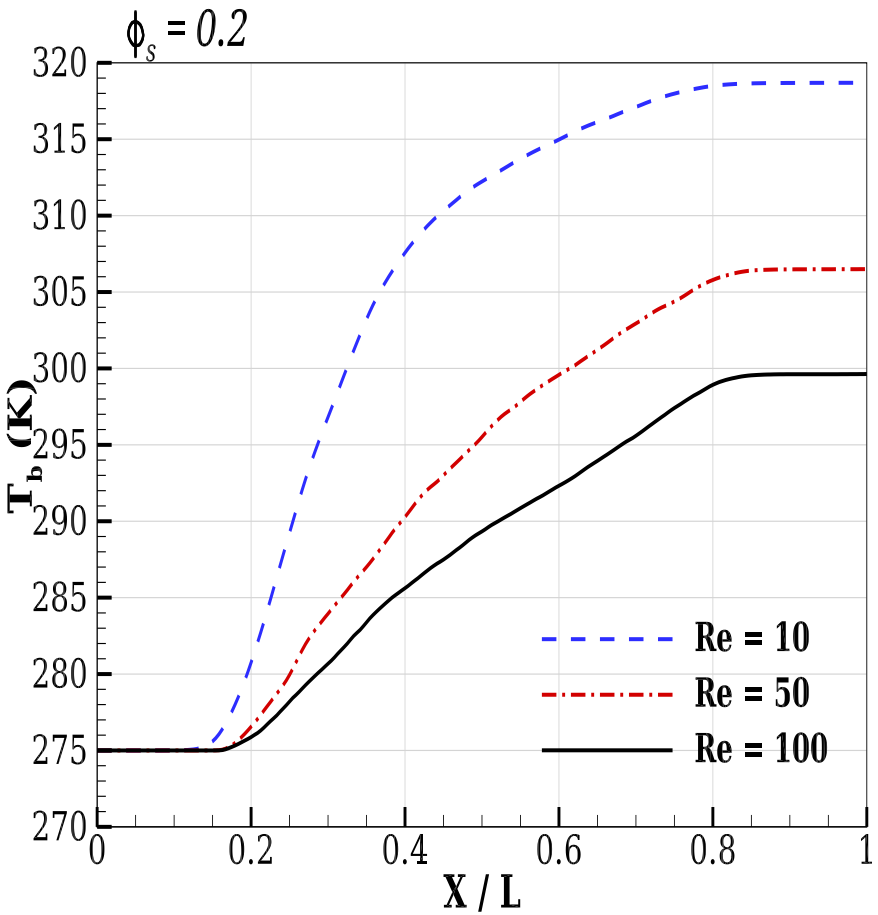
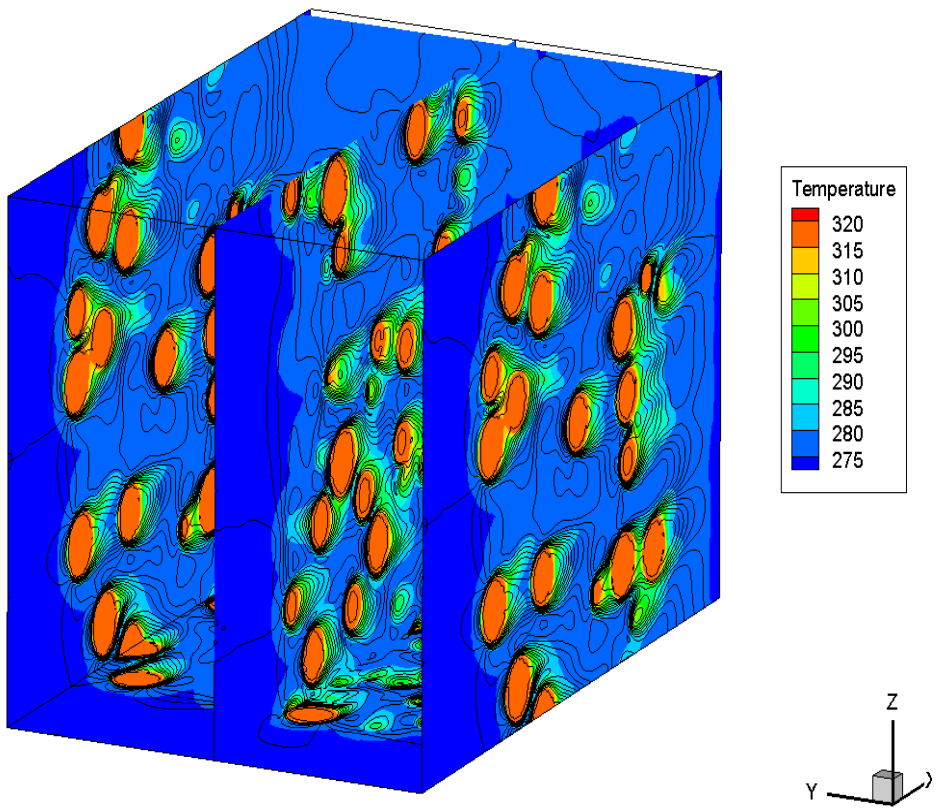
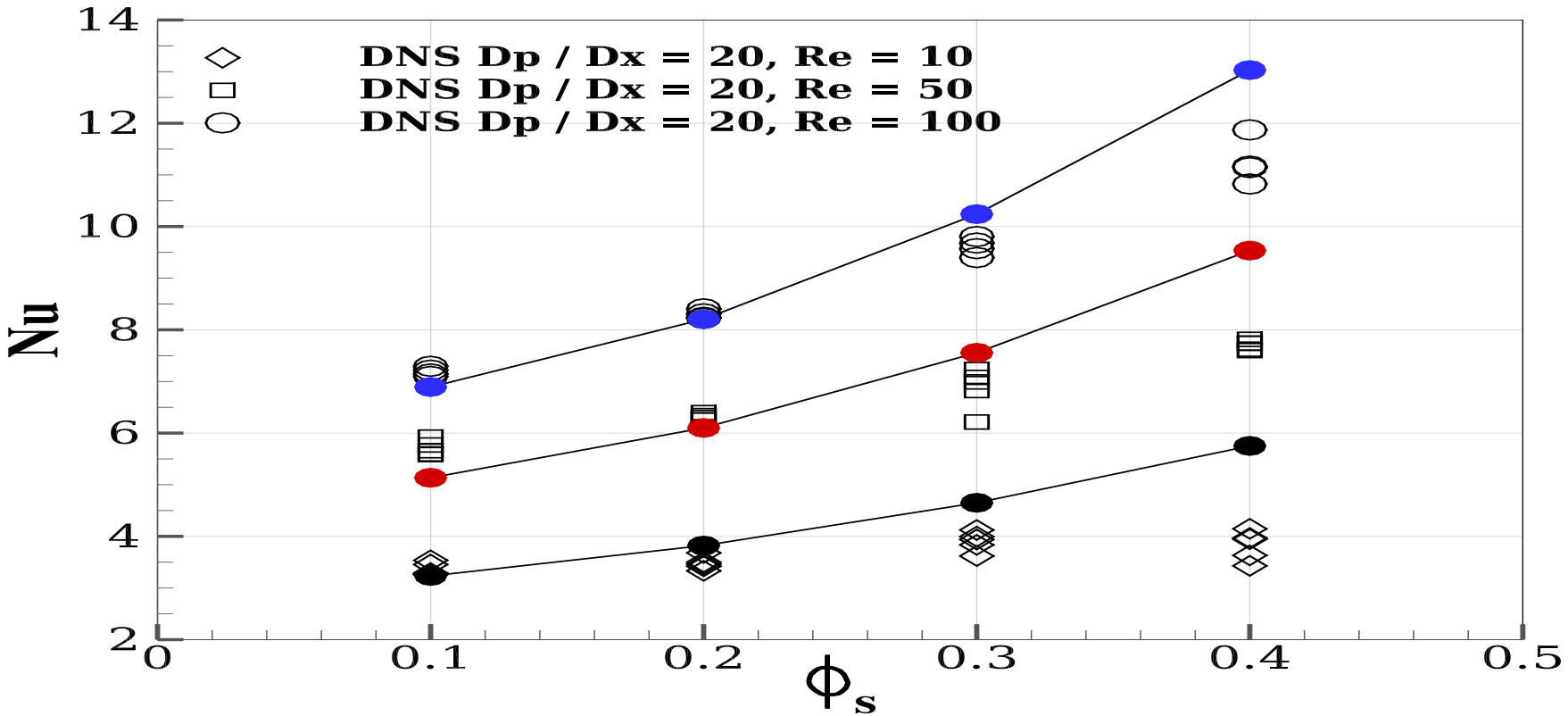




$$Nu \sim f(Re,\ \phi,\ P_r = 1)$$



Sun & al (Int. J. Heat and Mass Transfer 2015)

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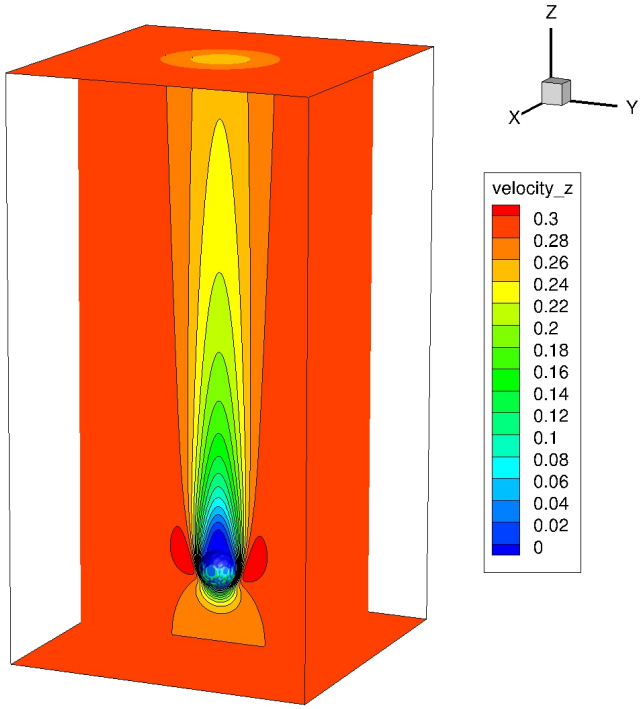
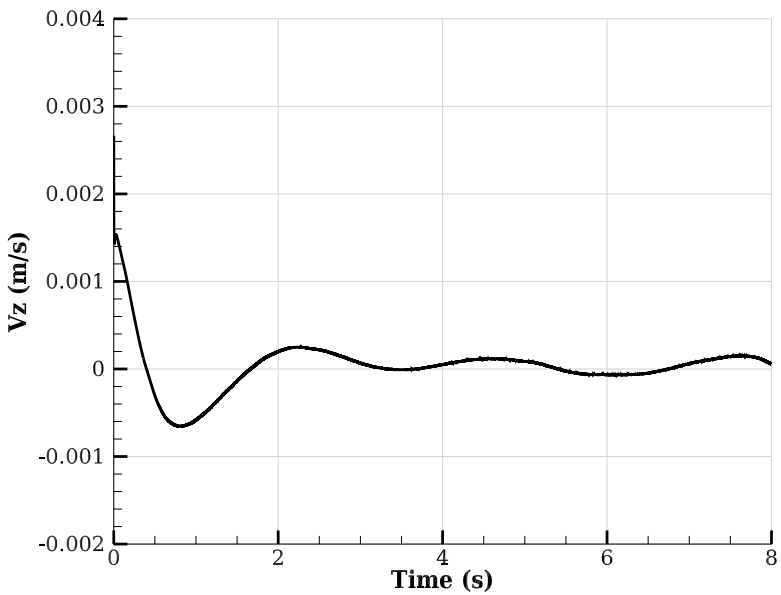
Suspended Particle

- Tensorial Penalty Method (TPM)



- Inlet velocity and gravity
- Balance of forces
- $R_e = 58$



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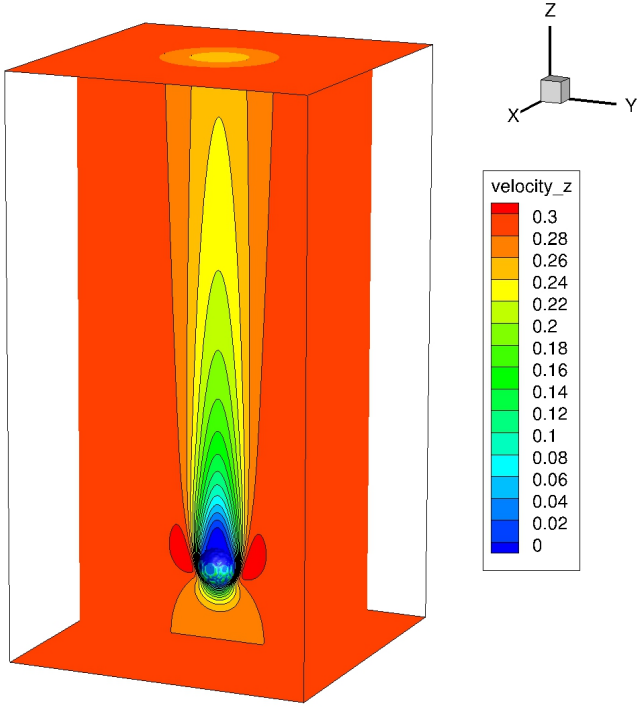
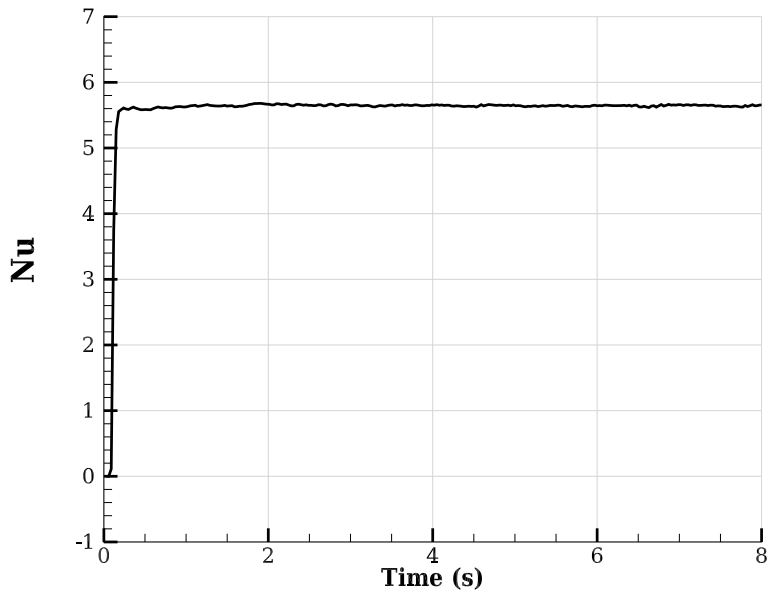


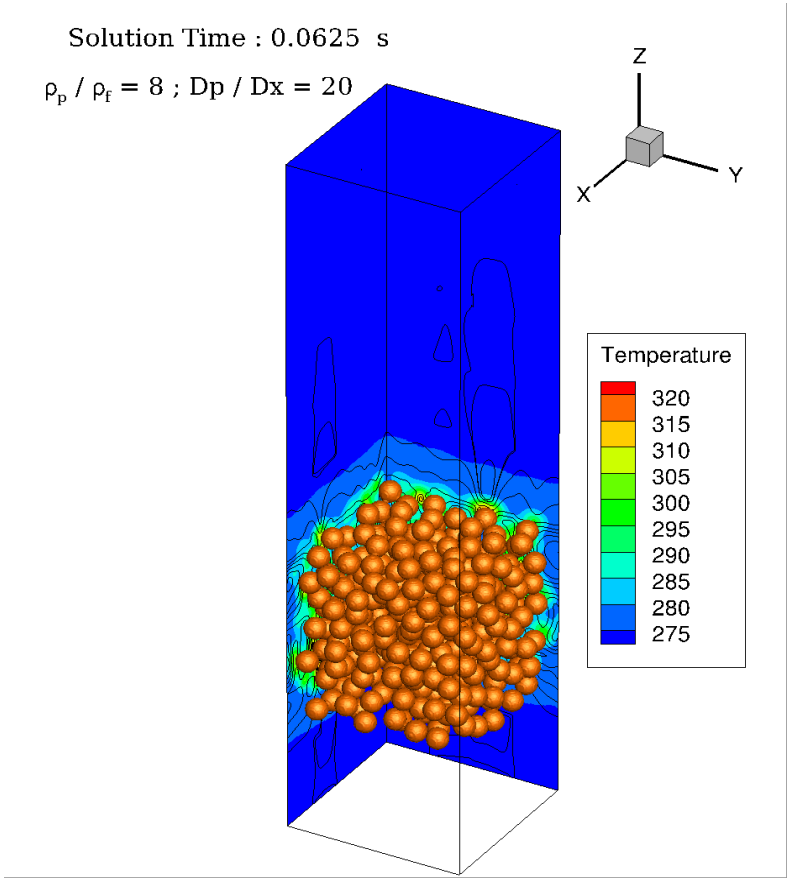


$R_e = 58,\ Nu = 5.4$ (DPM)

Heat transfer in fluidized bed

- Periodic and Circulating
- Porous Wall
- Soft Sphere collision
  - Particle-particle
  - Particle-wall

  J. C. B de Motta & al (Physics of Fluids 2013)
- Several solid fraction
  - Settling velocity
  - Fluidization velocity



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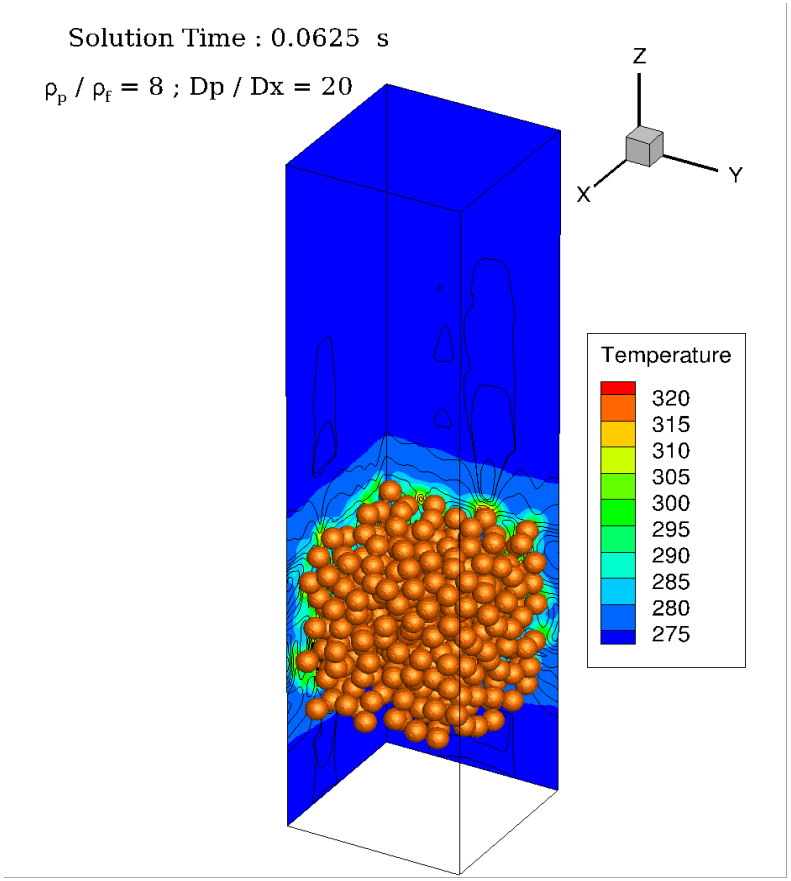

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- Heat transfer on isolated particle
  - Conduction
  - Forced convection

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- Convergence study and code validation
  - Grid Convergence
  - Tensorial Penalty method

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- Flow though random static array
  - Heat transfer Analysis
  - Statistical dependence

- Heat transfer on isolated particle
  - Conduction
  - Forced convection
- Convergence study and code validation
  - Grid Convergence
  - Tensorial Penalty method
- Flow though random static array
  - Heat transfer Analysis
  - Statistical dependence
- Random mobile suspension
  - Local heat transfer coefficient
  - Instantaneous distribution of particles
  - More random configurations of particles

Tanks to Université Paul Sabatier de Toulouse for the funding.
This work was granted access to the HPC resources of CALMIP supercomputing center
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References

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