MFIX-DEM Enhancement for Industry-Relevant Flows

2021 DOE/FE
Spring Project Review Meeting
Dr. Wyatt C.Q. LaMarche (PSRI)

May 2021

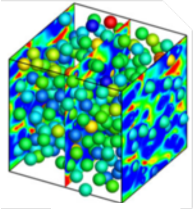
Project leads

Dr. Ray Cocco (PSRI, co-PI)
Dr. Ray Grout (NREL, co-PI)
Prof. Thomas Hauser (Univ. CO, co-PI)
Prof. Christine Hrenya (Univ. CO, PI)

Funding

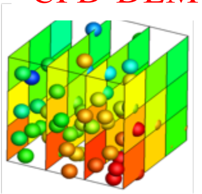
Background: Numerical Methods for Studying Gas-solid Flows

Tenneti & Subramaniam (2016)



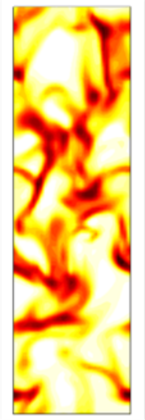
DNS

CFD-DEM



In-house

Two-Fluid Model



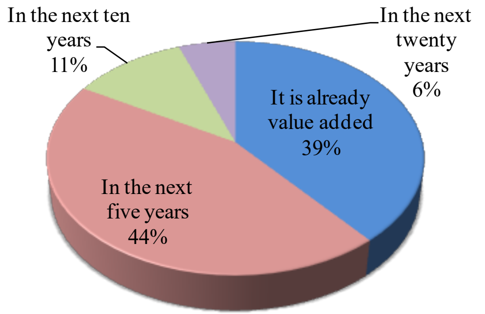
In-house

More detail, fewer closures ←

Less CPU time →

Fullmer and Hrenya
(*Ann. Rev. Fluid Mech.*, 2017)

Expected value added through DEM

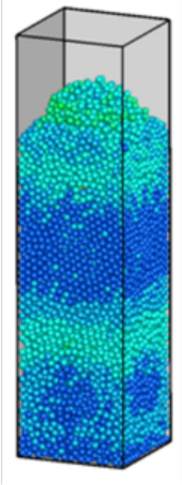


PSRI Industrial Survey
(Cocco et al., *Chem. Eng. Prog.*, 2017)

DEM:

a balance between computational overhead and sources of uncertainty

Motivation: Big picture



CFD-DEM

$N_p \sim 10^5$ - 10^7

Laboratory

$N_p \sim 10^9$ - 10^{10}

Industry

$N_p \sim 10^{14}$

Goal: DEM application toward industrially relevant flows

Challenges

- Speed ⇒ Optimization & Algorithms (this talk)
- Results reliability ⇒ **Validation (this talk)** & Uncertainty Quantification

Objective of this work (... and challenges)

Objective:

- DEM validation data set in an industrially relevant system
  - Push capability limits of DEM, but maintain a feasible number of particles: $N_p \lesssim 10^9$
  - Identified stripping operation as industrially relevant system for study
  - Characterize section of operation
  - Use large (Group B) particles

Challenges

- Design for operation with relatively dense FCC (Group A)
  - Typical measurement techniques did not perform for out-of-spec material/conditions
  - New development required/tested for characterization

Novelty

- First DEM validation set in industrially relevant (size and operation) system
- Well characterized material and operating conditions
- Axial and radial measurements of solids flow profiles within the system

Stripper units for industrially relevant DEM validation

A what????

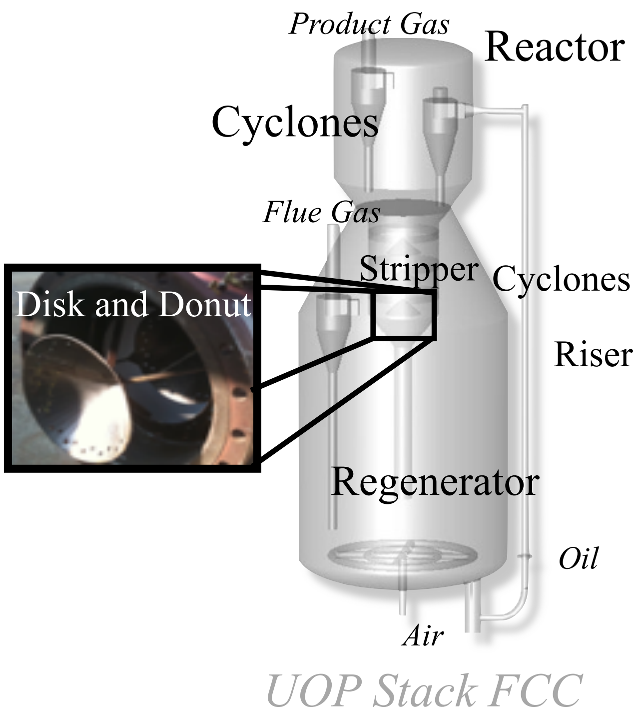
- Separate (strip) product gas from solid catalyst phase

How it works

- After initial separation (e.g., cyclone)
- Counter-current flow of feed gas to separate: Essentially a fluidized bed
- Need good distribution of incoming solids and feed gas to main good mixing and stripping

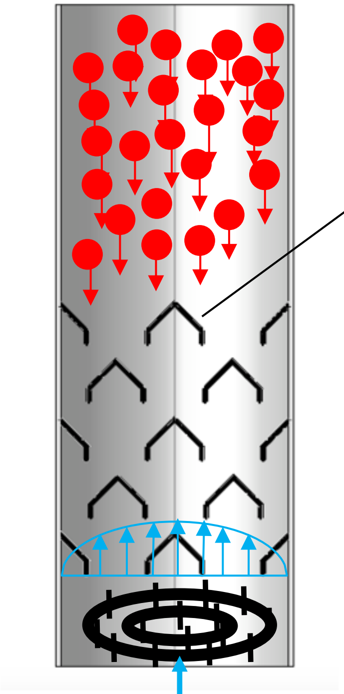
Problem: "flooding" at high solids flow rates reduces stripping gas and solid mixing

- Flooding: gas bypassing solids as large bubbles
- Internals (sheds) used to delay flooding point

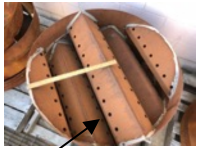


Strippers tend to be a bottleneck in FCC units

Stripper internals and delayed flooding

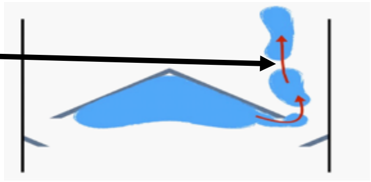


Stripping gas distributor

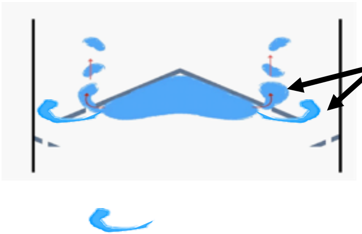


Without vent holes

Gas can only escape around sheds



With vent holes



Gas can escape through vents and around cone/donuts

As bubbles rise up stripper they occupy relatively larger volumes, which lower the overall bed density and a precursor to flooding.

Relatively small changes in stripper internals design can have significant changes the flooding point

PSRI's cold flow stripper experimental test unit

Cold flow operation
Large-scale system

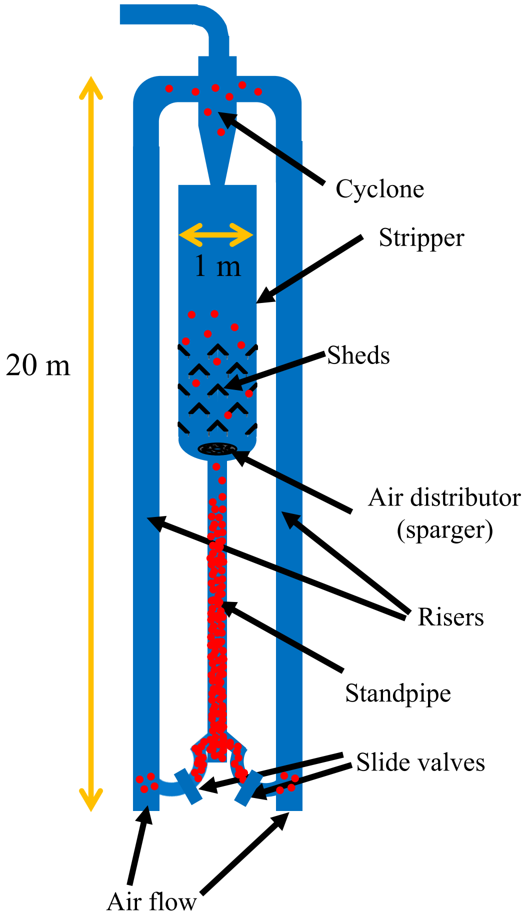
- 20 m tall system
- Risers 0.3 m diameter
- Stripper 1 m diameter

Solids recirculate

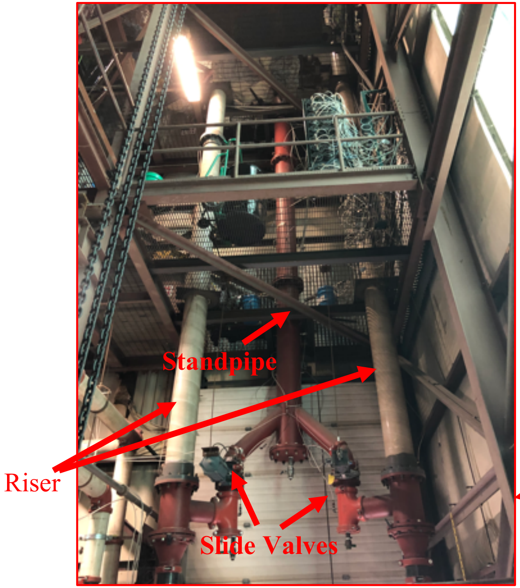
- Gas and solids transported up by risers

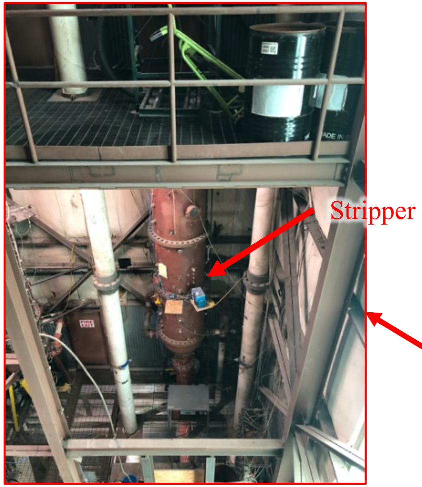
Separation at cyclone

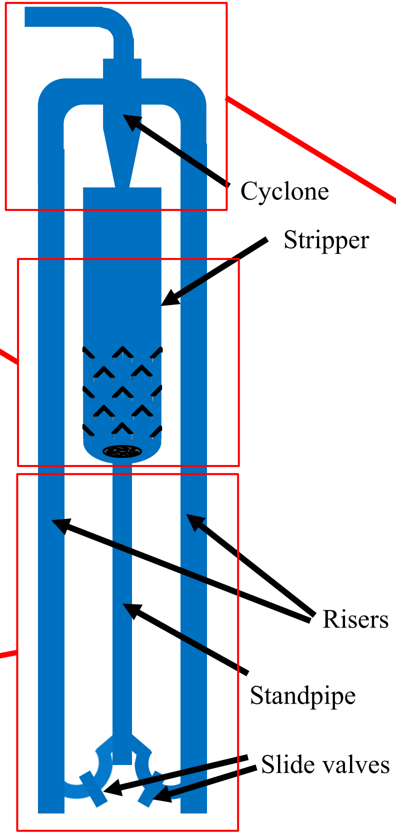
- Solids flow down the stripper unit
- Fluidizing air is distributed to the bottom of the stripper unit
- Gas and solids flow around sheds
- Solids flow into standpipe then to risers
- Slide valve opening can be controlled

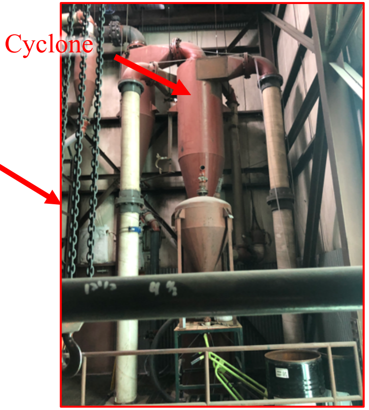


PSRI’s cold flow stripper experimental test unit

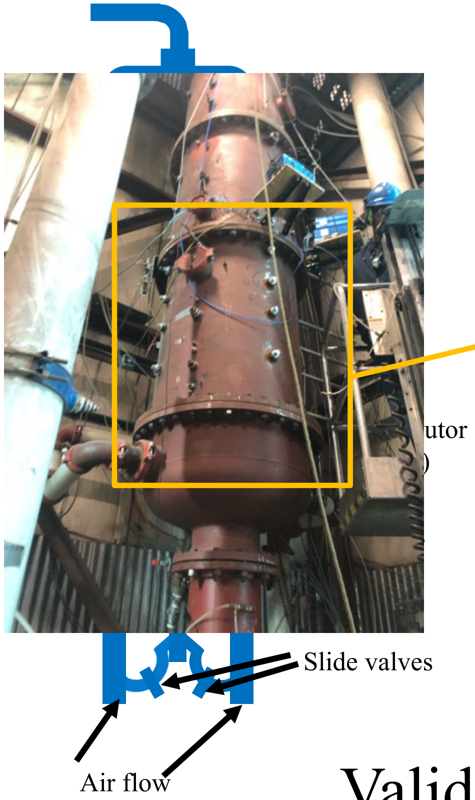


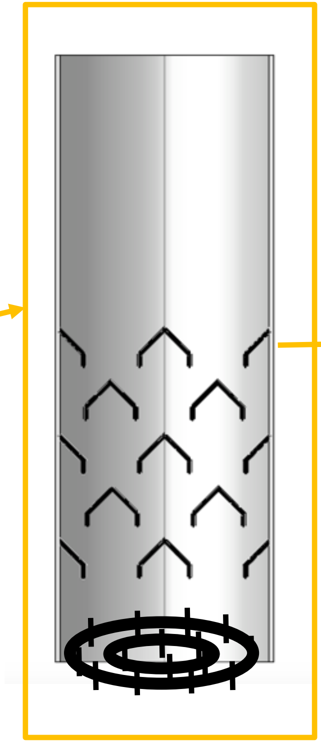






Details of stripper section





Validation using a large-scale system

Targeting DEM validation in PSRI’s Stripper Experimental System

DEM validation dataset

- Push limits of N_p , but still reasonable for DEM comparison
  - $N_p \lesssim 10^9$

- System too large for 1:1 comparison
- Validation using small subset of experimental system
- Target region around sheds of stripper unit

Shed section of stripper unit

Design considerations

- Shed placement
  - Must fit probes between
  - Larger separation reduces overall solids volume fraction
- Shed design
- Operating conditions:
  - Air distribution to the sparger
- Group B particles provide higher solids volume fraction for same N_p
  - 1000 kg 500 μm Soda Lime glass beads

Measurement Techniques

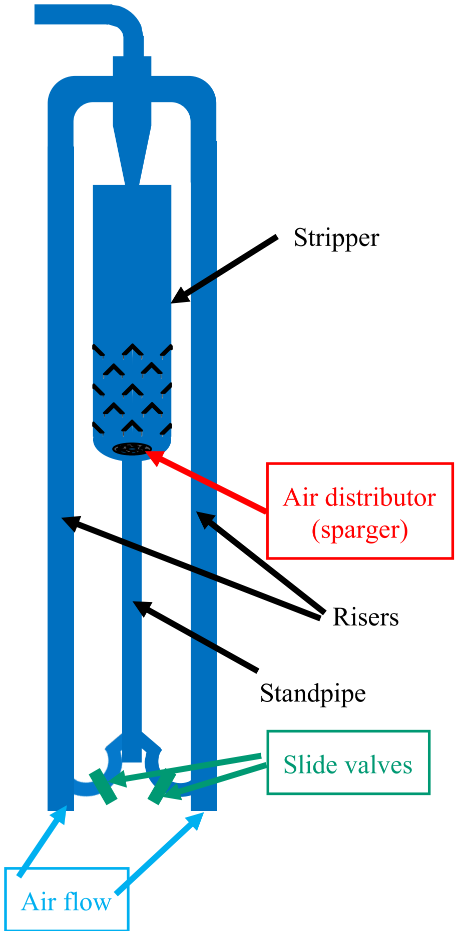
- Many tools available are targeted for FCC operation
- Development required
- Characterize solids flow into and out of section for boundary condition specification
- Measure internal flow profiles

Goal: measure axial and radial profiles of solids flow to prescribe boundary conditions for DEM validation as well as internal profiles for comparison

Controlling flow to the stripper section

Controllable operating conditions

- Air flow to the risers
  - Superficial air velocity in the risers
- Slide valve opening
  - solids flow to the riser
- Aeration to the slide valve
  - solids flow to the riser
- Air flow rate to the sparger
  - Superficial air velocity in the stripper



Characterizing system operation

? ✓ **Extraction probe measurements**

- Radial mass flux in the riser
  - Ensure consistency and repeatability
- Radial mass flux in the stripper
  - Required development

Pressure measurements

- $\Delta P = W/A$
- N_p in the stripper
- Pressure loop across the system

? ✘ **Bubble probes (fiber optic)**

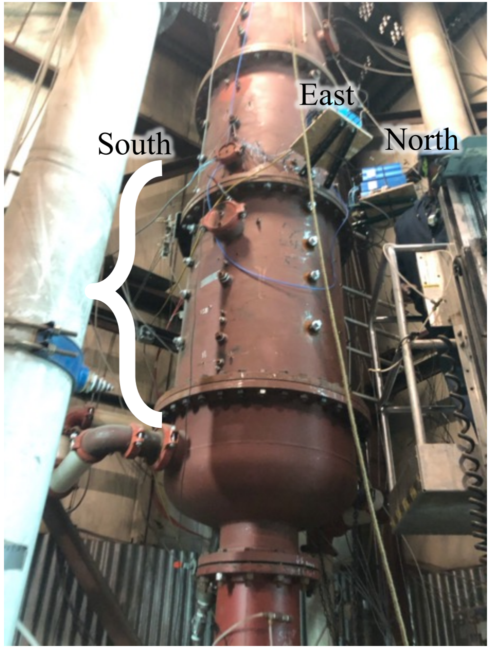
- Designed/optimized for dense FCC

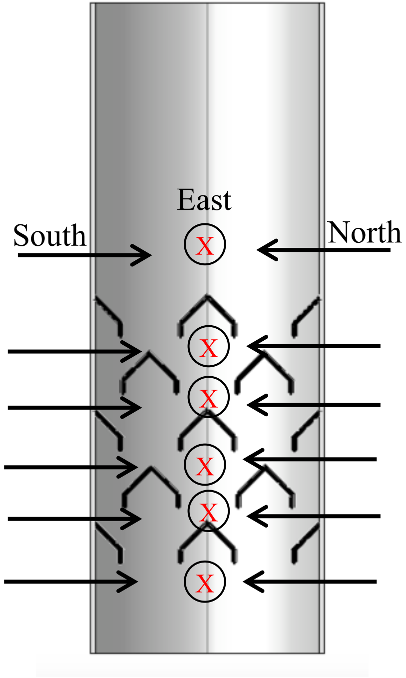
? **High-speed imaging**

- (Required development)

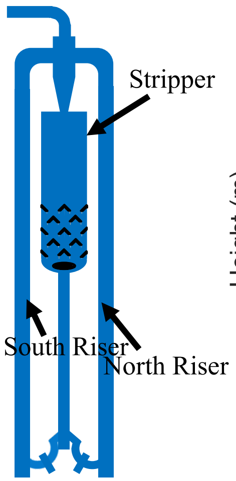
? ✘ **Helium gas tracing**

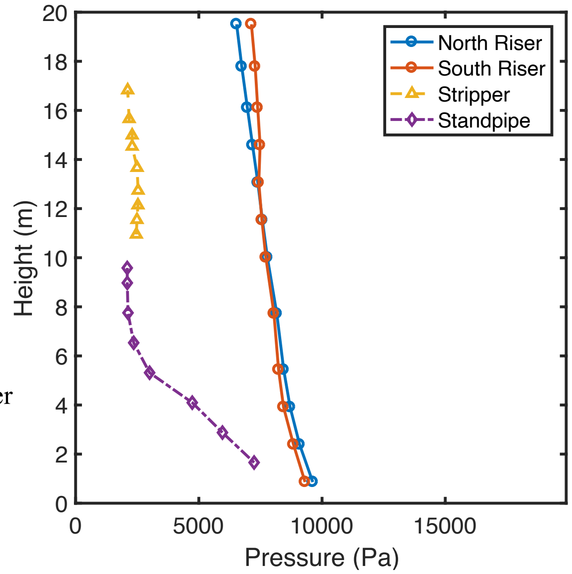
- Designed/optimized for dense FCC

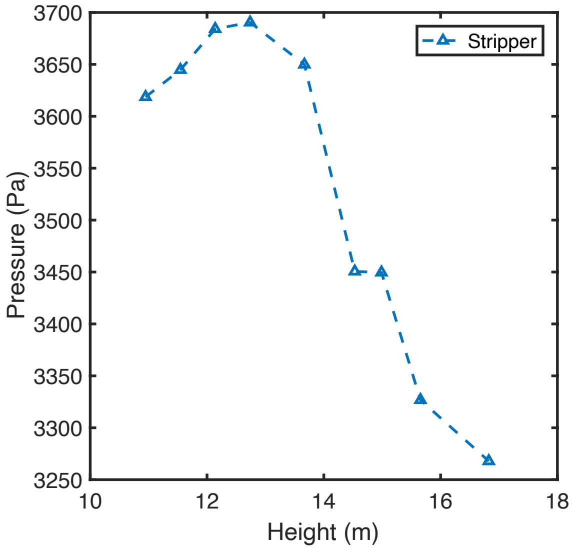




Pressure measurements

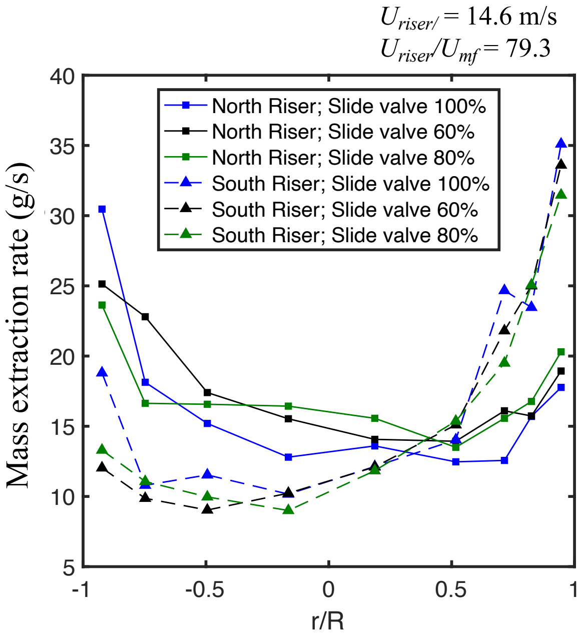


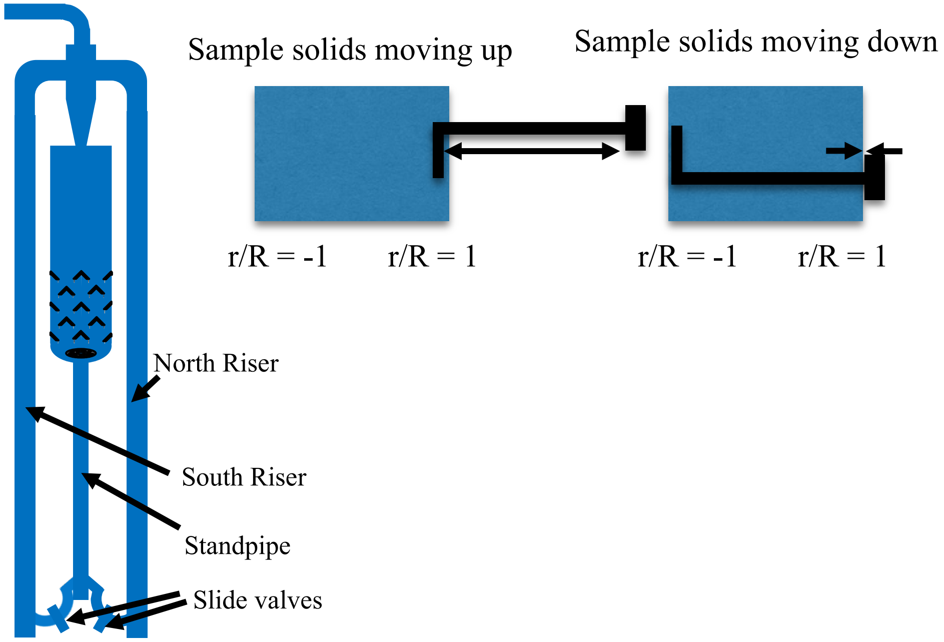




Pressure differentials are measured throughout the stripper experimental system

Riser mass extraction (solids mass flow rate) profile

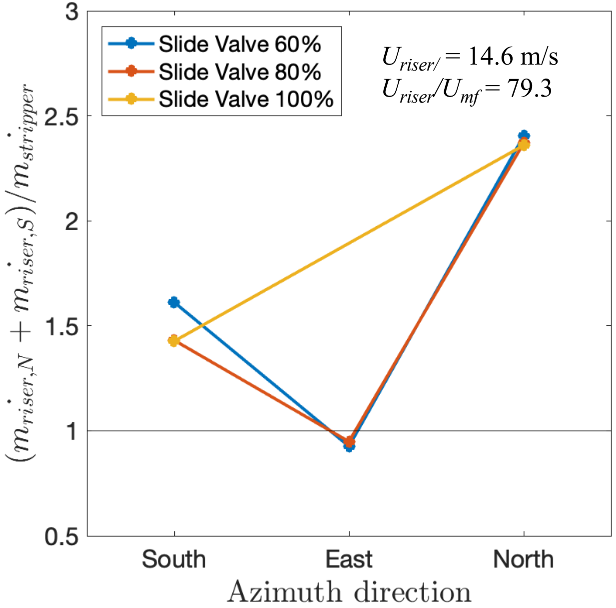


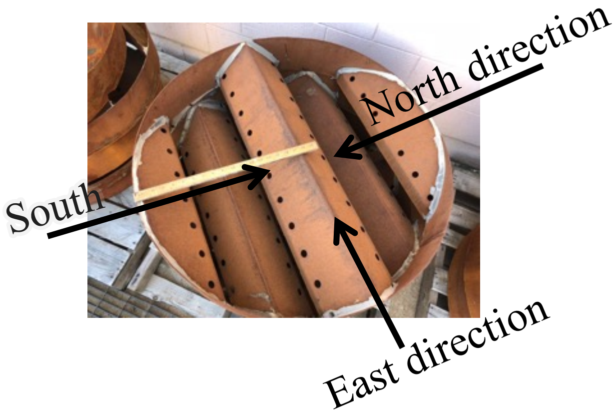


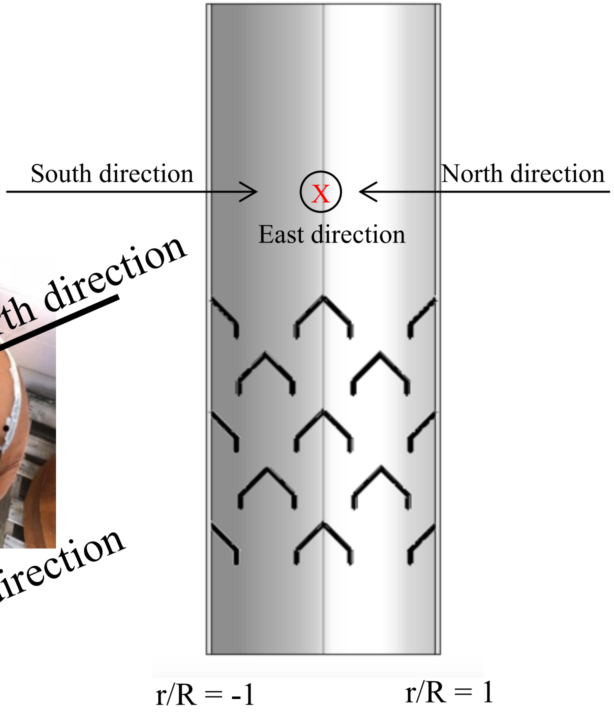
Difference between riser mass extraction profiles is relatively small, and integrated mass flux is consistent between the two risers

Adjusting slide valve opening does not have a significant influence on the mass flux in the risers

Mass balance: Consistency between risers and stripper

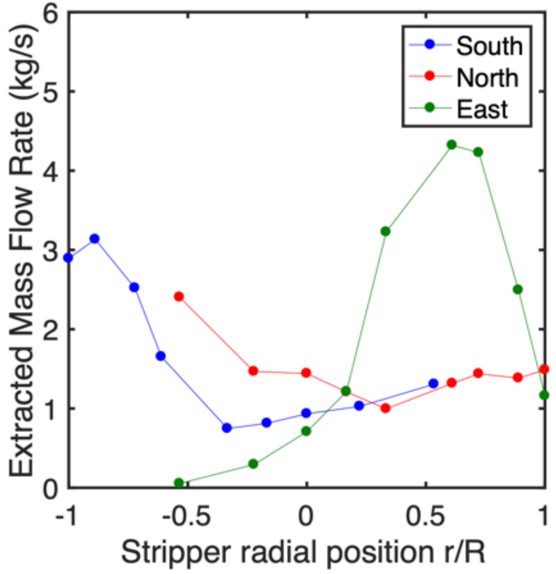


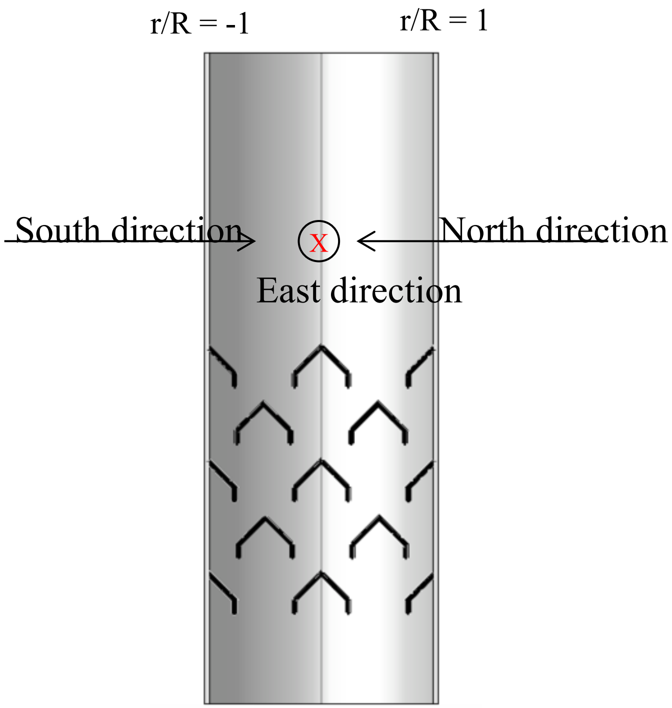


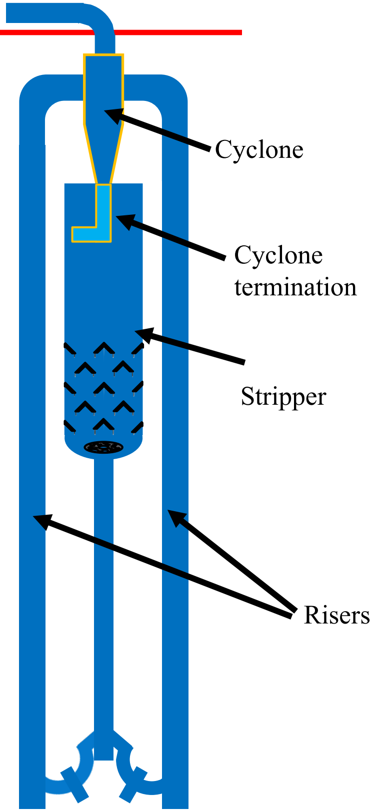


Large deviation between stripper mass flux measured from different azimuthal directions (integrated mass flow for each direction)

Radial mass extraction profiles of Group B glass in the stripper



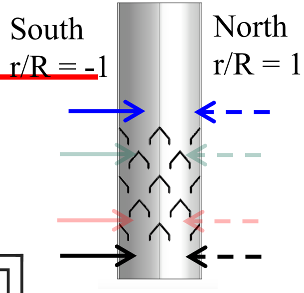


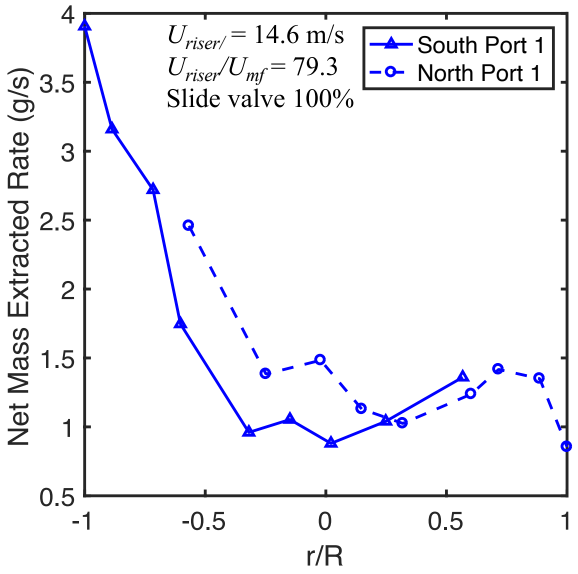


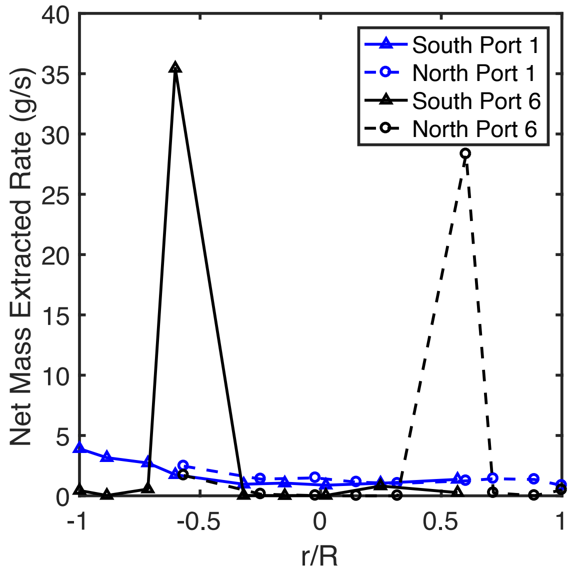
Above the top layer of sheds the solids are not distributed asymmetrically

Cyclone termination is expected source of non-uniform/symmetric distribution

Radial and axial profiles of mass extraction in stripper

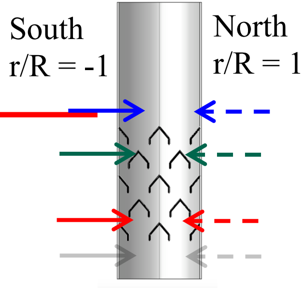


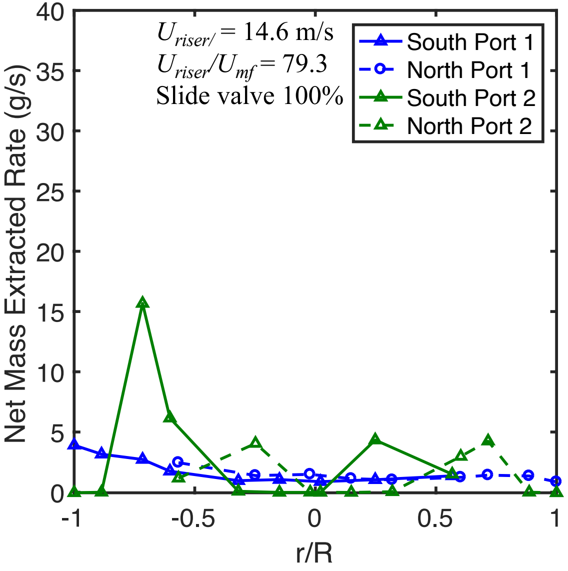


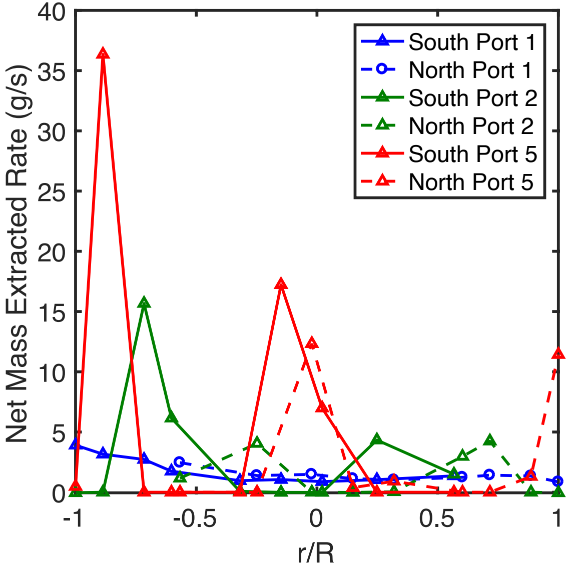


Top and bottom mass flux profiles can be used for simulation boundary conditions

Radial and axial profiles of mass extraction in stripper

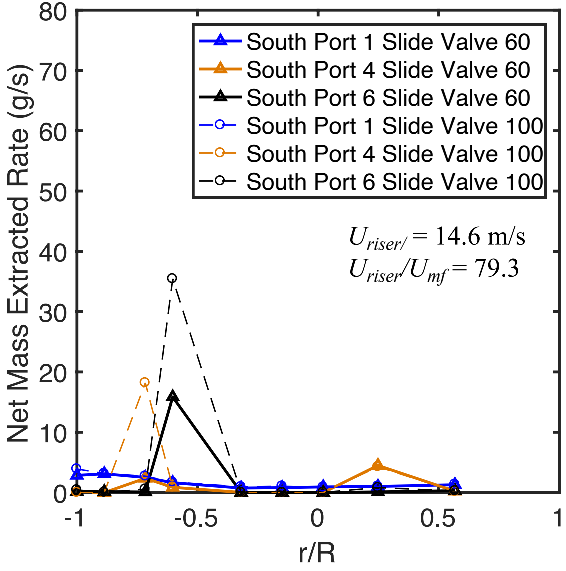


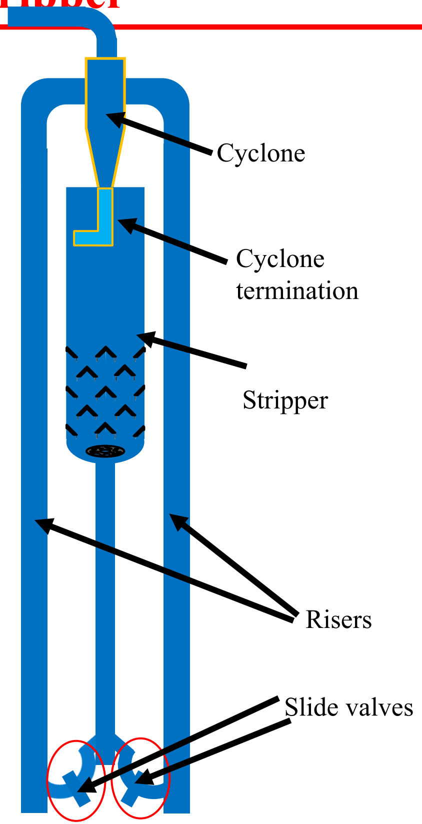


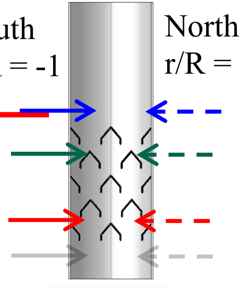


Internal mass flux radial profiles capture “migration” of solid material between sheds and redistribution and continues developing down the unit.

Radial and axial profiles of mass extraction in stripper







Internal mass flux radial profiles capture "migration" of solid material between sheds and redistribution and continues developing down the unit.

Concluding remarks

Industrially relevant DEM validation data set

- Understanding gas-solids flow in a stripper can help improve stripper design and increase FCC reactor throughput
- Stripper system operated with a dilute bed to target < 10^9 particles
- Pressure drop measurements throughout the system collected
- Solids flux profiles in the stripper show complex flow patterns through the stripper internals

Challenges

- Operating stripper outside of system design
  - Low-density in stripper bed challenging
- Adjustment to or replacement of typically measurement tools needed
  - Probes, etc.

Next Steps

- Attempt to characterize flow with high-speed camera

Team

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DEM modeling of granular and gas-solid flows, MFIX

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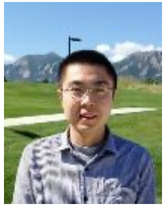

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