MFIX-DEM Enhancement for Industry-Relevant Flows

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

More detail, fewer closures

Less CPU time

Tenneti & Subramaniam (2016)

Two-Fluid Model

CFD-DEM

DNS

In-house

Expected value added through DEM

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

In the next five years 44%

In the next ten years 11%

It is already value added 39%

In the next twenty years 6%


DEM:

a balance between computational overhead and sources of uncertainty
Motivation: Big picture

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 \(\Rightarrow\) Optimization & Algorithms (this talk)
• Results reliability \(\Rightarrow\) 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

Gas can only escape around sheds

With vent holes
Gas can escape through vents and around cone/donuts

Without vent holes

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**
- \( \Delta P = \frac{W}{A} \)
- \( N_p \) 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

$U_{r/er} = 14.6 \text{ m/s}$

$U_{r/er} / U_{inj} = 79.3$

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.
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

\[ U_{\text{riser}} = 14.6 \text{ m/s} \]
\[ U_{\text{riser}}/U_{mf} = 79.3 \]
Slide valve 100%

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

University of Colorado
Chemical & Biological Engineering
DEM modeling of granular and gas-solid flows, MFIX

Prof. Christine Hrenya
Dr. William Fullmer (now at NETL)
Dr. Peiyuan Liu
Dr. Steven Dahl

University of Colorado
Research Computing
High-performance computing, CFD

Prof. Thomas Hauser

NREL
Computational Science
High-performance computing, CFD

Dr. Ray Grout
Dr. Hari Sitaraman
Deepthi Vaidhynathan

PSRI
Industrial Application And Experiments of Particle Flows

Dr. Ray Cocco

Shadong Lao

Dr. Wyatt C. Q. LaMarche

Aaron Holt

Dr. Steven Dahl

Dr. Peiyuan Liu

Dr. William Fullmer (now at NETL)

Prof. Christine Hrenya

University of Colorado
Chemical & Biological Engineering
DEM modeling of granular and gas-solid flows, MFIX

University of Colorado
Research Computing
High-performance computing, CFD

NREL
Computational Science
High-performance computing, CFD

PSRI
Industrial Application And Experiments of Particle Flows

Dr. Ray Cocco

Shadong Lao

Dr. Wyatt C. Q. LaMarche

Aaron Holt

Team

University of Colorado
Chemical & Biological Engineering
DEM modeling of granular and gas-solid flows, MFIX

Prof. Christine Hrenya
Dr. William Fullmer (now at NETL)
Dr. Peiyuan Liu
Dr. Steven Dahl

University of Colorado
Research Computing
High-performance computing, CFD

Prof. Thomas Hauser

NREL
Computational Science
High-performance computing, CFD

Dr. Ray Grout
Dr. Hari Sitaraman
Deepthi Vaidhynathan

PSRI
Industrial Application And Experiments of Particle Flows

Dr. Ray Cocco

Shadong Lao

Dr. Wyatt C. Q. LaMarche

Aaron Holt
Acknowledgement

This material is based upon work supported by the Department of Energy Award Number DE-FE0026298

Disclaimer: This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.