Understanding the Hydrodynamics in Biomass Gasifiers

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Fluidized Bed Gasifier Concept

- Typical feeds
  - Coal
  - Black liquor
  - Wood
  - Everything else
- Bed mixtures
  - Biomass and sand or olivine
  - Biomass co-gasification with coal
Outline

- Particle behavior and flow regimes
- Bed behavior
- Entrainment
- Bubble
- Multiphase jet
  - Gas jets
  - Gas-liquid jets
- Summary
Outline

• Particle behavior and flow regimes
• Bed behavior
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  • Gas jets
  • Gas-liquid jets
• Summary
• Sand is “inert” and remains a Geldart Group B Particle
• Coal is typical fed in as Geldart Group B but bed properties can be more indicative of Geldart Group A
# Differences Between Geldart Groups A and B

<table>
<thead>
<tr>
<th>Properties</th>
<th>Geldart Group A</th>
<th>Geldart Group B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bubbles</td>
<td>Small, 2 to 4 inches</td>
<td>Large! Prone to Slugging</td>
</tr>
<tr>
<td>Permeability</td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td>Heat and Mass Transfer</td>
<td>High</td>
<td>Low</td>
</tr>
<tr>
<td>Bed Expansion</td>
<td>Significant!</td>
<td>Moderate</td>
</tr>
<tr>
<td>Entrainment</td>
<td>High</td>
<td>Low</td>
</tr>
</tbody>
</table>
Flow Regimes

- To date, most biomass gasifier concepts are bubbling and churning fluidized beds.
## Difference Between Flow Regimes

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<thead>
<tr>
<th>Properties</th>
<th>Bubbling</th>
<th>Turbulent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bubbles</td>
<td>Regular Shaped, Stable</td>
<td>Elongated, Irregular, Unstable</td>
</tr>
<tr>
<td>Mass Transfer</td>
<td>High</td>
<td>Higher</td>
</tr>
<tr>
<td>Heat Transfer</td>
<td>Good</td>
<td>Best</td>
</tr>
<tr>
<td>Bed Profile</td>
<td>Relatively Uniform</td>
<td>Core-Annulus</td>
</tr>
<tr>
<td>Reactor Height</td>
<td>Short</td>
<td>Tall</td>
</tr>
</tbody>
</table>
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- Particle behavior and flow regimes
  - Bed behavior
    - Slugging
    - Bed expansion
    - Jetsam/flotsam?
      - Biomass feeds
      - Agglomerates
    - Gas bypassing
  - Entrainment
  - Bubble
  - Multiphase jet
  - Gas jets
Slugging

- Larger particles produce larger bubbles
- Larger bubbles rise faster than smaller bubbles
- Bubbles larger than 2/3 the diameter of the bed can cause the bed to slug
- Issue with slugging
  - Unstable fluidization operation
  - May flood cyclones
  - Lower mass transfer
  - Residence time of gas in bubble
  - Surface to volume of exposure to emulsion

\[ U_0 = 1 \text{ ft/sec} \]
Bed Expansion

Group A - Low Pressure
Group A - High Pressure
Group B - Low Pressure
Group B - High Pressure

Stagnant Bed
Fluidized Bed
Jetsam & Flotsam - A Biomass Problem

- Coal injection into a 25-foot (7.6-m) diameter fluidized bed of coal
- Neutrally buoyant particles
Jetsam & Flotsam - A Biomass Problem

- Little penetration in the bed
- Particle buoyancy seems to be important
Agglomerates

- Low quality coal
- Silica sand (bed and feed)
Gas Bypassing and Bed Heights

- Gas bypassing is a function of bed height or dense particles
- Gas compression is the real issue
- What may be good in your pilot plant may not be sufficient in your commercial unit
- May be due to compression of the emulsion phase and bed permeability
- Mostly a Geldart Group A issue at low pressures

$U_g = 0.46 \text{ m/sec with FCC powder (3\% fin}$
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Ug = 0.46 m/sec with FCC powder (3% fines)
Pressure Fluctuations as an Indicator of Gas Bypassing

- Pressure fluctuations increased when jet streaming was present
- But this was mostly a local detection
Precession of Gas Bypassing as Detected from Pressure Fluctuations

- Pressure taps need to be near jet stream
- Jet stream is not stationary
- It seems to precess around the vessel
- As evidenced in signal fluctuations
Applying the Fundamentals

Managing Gas Bypassing

• Jet streaming is a function of gas permeability and bed weight
• Most with Geldart Group A powders
• Jet streaming can be managed
  • Limiting the bed height
  • Not always possible
  • Adding particle fines
  • Increasing the pressure
  • More gas can get into the emulsion
  • Adding baffles
Effects of Imposed Solids Flux

Solids Volume Fraction

- 3% Fines, No Flux
- 9% Fines, No Flux
- 3% Fines with Flux
- 9% Fines with Flux

Barracuda®

High Loadings

Low Loadings

2 ft/sec (0.6 m/sec) Superficial Gas Velocity
Modeling Gas Bypassing

- Barracuda® was able to simulate the role of fines and jet streaming
- In low fines case, regions of dense emulsions, 55% loading, were observed
- In high fines case, maximum bed density did not exceed 40% loading.
Validation with Pressure Fluctuations

- Barracuda™ was able to capture the trends but over predicted pressure fluctuations for the imposed solids flux cases.

![Graph showing pressure fluctuations vs. superficial gas velocity](image-url)

- Denotes data
- ° Denotes simulation results

Case 1: 3% Fines, No Flux
Case 2: 9% Fines, No Flux
Case 3: 3% Fines with Solids Flux
Case 4: 9% Fines with Solids Flux

Superficial Gas Velocity, ft/sec
Pressure Fluctuations, in H2O
Validation with Pressure Fluctuations

- Barracuda™ was able to capture the trends but overpredicted pressure fluctuations for the imposed solids flux cases.
Mixing and Gas Bypassing

Exterior View - Wall

Sliced View

Solids Feed in Red
Initial Bed in Green
Gas in Blue

3% Fines with Imposed Flux
9% Fines with Imposed Flux

3% Fines with Imposed Flux
9% Fines with Imposed Flux

Barracuda™

Cells Species

Cutplane Species

PSRI
Gas Bypassing at the Interface

3% Fines with Imposed Flux

9% Fines with Imposed Flux

Species legend
• Species 0 - Gas
• Species 1 - Bed
• Species 2 - Dipleg

Gas bypassing with low fines level appears to reside at the interface of bed particles and dipleg particles.
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Entrainment

Transport Disengagement Height

Freeboard

Fluidized Bed

Cyclone

Plenum

Grid

(1-ε)

TDH

Height
Bubble Burst with FCC Powder
6,600 frames per second
with University of Chicago
Calculated Entrainment Rates in a Fluidized Bed

- Why do we see such a wide range of entrainment rates for small particles?
- Are some smaller particles behaving differently than others?

Entrainment rate calculations based on FCC catalyst powder with 9% fines in a 3-meters ID x 12-meters tall fluidized bed with a bed height of 6 meters and superficial gas velocity of 1 m/sec at room temperature.


Batch Fluidization Test

- Replicated what was experienced in a commercial fluidized bed reactor
- The increase in entrainment rate corresponded to a decrease in the fines level in the bed and with the entrained solids
Particle Clusters in the Freeboard

Bayway FCC fines with $d_{50}$ of 27 microns in 6-in (15-cm) ID fluidized bed with superficial gas velocity of 2 ft/sec (0.6 m/sec)

Phantom V7.1 @ 6,500 fps (University of Chicago)
Hypothesis: Particle Clusters

- Wilhelm and Kwauk postulated that particle clusters exist in 1948.
- Kaye and Boardman suggested that particle clusters are possible when solids concentrations exceeded 0.05%.
- Yerushalmi et al. proposed that particle clustering explained the larger than expected slip velocity measured in a fast-fluidized bed.
- Geldart and Wong noted similar observations and conclusions.
- Baeyens et al. proposed that there is a critical particle size where clustering can occur.
- Karri et al. noted similar findings.

Wilhelm, R.H., Kwauk, M., Chemical Engineering Progress 44 (1948) 201.
Looking Beyond the Walls

- Olympus R100-038-000-50 Industrial Rigid Borescope
  - 38 cm effective length
  - 50° field of view
  - 5 to ∞ mm depth of field
  - 6 mm Optical Glass Spacer
  - With stainless steel Guard Collar (not shown)
  - Liquid Filled Light Guide
  - External lighting
  - High speed camera ready

6 mm Optical Glass Spacer (Guard Collar Removed)
Polyethylene Clusters in Freeboard

- Clusters can be traced and sized
- Average cluster size was 23 particles

Polyethylene with \( d_{p50} \) of 70 microns in 6-in (15-cm) ID fluidized bed with superficial gas velocity of 1 ft/sec (0.3 m/sec)

Phantom V7.1 @ 4000 fps, 20 \( \mu \)s exposure (NETL)
FCC Catalyst Clusters in Freeboard

- 30% of the material in the freeboard was observed as clusters
- Average cluster size was 11 particles

FCC powder with $d_{50}$ of 72 microns in 6-in (15-cm) ID fluidized bed with superficial gas velocity of 1 ft/sec (0.3 m/sec)

Phantom V7.1 @ 4000 fps, 20 µs exposure (NETL)
FCC Catalyst Clusters in the Fluidized Bed

- Cluster observed near bubble region
- Can not distinguish if clusters are in the emulsion phase or not

FCC powder with $d_{p50}$ of 72 microns in 6-in (15-cm) ID fluidized bed with superficial gas velocity of 1 ft/sec (0.3 m/sec)

Phantom V7.1 @ 4000 fps, 20 μs exposure (NETL)
Effects of Baffles

- In a bed of FCC powder, the addition of baffles resulted in an increase in the entrainment rate at the higher velocities.
- This was not observed for Geldart Group B particles.
- Not a bed diameter effect.
Effects of Baffles

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- This was not observed for Geldart Group B particles.
- Not a bed diameter effect.
**Effects of Bed Height**

- Fines recycled back into the bed
- At 4500 seconds, the bed height was decreased by 25%
- Entrainment rate increase corresponded with drop in bed height
Applying the Fundamentals

- Same material in the same unit
- Entrainment rate was measured at various bed heights
- Entrainment rate is inversely proportional to bed height

**Effects of Bed Height**

- **FCC Cyclone Fines** ($d_{p50}=27 \, \mu m$)
- Superficial Gas Velocity = 0.56 m/sec

![Graph showing entrainment rate vs. fluidized bed height](image)
Particle Cluster Formation and Stability in Fluidized Beds

- Particle clusters may form near the bottom of the bed and continue to grow as they migrate to the top of the bed, possibly with the help of bubbles.
- At the top of the bed, clusters are either entrained or circulate back down to the bottom of the bed.
- Several cycles of the circulation may be needed to build large clusters.
- As bed height is increased, the large circulation zone becomes more dominant and the possible residence time of a particle cluster in the bed becomes extended.
- Baffles can inhibit cluster formation as these clusters appear to be weakly bound together.
Implications

- Prediction of entrainment rate
  - Over prediction of entrainment rate can lead to over design of cyclone diplegs
  - Sizing a primary cyclone too large would result in too low of a flux in the dipleg
  - For some systems, many of the available entrainment rate correlations are not even close
  - There may be merit to a critical particle size for cluster formation
- Adding fines to your fluidized bed could actually lower your entrainment rate, significantly
  - Validated on a commercial unit
  - CFD and other “fundamental” models can’t predict this, yet.
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- Summary
• Bubbles in Group A particles are small and reach an equilibrium bubble size quickly
• Bubbles in Group B particles continue to grow and can get very large
  • Poor heat and mass transfer
  • Mechanical stresses
Bubbles with Group A and B Particles

- 1.2 ft/sec superficial gas velocity in 36” diameter bed
- Good fluidization for Geldart Group A particles
- Poor fluidization for Geldart Group B particles
- Bubbles exceeded 2/3 the diameter of the bed
- Note bed expansion for Group A particles
Should They Be Called Bubbles
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Jet Penetration at High Pressures

- Three materials
  - Siderite
  - Coal char
  - Ottawa sand
- Jet velocity = 7.6 m/sec for all cases
- Superficial gas velocity = complete fluidization velocity
  - This changes with pressure

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<td>FMC Char</td>
<td>2629</td>
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<tr>
<td>Ottawa Sand</td>
<td>1158</td>
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<tr>
<td>Siderite</td>
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Simulations: Particle Density Effects

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![Simulations: Particle Density Effects](image_url)
Simulations: Pressure Effects With Sand

424.7 KPa

1111.8 KPa

3509.2 KPa

5296.7 KPa

Higher Pressures
Jet Penetration Correlations

- Both Barracuda™ and PSRI correlations do well for all three materials at all pressures.
- Merry and Shakhova did not fare well.

Merry, J.M.D., AIChE J., 21 (1975) 507
FCC/Fines Penetration in Jets

- FCC into Air
- FCC into FCC
- FCC into 6mm spheres
Simulating Where The Particles Go

- Four nozzles start at 30 seconds
Biomass Injection

- Penetration does not go far from the wall
Biomass Jet Penetration

- Biomass never really gets past the wall and buoyancy keeps it there
Particle Laden Jets via PSRI

Jet Penetration Correlation

- Particle momentum form a jet significantly increase the jet penetration length

Air and Air-Sand Particles into a Fluidized Bed of Sand at 103 KPa and 800°C
Jet Penetration Length

![Graph showing the jet penetration length for different media types.]

- Gas-Coal Jet into Coal
- Gas-Biomass Jet into Sand
- Gas Jet into Coal
- Gas Jet into Sand

Jet Penetration Number, \( P/do \)
Jet Velocity, \( \text{ft/sec} \)

0 20 40 60 80
0 5 10 15 20
Liquid Injection into a Fluidized Bed
Liquid Injection into a Fluidized Bed

- Phantom VII Color High-Speed Video Camera
- 9900 fps at 20 microsecond shutter speed
- Red dye in liquid to enhance contrast
Liquid Injection into a Fluidized Bed

- Phantom VII Color High-Speed Video Camera
- 9900 fps at 20 microsecond shutter speed
- With liquid dye for contrast

8-inches (20 cm) from injector face

2-inches (5 cm) from injector face
Jet - Fluidized Bed Boundary Layer

- Little liquid jet penetration after initial wetting of particles
- Little particle exchange between wetted particles and dry particles beyond boundary
- Boundary layer estimated at 0.18 ± 0.04 cm
Jet - Fluidized Bed Boundary Layer

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- Little particle exchange between wetted particles and dry particles beyond boundary
- Boundary layer estimated at $0.18 \pm 0.04$ cm
Liquid-Particle Interactions in a Fluidized Bed

- 1000 fps at 990 microseconds shutter speed
- 5-inches (12.7-cm) from nozzle face
- 1.5-inches (3.8-cm) from face plate (wall)
- Estimated to be within the of jet
- 20 SCFH (0.6 SCMH) sweeping gas
- Liquid injection contains dye
- Small particles coating liquid droplets
Liquid-Particle Interactions in a Fluidized Bed

- 1000 fps at 990 microsecond shutter speed
- 9-inches (23-cm) from nozzle face
- 1.0-inches (2.5-cm) from face plate (wall)
  - Estimated to be at the boundary of the jet
- 5 SCFH (0.15 SCMH) sweeping gas
- Liquid injection contains dye
- Bigger particles coating droplets
Summary

- Particle properties under reaction conditions (including particle size) are a key design parameters
- Geldart Group A powders have small bubbles even in large units
  - Smoother fluidization
  - Significant bed expansion especially at higher pressures
  - Good heat and mass transfer
  - Gas bypassing could be an issue
  - Particle clustering could be an issue
- Geldart Group B powders have large bubbles in commercial units
  - Poorer heat and mass transfer
  - Unstable bed operations in some cases
  - Slugging could be an issue, even in commercial units
- Jet penetration is mostly driven by buoyancy!