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FACULTY OF ENGINEERING AND ARCHITECTURE

Computational Study of Hydrodynamics in a Gas/Solid Vortex Reactor

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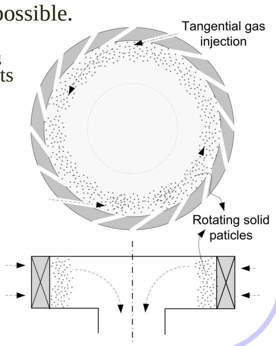
Gas/Solid Vortex Reactor (GSVR)

Utilizes tangential injection of a gas phase to induce rotation and fluidization of a dense bed of solid particles. Alternative gas/ liquid/solid combinations are possible.

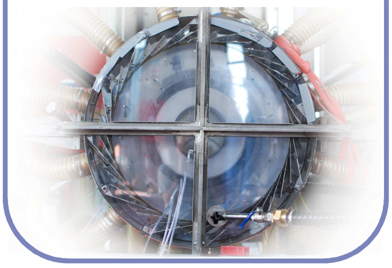
- High slip velocities because $F_c >> F_g$
- High heat & mass transfer coefficients
  - h ~ 0.1 – 1 kW/m²·K
  - k_C ~ 0.1 – 1 m/s
- High solid volume fractions
  - VF_{solid} ~ 0.3 – 0.6
- Short gas/solid contact time
  - $t_{g/s}$ ~ 10 ms
- Short reactor residence time
  - t_{res} ~ 50 ms

→ *Process intensification*



Experimental GSVR Setup

- Dimensions: R_{active} = 0.27 m, L = 0.1 m
- Gas: air; 0.5 – 1.0 kg/s
- Solid: polyethylene (0.9 mm), < 4.5 kg
- Solid velocity: 5 – 10 m/s
- Centrifugal acceleration: 20 – 40 g's
- Visual measurement of bed thickness



Phenomena Critical to Operation

The centrifugal and drag forces on the solid particles are critical to bed dynamics & operational stability.

- Fluid/Solid Interaction Coefficient, β:

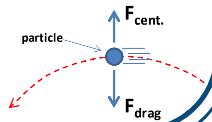
$$\beta(\mathrm{Re},\phi_s) = 18\cdot\mu_g\cdot(1-\phi_s)^2\cdot\phi_s\cdot\frac{F(\mathrm{Re},\phi_s)}{d^2}$$

- Drag force model: [1]

$$F(\mathrm{Re},\phi_s) = \frac{0.413}{24(1-\phi_s)^2}\cdot\left[\frac{(1-\phi_s)^{-1}+3\phi_s\cdot(1-\phi_s)+8.4\cdot\mathrm{Re}^{-0.343}}{1+10^{3\phi_s}\cdot\mathrm{Re}^{-(1+4\cdot\phi_s)/2}}\right]$$

- Centrifugal force on particles:

$$F_{cent}(r, v_{s,\tan}) = \frac{m_{particle}\cdot v_{s,\tan}^2}{r}$$

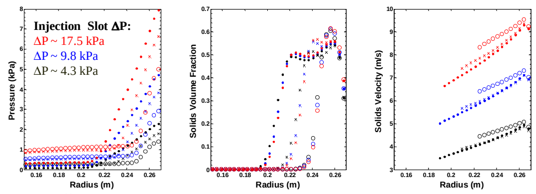


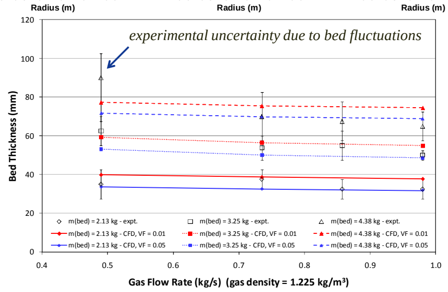
2D Periodic Simulations

- Data averaged over time (0.5 s) and theta coordinate
- Slip velocities of 4 – 12 m/s
- Thickness defined to solids volume fraction of 0.01 or 0.05 in CFD results

default legend

- 0.48 kg/s air, m(bed) = 2.13 kg
- 0.48 kg/s air, m(bed) = 3.25 kg
- 0.48 kg/s air, m(bed) = 4.38 kg
- 0.74 kg/s air, m(bed) = 2.13 kg
- 0.74 kg/s air, m(bed) = 3.25 kg
- 0.74 kg/s air, m(bed) = 4.38 kg
- 0.98 kg/s air, m(bed) = 2.13 kg
- 0.98 kg/s air, m(bed) = 3.25 kg
- 0.98 kg/s air, m(bed) = 4.38 kg

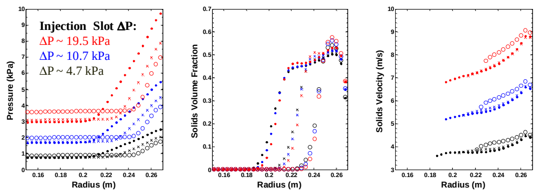


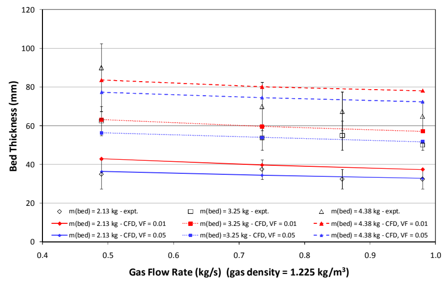


- ***CFD results generally match well with observed bed thickness***
- ***Under-estimation at low air flow/high bed mass… gravity effect?***

3D Periodic Simulations

- Data averaged over time (0.5 s) and theta + axial coordinates
- Slightly extended/less dense bed compared to 2D case
- Comparable pressure drop across the bed, 1 – 7 kPa, with ~10% larger pressure drop across the injection slots
- General agreement with experimental data

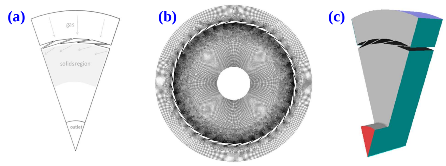




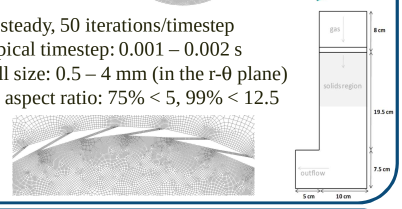
- ***CFD results generally match well with observed bed thickness***
- ***Slightly expanded bed relative to 2D periodic results***

Computational Model

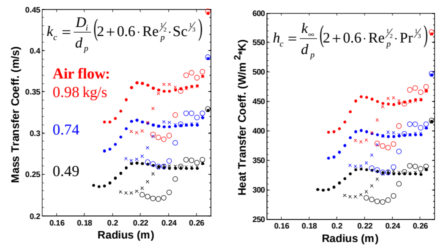
- Computational fluid dynamics → Fluent 13.0
- GSVR geometries:
  a) 2D, 40° section, periodic BCs (12,000 cells)
  b) 2D, full 360° model (100,000 cells)
  c) 3D, 40° section, periodic BCs (250,000 cells)



- Unsteady, 50 iterations/timestep
- Typical timestep: 0.001 – 0.002 s
- Cell size: 0.5 – 4 mm (in the r-θ plane)
- 3D aspect ratio: 75% < 5, 99% < 12.5



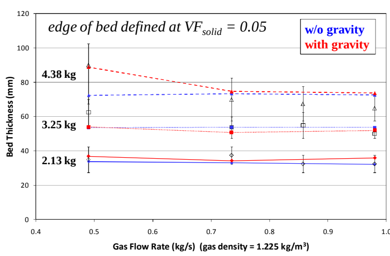
Mass/Heat Transfer Coefficient

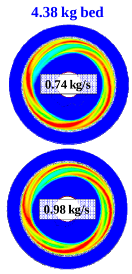


- ***Based on room temperature air properties***
- ***From 3D periodic simulations; insensitive to geometry***

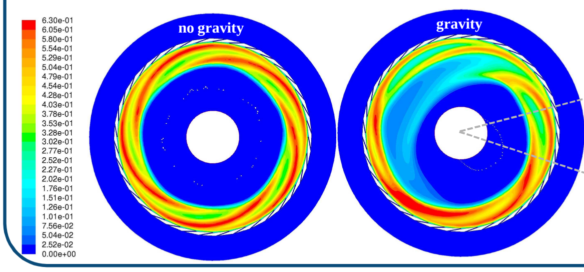
Gravitational Effects - 2D Simulations

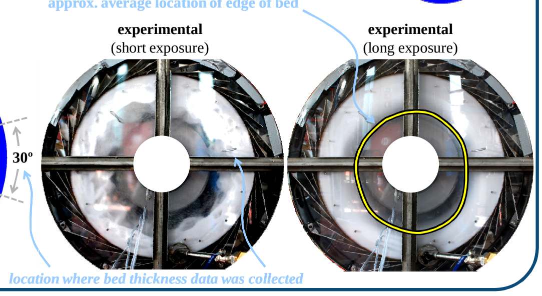
- Gravity effects appear to be responsible for low velocity, high bed mass deviations
- Minimal gravity effects at high velocity/low mass
- CFD captures time-averaged behavior adequately
- Unable to reproduce fine-detail and complexity of the freeboard region seen in experiment
- Solids "rollover" due to gravity is over-predicted in simulation results, compared to experiment





VF_{solid} Results: 0.49 kg/s air w/4.38 kg bed mass





Future Research Activities

- Analyze the effect of simple reacting flows on the operating characteristics & bed stability
- Identify industrial processes that may benefit from GSVR technology
- Simulate targeted industrial processes with lumped kinetic models to gauge technology impact
- Examine feasibility of industrial implementation

References

1. R. Beetstra, M. A. van der Hoef, J. A. M. Kuipers, *AIChE Journal* 53 (2007) 489-501.

Acknowledgements

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