Heat transfer in fluidized bed – tube heat exchanger

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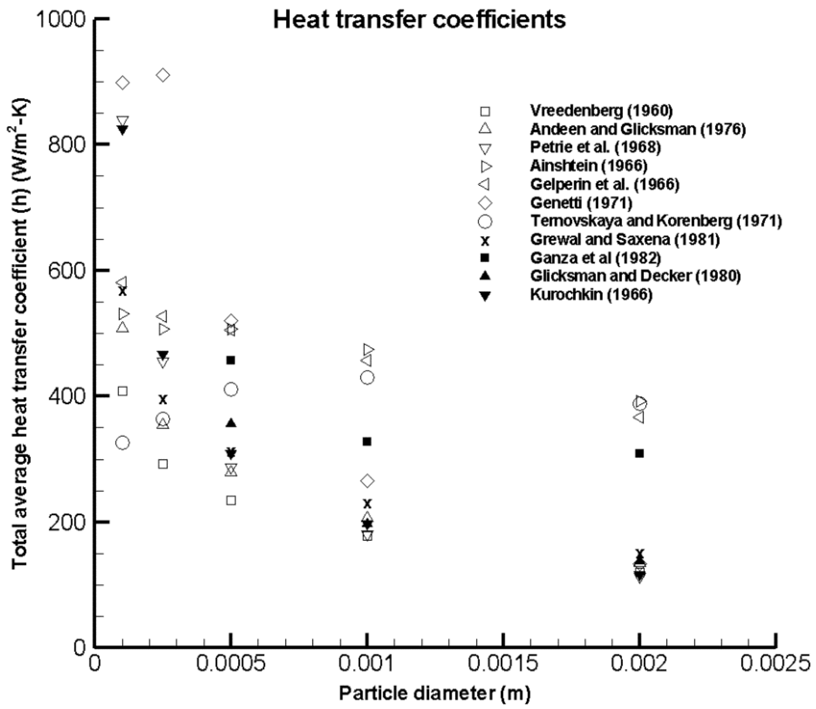
Multi-phase heat transfer with fluidized bed

- **Temperature control, heat addition, extraction in fluidized beds**
    - **Example – CO_2 capture and regeneration (post combustion)**
        - **Temperature control is essential for optimal operation**
        - **Capture is exothermic**
        - **Regeneration is endothermic**
- **Experimental studies and mechanistic theory have been used to develop correlations for heat transfer coefficients**

Uncertainties in heat transfer correlations

- **Experimental correlations for heat transfer coefficient in a fluidized bed of polypropylene particles with a horizontal tube**

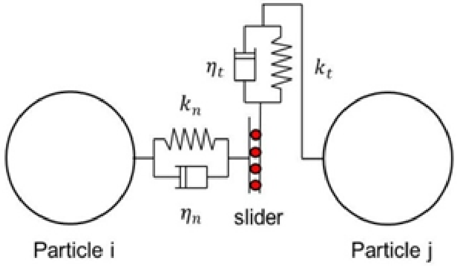


Objectives

- **Heat transfer analysis using a fluidized bed – tube heat exchanger**
  - **High fidelity using particle scale heat transfer analysis**
    - **CFD-DEM technique to analyze the system**
    - **Capture the 3D multiphase flow physics**
  - **Estimate heat transfer coefficient around an immersed tube heat exchanger**

Methodology

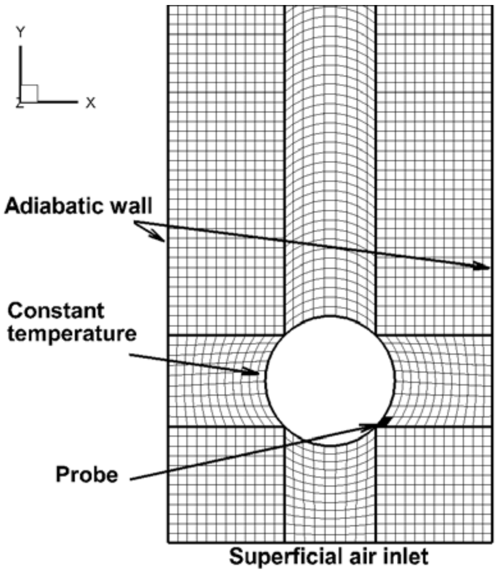
- Use of in-house code GenIDLEST
  - Turbulent flows in complex geometries– RANS/LES
  - Heat Transfer
  - ALE & IBM for dynamic geometries
  - Coupled CFD-DEM
- Soft sphere model for collisions
- Heat transfer models
  - Particle-fluid convection
    - Gunn correlation[1]
  - Radiation heat transfer
    - Neglected (T_{max} < 700K)
  - Particle-particle and Particle-surface
    - Conduction
      - Quasi-steady model[2]
      - Adjustments to account for "soft sphere"



[1]D.J. Gunn, Transfer of heat or mass to particles in fixed and fluidised beds, International Journal of Heat and Mass Transfer, 21 (1978) 467-476.

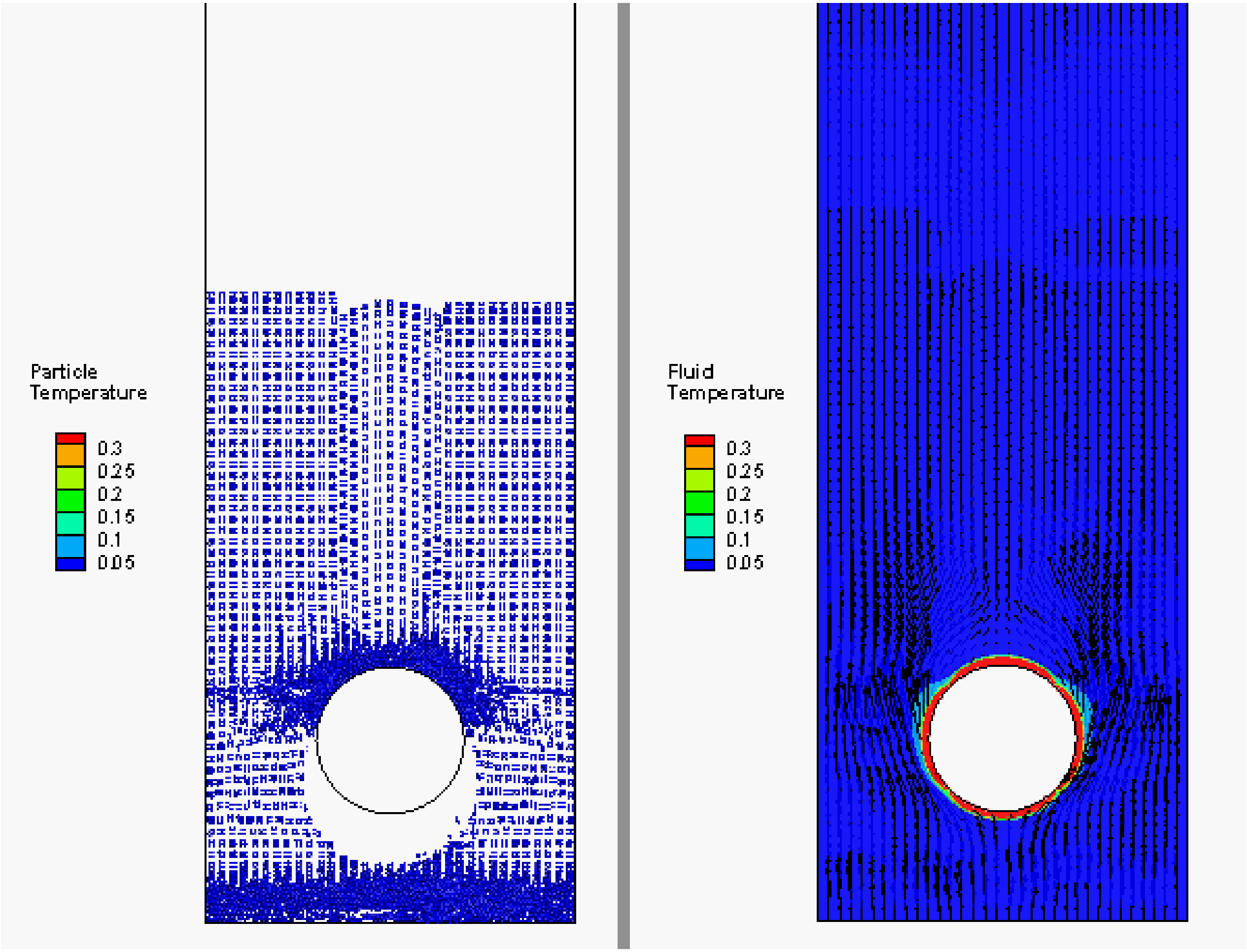
[2]G.K. Batchelor, R.W. O'Brien, Thermal or Electrical Conduction Through a Granular Material, Proceedings of the Royal Society of London. Series A, Mathematical and Physical Sciences, 355 (1977) 313-333.

Fluidized bed with tube heat exchanger



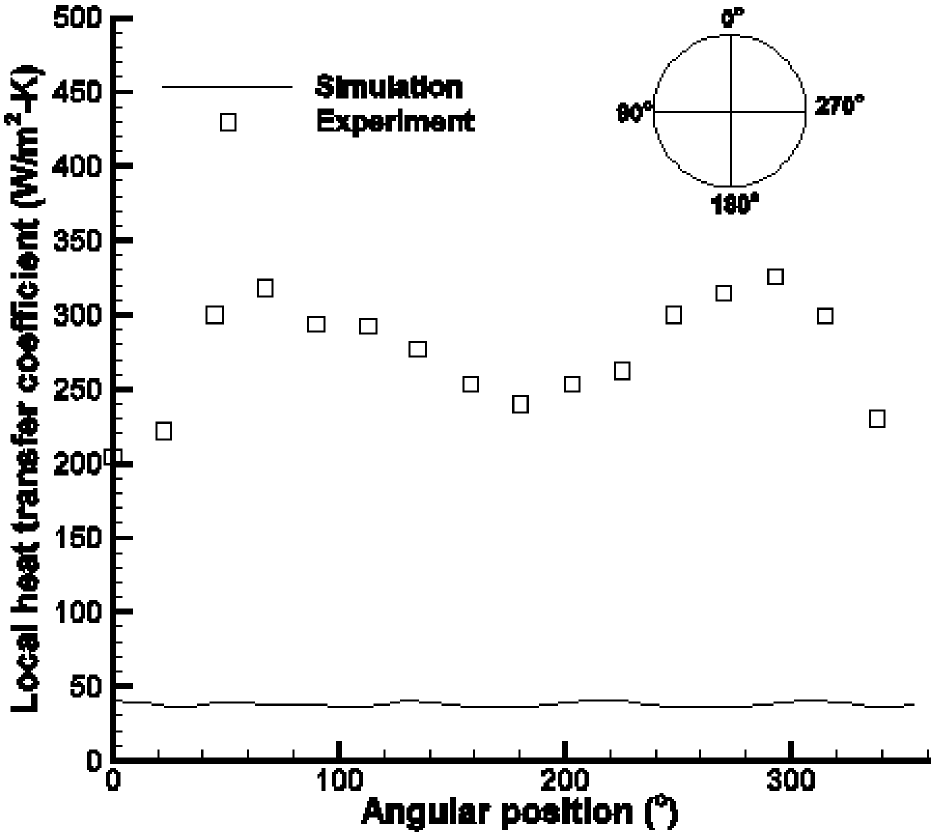
Bed			
Width (m)	W	0.06	
Transverse Thickness (m)	T	0.0054	
Height (m)	H	0.768	
Tube			
Height from bottom of bed (m)		0.03	
Diameter (m)	D_t	0.024	
Simulation parameters	Notation	Sand particles	Tube/Wall properties
Density (kg/m^3)	ρ	2600	
Thermal conductivity (W/m-K)	κ	1.1	380
Heat capacity (J/Kg-K)	Cp	840	24.4
Elastic modulus (MPa)	E	10	10
Poisson's ratio	σ_p	0.3	0.3
Coefficient of normal restitution	e_n	0.9	0.9
Coefficient of friction	$\mu_{p\text{-}p}$	0.3	0.3
Spring stiffness coefficient (N/m)	K	800	800
Initial temperature (K)	T_{init}	298	298
Sphericity	Sp	1	
Number	N	67500	
Diameter (mm)	D_p	0.6	
Time step (seconds)	Δt	2×10^{-5}	

Fluidized bed with immersed tube heat exchanger



Initial estimates of heat transfer coefficient (HTC) around the tube

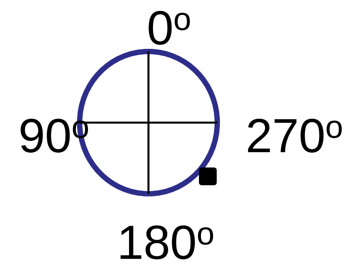
- **Experiments by Wong et al. 2006**

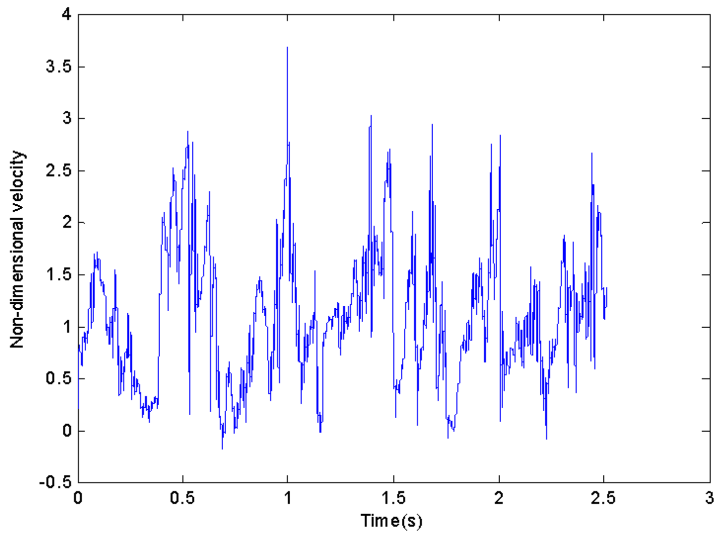


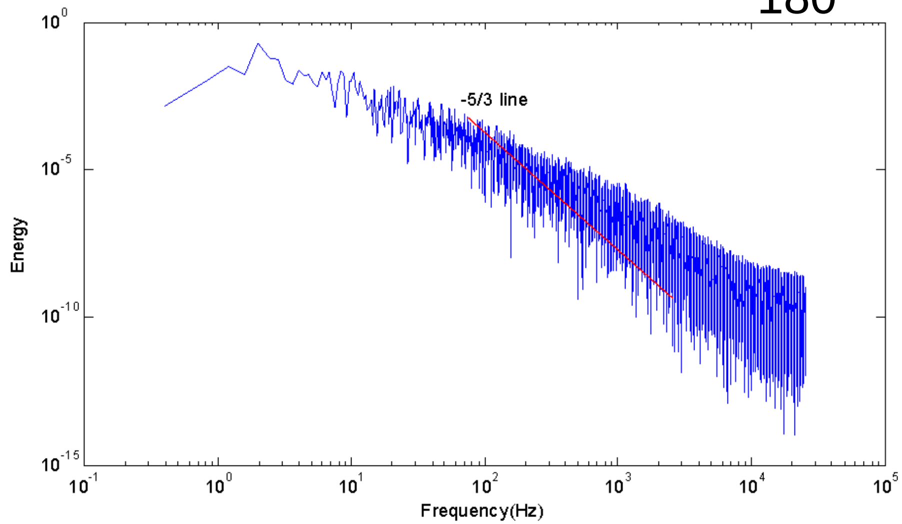
- Convective heat transfer dominant
- Past efforts do not resolve surface convective heat transfer but model using the Dittus-Boelter correlation at tube surface
- Grid too coarse to resolve thermal boundary layer!

Investigation of differences between simulations and experiments

- **Velocity signal 45° from stagnation**



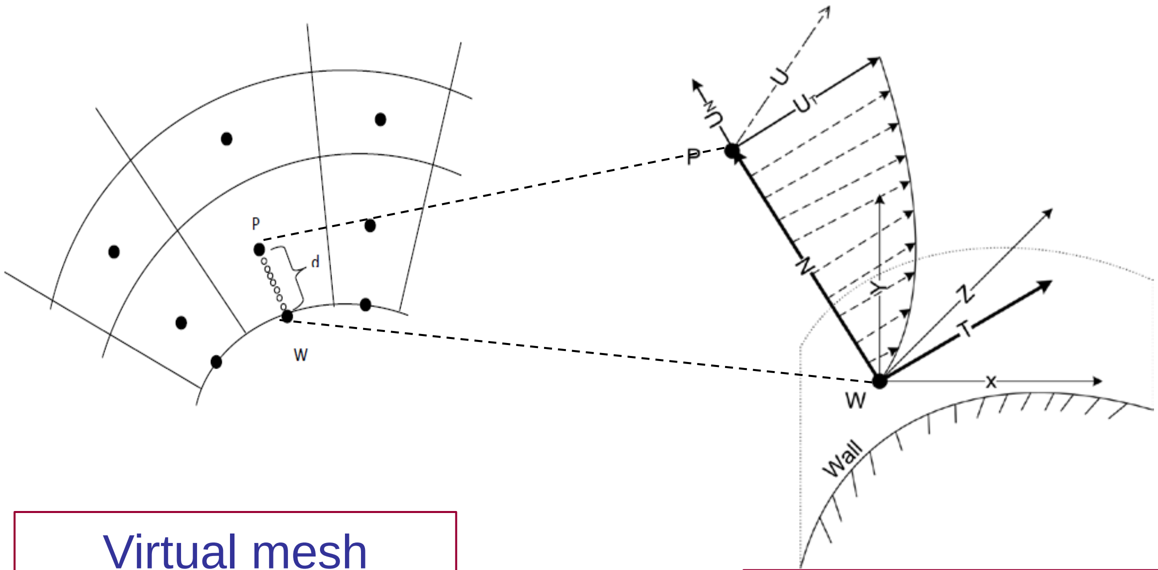




- **Archimedes number** $Ar = \frac{g d_p^3 \rho_f (\rho_p - \rho_f)}{\mu_f^2} \approx 22000$
  - **For 3 < Ar < 21700 laminar, Ar > 1.6×10^6 turbulent (Saxena et al.)**

LES with subgrid modeling

- **Dynamic Smagorinsky subgrid stress model in outer flow**
- **Wall layer model in inner layer[1].**



$$\frac{d}{dn}\left[\left(\frac{1}{\mathrm{Re}}+\frac{1}{\mathrm{Re}_t}\right)\frac{du_t}{dn}\right]=\frac{dP}{dt}$$

$$\frac{d}{dn}\left[\left(1+\frac{\mathrm{Re}\,\mathrm{Pr}}{\mathrm{Re}_t\,\mathrm{Pr}_t}\right)\frac{dT}{dn}\right]=0$$

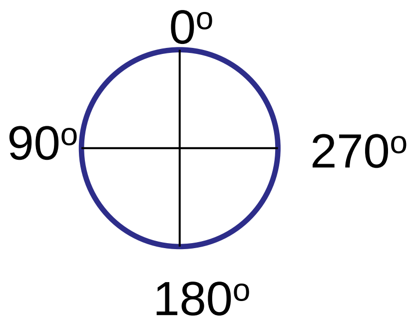
Virtual mesh embedded in outer LES grid

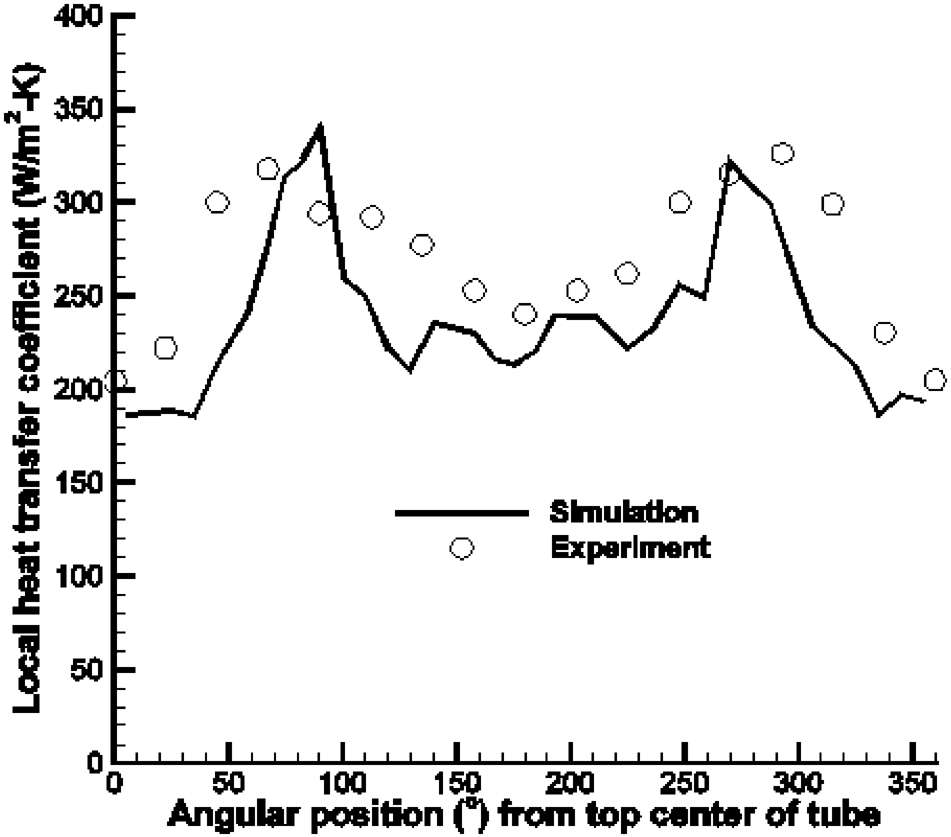
Tangential velocity formulation

[1] ***Patil and Tafti (2011)***

Local HTC with WMLES

- **Use of Wall function LES**
  - **± 20% of experiments**





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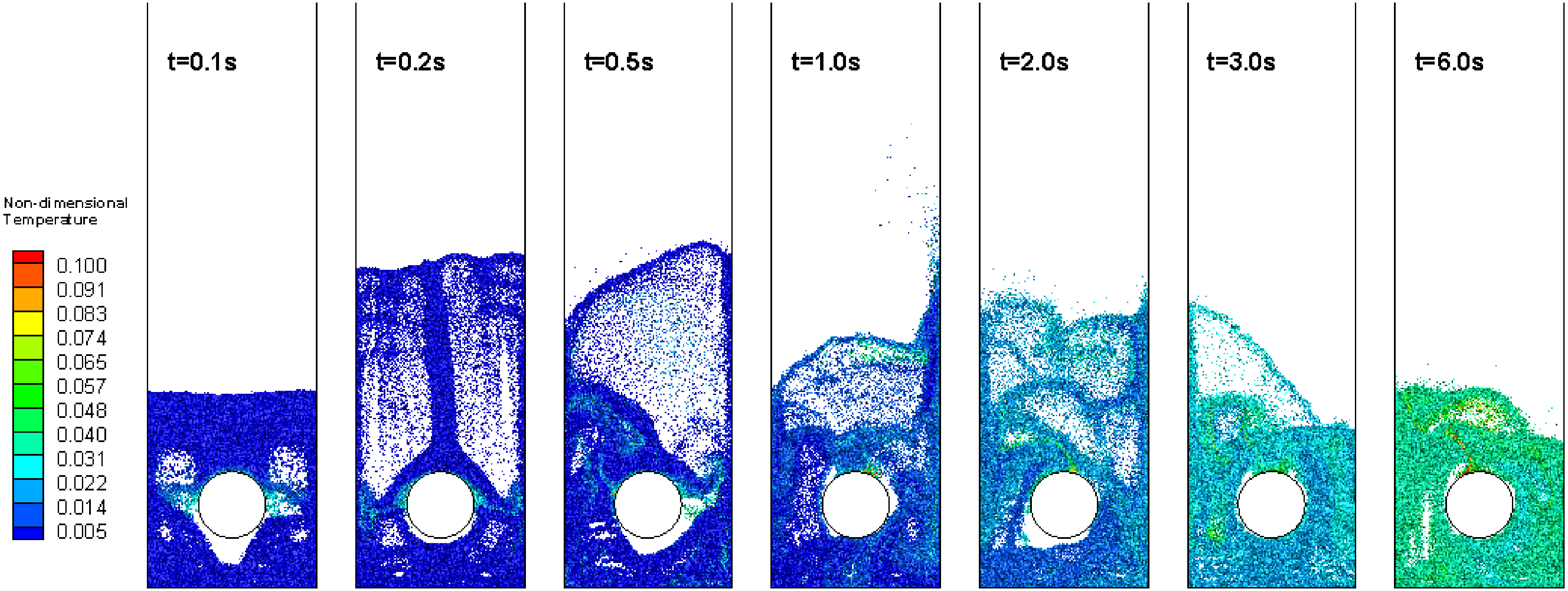
Particle temperature evolution

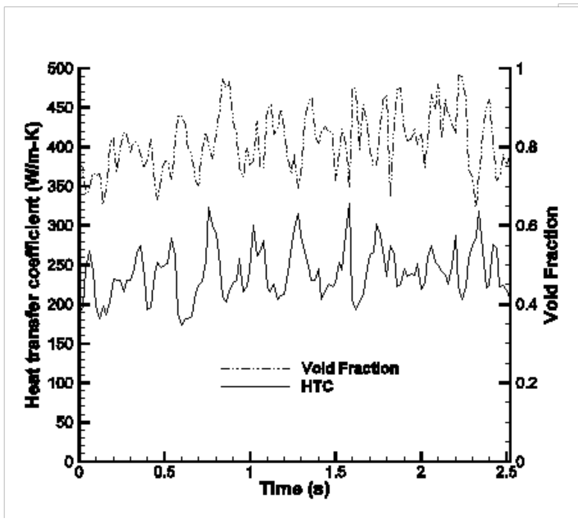
- **Snapshots of particle temperature**

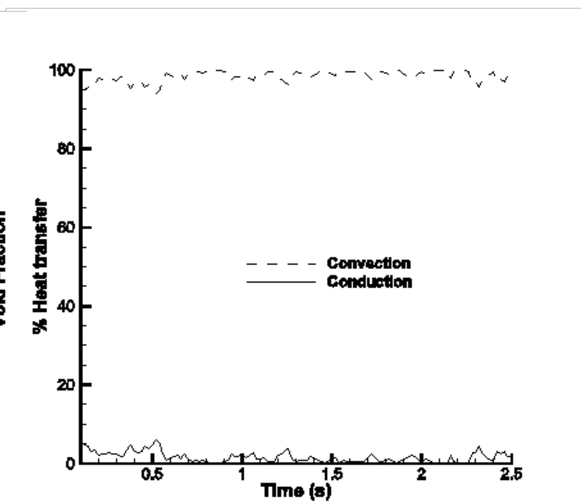


Time/space averaged quantities

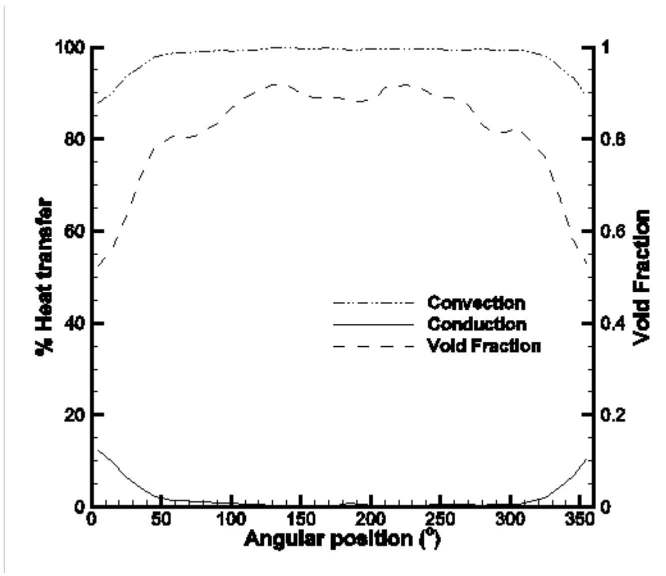
Space averaged

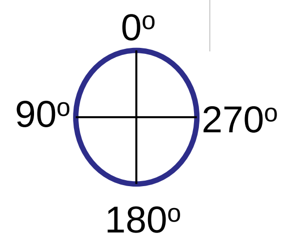
- Void fraction and HTC
- Heat transfer mechanism



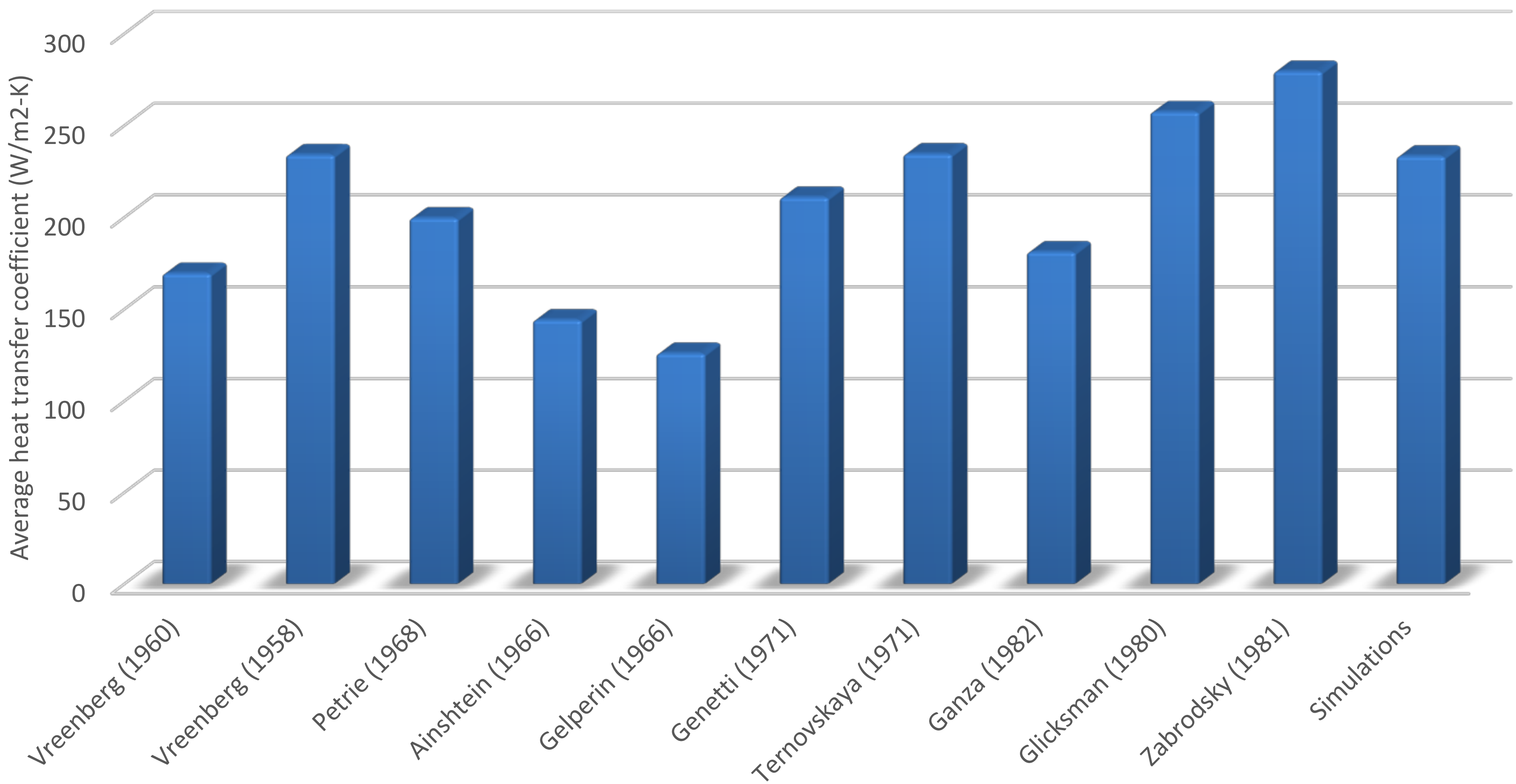


Time averaged





Comparison with empirical correlations



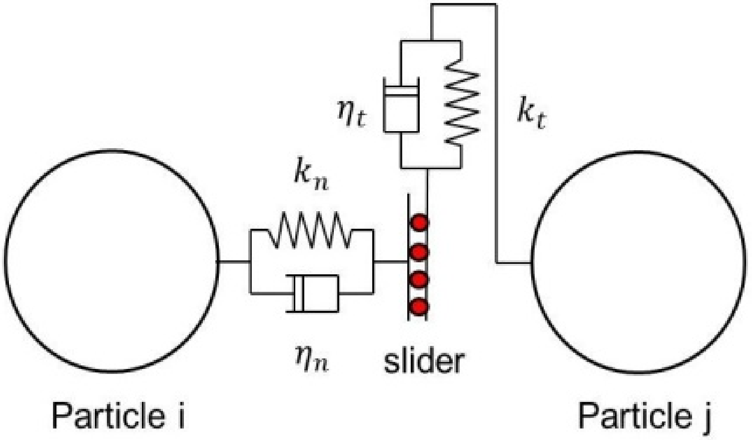
Conclusion and Future work

- Average HTC estimated using WMLES
  - ± 20% of experiments
  - Limited to non-laminar flows

- Use of separate grids
  - Fluid phase
    - Can be solved using LES grid
  - Particulate phase
    - Larger grid size for smooth void fractions

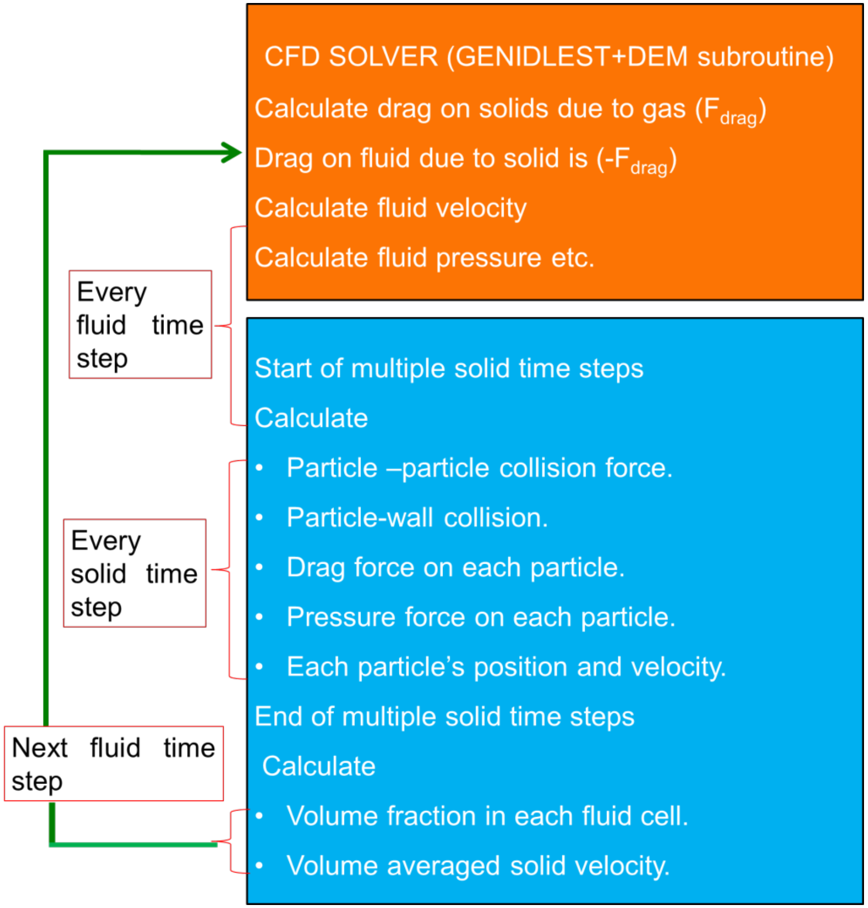
Discrete element method (DEM)

- **Soft sphere model**
  - **Normal direction**
    - **Forces modeled as spring-mass damper system**
  - **Tangential direction**
    - **Forces modeled as spring-mass damper system with a slider in series for particle sliding**
  - **Softening treatment**
    - **Reduced spring stiffness**
  - **Applied to**
    - **Particle-particle collision**
    - **Particle-wall collision**



DEM-CFD coupling algorithm

- **Procedure of DEM + GenIDLEST coupling**



Solid phase - Governing Equations

- **Newton's second law**

$$m_{p,i}\frac{d\vec{u}_{p,i}}{dt} = \underbrace{(\rho_p - \rho_f)V_{p,i}\vec{g}}_{\text{Buoyancy}} + \underbrace{\frac{V_{p,i}\beta}{1-\varepsilon}(\vec{u}_f - \vec{u}_{p,i})}_{\text{Drag}} + \underbrace{\sum \vec{F}_{p,ij}}_{\text{Particle-particle /surface}} + \vec{F}_{p,other}$$

- **Energy conservation**

$$m_{p,i}c_{p,i}\frac{dT_{p,i}}{dt} = \underbrace{Q_{fp,i}}_{\text{Convective}} + \underbrace{Q_{p,i}}_{\text{Particle-particle /surface}}$$

Thermal Discrete Element Method (TDEM)

- **Solving the energy equation for particulate phase**
  - **Using the soft sphere model**

- **Coupling the particle and fluid energy equations**
  - **Source terms in respective energy equations**

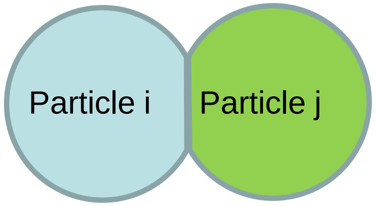
- **Modeling heat transfer at particle level**
  - **Particle-fluid**
  - **Particle-particle**
  - **Particle-surface**

Particle/surface – particle heat transfer

Modes of heat transfer during particle collision

- **Radiation**
  - Generally neglected for temperatures < 700 K
- **Friction heating**
  - Experiments show it to be negligible
- **Gas lens / liquid bridge effect**
  - For flows with stagnant fluid around particles
- **Conduction heat transfer**
  1. Quasi steady approach
  2. Unsteady approach

Particle/surface – particle conduction heat transfer



- **Quasi steady modeling approach**
  - **Steady state solution at each time step**
  - **Assumption of Biot number << 1**
  - **Analytical solution of contact conductance**

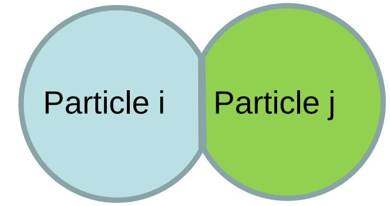
$$H_{pc,ij} = 2\kappa_{p,i} r_{c,ij}$$

  - **Using the Hertz's theory for contact radius** $r_{c,ij}$

$$H_{pc,ij} = 2\kappa_{p,i} \left[\frac{\vec{F}_{p,ij,n} \, {R^*}_{ij}}{{E^*}_{ij}} \right]^{1/3}$$

  - **Heat transported across the collisional interface per unit time** $Q_{pc,ij} = H_{pc,ij}\left(T_j - T_i\right)$

Particle/surface – particle conduction heat transfer



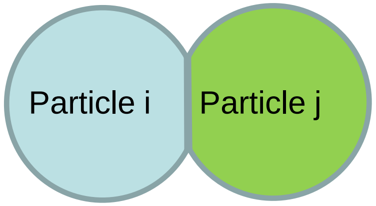
- **Unsteady solution approach**
  - **Heat Equation** $$\frac{1}{\alpha}\frac{\partial T}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}\left(\frac{\partial T}{\partial r}\right) + \frac{\partial^2 T}{\partial z^2}$$
  - **Assumptions**
  - **Elastic collision**
  - **Perfectly smooth particles with no contact resistance**
  - **Contact radius << particle radius**
  - **Two particles are treated as infinite mediums**

  - **Solution for 1D assumption of** $Fo_{pij} \ll 1$ $\quad (Fo_{pij} = \alpha_i t_c / r_c^2)$

    - **Heat Flux** $$q_{0,ij} = \left(0.87\beta_{p,i}\beta_{p,j}\left(T_{p,j} - T_{p,i}\right)A_c {t_c}^{-0.5}\right) / \left(\beta_{p,i} + \beta_{p,j}\right)$$

    where t_c **is calculated from Hertz's theory**
    A_c **is calculated from DEM simulations**

Particle/surface – particle conduction heat transfer



- **Higher Fourier number**
  - **Correction factor to account for 2D heat transfer**
    - $Q_{pc,ij} = Cq_{0,ij}$
    - Solving the 2D conduction equation once to get ‘C’
    - Interpolating the data from Sun and Chen, 1988

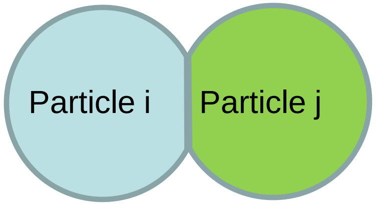
- **Total conduction heat transfer**

$$Q_{pc,i} = \sum_{j=1}^{n_{p,i}} Q_{pc,ij} \qquad \& \qquad Q_{pcw,i} = \sum_{j=1}^{n_{w,i}} Q_{pcw,ij}$$

Challenges

- **Contact time dependent calculations**
  - **The contact time and contact area depend on the material properties**
    - **Restoration method (Lu et al.)**
      - Correction to contact time and area of contact

$$\frac{t_1}{t_a} \approx \sqrt{\frac{k_a}{k_1}} \qquad \frac{a_1}{a_a} = \sqrt[4]{\frac{k_a}{k_1}}$$



    - **Zhou et al. correction**

$$c = r_{ca}/r_{ci} = \left(E_{ij}/E_{ij}^{*}\right)^{1/5}$$

- **Convective heat transfer coefficient**
  - **Nusselt number correlations**
    - **Function of void fraction**

Nusselt number correlations

- **Calculation of h based on void fraction**
  - **Agarwal's expression (1988)**

$$Nu_{p,i} = 2 + 0.6\varepsilon_i^{-1.23} Re_{p,i}^{0.5} Pr^{\frac{1}{3}}$$

  - **Li and Mason correlation (2000)**

$$Nu_{p,i} = \begin{cases} 2 + 0.6\varepsilon_i^{3.5} Re_{p,i}^{0.5} Pr^{\frac{1}{3}} & Re_{p,i} < 200 \\ 2 + \varepsilon_i^{3.5}\left(0.5 Re_{p,i}^{0.5} + 0.02 Re_{p,i}^{0.8}\right) Pr^{\frac{1}{3}} & 200 < Re_{p,i} < 1500 \\ 2 + 0.000045\varepsilon_i^{3.5} Re_{p,i}^{1.8} & Re_{p,i} > 1500 \end{cases}$$

  - **Ranz (1992)**

$$Nu_{p,i} = 2\varepsilon + 0.69 Re_{p,i}^{0.5} Pr^{\frac{1}{3}}$$

$$Nu = (7 - 10\varepsilon + 5\varepsilon^2)\left(1 + 0.7 Re_p^{0.2} Pr^{\frac{1}{3}}\right) + (1.33 - 2.4\varepsilon + 1.2\varepsilon^2) Re_p^{0.7} Pr^{\frac{1}{3}}$$

Heat transfer validation

- **Validation of particle/surface-particle heat conduction with experiments**

Total energy transferred per impact	Ben-Ammar et al.	Kuwagi at al.
Experimental (J)	1-3E-04	2.788E-02
2D corrected unsteady solution as in Lu et al. A_c and T_c corrections (J)	2.339E-04	5.173E-02
2D corrected unsteady solution as in Zhou et al. A_c corrections (J)	1.106E-04	2.289E-02
Quasi steady approach (J)	1.220E-04	3.949E-03