ROTATING FLUIDIZED BEDS

Juray De Wilde

Université catholique de Louvain
Materials and Process Engineering, iMMC - IMAP
Place Sainte Barbe 2, 1348 Louvain-la-Neuve, Belgium

juray.dewilde@uclouvain.be

Process Intensification, MSc course 2012-2013, TUDelft
• **Introduction**
  - Process Intensification
  - Rotating fluidized beds

• **Hydrodynamic characteristics of RFB-SGs**
  - Experimental study
  - Theoretical and design considerations

• **Potential & applications of RFB-SGs**
  - Theoretical and CFD study on interfacial mass and heat transfer
  - Experimental study of biomass drying and particle coating/granulation
  - Numerical study of biomass pyrolysis and Fluid Catalytic Cracking
  - Multi-zone operation

• **Conclusions and perspectives**
INTRODUCTION: Process Intensification

Remove limitations of chemical reactors introduced by:

- Intrinsic reaction rates (e.g. using more active catalyst)
- Transport phenomena:
  - Inter-phase mass- and heat transfer
  - Inter-phase momentum transfer
  - Intra-particle mass transfer

Methods for Process Intensification:
1. Structuring from the macro- to the micro-scale
2. High-G
3. Multifunctionality
4. Hybrid methods
5. Alternative forms and sources of energy
6. Novel methods of process / plant development and operation

(Stankiewicz and Moulijn, 2004)
INTRODUCTION: Rotating Fluidized Beds

Example: Riser reactor (FCC):
- dilute riser
- limited slip velocity
- stand pipe height

Role of earth gravity!
High-G operation!

Conventional fluidized bed
Magnetic field
Rotating fluidized bed
INTRODUCTION: Rotating Fluidized Beds

Fluidization chamber

Static (vortex chamber)

Rotating

Chimney

Gas

Static

Rotating

Chimney

Gas

Gas
INTRODUCTION: Rotating Fluidized Beds

The Rotating Fluidized Bed in a Static Geometry (RFB-SG)

(De Wilde & de Broqueville, AIChE J., 2007)
• **Introduction**  
  • Process Intensification  
  • Rotating fluidized beds

• **Hydrodynamic characteristics of RFB-SGs**  
  • Experimental study  
  • Theoretical and design considerations  

• **Potential & applications**  
  • Theoretical and CFD study on interfacial mass and heat transfer  
  • Experimental study of biomass drying and particle coating/granulation  
  • Numerical study of biomass pyrolysis and Fluid Catalytic Cracking  
  • Multi-zone operation

• **Conclusions and perspectives**

**OUTLINE**

**Aspects:**  
• Bed stability and large-scale uniformity  
• Operating conditions: gas and solids flow rates  
• Flow pattern: gas and particles  
• Attrition  
• Influence of the type of particles  
  • Forces, bed expansion & solids losses, bubbling
HYDRODYNAMIC CHARACTERISTICS OF RFB-SGs: Experimental study

**Design:**
- Fluidization chamber
- Chimney

**Operating conditions:**
- Fluid. gas flow rate
- Solids loading
- Solids feeding rate
- Particle type

**Polymer particles:** 1G Geldart D  
Cylinders: 2 mm (l), 5 mm (d)  
Density: 950 kg/m³

**Biomass granules:** 1G Geldart D  
Average size: 4 mm  
Density: 600 kg/m³

**Alumina / salt particles:** 1G Geldart B  
Average size: 350 µm  
Density: 2100 kg/m³

**FCC catalyst powder:** 1G Geldart A  
Average size: 60 µm  
Density: 1500 kg/m³

**Organic powder:** 1G Geldart C  
Average size: 70 µm  
Density: 260 kg/m³
HYDRODYNAMIC CHARACTERISTICS OF RFB-SGs: Experimental study

BED STABILITY AND LARGE-SCALE UNIFORMITY

- Process gas bypassing the particles ⇒ Poor gas-solid contact!
- 1G Geldart D-type particles
- 24-cm diameter fluid. chamb.

Stable bed

Slugging

Graph showing solids loading [kg] vs. gas flow rate [Nm³/h]

channeling

slugging

low gas flow rate

high gas flow rate

(De Wilde & de Broqueville, 2008)
HYDRODYNAMIC CHARACTERISTICS OF RFB-SGs: Experimental study

OPERATING CONDITIONS: GAS AND SOLIDS FLOW RATES

- 1G-GELDART D-TYPE PARTICLES
- 24-cm DIAMETER FLUID. CHAMBER

LIMITED RADIAL BED EXPANSION, EVEN RADIAL BED CONTRACTION

Average radial gas-solids drag force

Average centrifugal force

FLEXIBILITY IN THE PROCESS GAS FLOW RATE!
HYDRO_DYNAMIC CHARACTERISTICS OF RFB-SGs: Experimental study

OPERATING CONDITIONS: GAS AND SOLIDS FLOW RATES

(Left) Figure 3.3.1. Bed porosity in the vortex chamber as a function of the gas inlet velocity / gas flow rate for different solids loadings and for given vortex chamber design and particles (grain drying). (From Volchkov et al., 2003;)

(Not high-G) => Effect of earth gravity

(Right) Figure 4.2.1. A rotating particle bed in a vortex chamber with a single gas inlet slot, tangentially injecting the gas-solid mixture. Vortex chamber: D = 24 cm, L = 3.5 cm, n·s = 1.5 cm, λ = 0.02. (From Kochetov et al., 1969b.) Solids retention capacity (zero solids feeding rate) as a function of the air flow rate for different gas inlet configurations. 1. Five gas inlet slots in the lower part of the chamber; 2. One single gas inlet slot; 3. Six uniformly distributed gas inlet slots. Vortex chamber as in (a)-(b), but n·s = 2 cm, λ = 0.027. (From Kochetov et al., 1969a.)
Figure 4.2.2. Fluidization of different types of particles in a vortex chamber of given design. 
(a) Solids retention capacity (zero solids feeding rate) as a function of the air flow rate. Polystyrene particles: ◦ $d_p = 0.25-0.5$ mm; △ $d_p = 0.5-1.0$ mm; ▲ $d_p = 1.2-1.5$ mm; ● $d_p = 1.5-2.0$ mm. Vortex chamber: $D = 24$ cm, $L = 3.5$ cm, $n = 15$ cm, $\lambda = 0.02$. (From Kochetov et al., 1969b.) (b)-(d) Fluidization at given gas (700 Nm$^3$/h) and solids (8.35 g/s) feeding rates. Vortex chamber: $D = 24$ cm, $L = 5$ cm, $n = 24$, $s = 3$ mm, $\lambda = 0.096$. (From Trujillo and De Wilde, 2012b.)
HYDRODYNAMIC CHARACTERISTICS OF RFB-SGs: Experimental study

FLOW PATTERN: GAS AND PARTICLES

PARTICLE BED MIXING

Concentration colored particles [wt%]

solids inlet (imposed step)

local response *

chimney outlet response

Time [s]

* local fluidization chamber response measured at the end plate opposite the solids inlet by rapid camera

ˇ chimney outlet response measured between the chimney and the cyclone by sampling
HYDRODYNAMIC CHARACTERISTICS OF RFB-SGs: Experimental study

FLOW PATTERN: GAS AND PARTICLES

CSTR AT SUFFICIENTLY HIGH PARTICLE BED ROTATIONAL SPEEDS

1G Geldart D-type particles, 24-cm diameter fluidization chamber

PARTICLE BED MIXING

G = 650 Nm³/h
G = 800 Nm³/h
CSTR
HYDRODYNAMIC CHARACTERISTICS OF RFB-SGs: Experimental study

FLOW PATTERN: GAS AND PARTICLES

GAS PHASE
FLOW PATTERN

FLOW PATTERN: GAS AND PARTICLES

SMOKE VISUALIZATION TECHNIQUE
HYDRODYNAMIC CHARACTERISTICS OF RFB-SGs: Experimental study

FLOW PATTERN: GAS AND PARTICLES

Smoke injection (gas inlet \(i\))

Smoke leaving particle bed

GAS PHASE FLOW PATTERN

- GASES INJECTED VIA SUCCESSIVE GAS INLETS HARDLY MIXED
- PLUG FLOW TYPE PATTERN FOR THE FLUIDIZATION GAS
- RTD GAS DETERMINED BY THE RADIAL VELOCITY COMPONENT
FLOW PATTERN: GAS AND PARTICLES

- GASES INJECTED VIA SUCCESSIVE GAS INLETS HARDLY MIXED
- PLUG FLOW TYPE PATTERN FOR THE FLUIDIZATION GAS
- RTD GAS DETERMINED BY THE RADIAL VELOCITY COMPONENT
HYDRODYNAMIC CHARACTERISTICS OF RFB-SGs: Experimental study

FLOW PATTERN: INFLUENCE OF THE TYPE OF PARTICLES

24-cm diameter fluidization chamber

1G Geldart D-type particles
- Tangentially, but not radially fluidized particle bed

1G Geldart B-type particles
- Tangentially & radially fluidized particle bed

Baseline: 0.5 kg solids loading

Fluidization gas flow rate [Nm3/h]

Particle bed pressure drop relative to the baseline [Pa]

Solids loading [kg]
- - Baseline: 0.5 kg solids loading
- ■ 1.8
- ▲ 1.5
- × 1.0

Solids loading [kg]
- - Baseline: 0.5 kg solids loading
- ■ 3.0
- ▲ 2.5
- × 2.0
- × 1.5

HYDRODYNAMIC CHARACTERISTICS OF RFB-SGs: Experimental study

FLOW PATTERN: INFLUENCE OF THE TYPE OF PARTICLES

24-cm diameter fluidization chamber

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- Tangentially, but not radially fluidized particle bed

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- Tangentially & radially fluidized particle bed

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Solids loading [kg]
- - Baseline: 0.5 kg solids loading
- ■ 3.0
- ▲ 2.5
- × 2.0
- × 1.5
COMPARE TO PRESSURE DROP OVER THE PARTICLE BED AS A FUNCTION OF THE SUPERFICIAL AIR VELOCITY IN A CONVENTIONAL FLUIDIZED BED

(Froment, Bischoff and De Wilde, 2010)
HYDRODYNAMIC CHARACTERISTICS OF RFB-SGs: Experimental study

FLOW PATTERN: INFLUENCE OF THE SOLIDS LOADING

Figure 3.2.1. (a) Normalized circulation ($\Gamma = v_r R$) as a function of the normalized radial position in the vortex chamber (subscript 0 indicates at the chamber outer wall) in the absence and presence of particles. Vortex chamber: $D = 36$ cm, $L = 6$ cm, $D_c = 8$ cm, $n > 20$, $\lambda = 0.099$. Operating conditions: solids loading: 1 kg of sand particles ($\rho_s = 1900$ kg/m$^3$, $d_p = 2$ mm). (Adapted from Volchkov et al., 1993.) (b) Rotational speed as a function of the solids loading for different radial positions in the vortex chamber. Vortex chamber: $D = 30.5$ cm, $L = 6.3$ cm, $D_c = 15 \rightarrow 8$ cm (convergent), $n = 12$, $s = 0.3$ mm, $\lambda = 0.00376$. Operating conditions: talc particles ($\rho_s = 2700$ kg/m$^3$, $d_p = 20$ $\mu$m). (From Anderson et al., 1972.)
**Figure 3.6.3.** Fluidization of fine talc powder \( (d_p = 20 \, \mu m, \rho_s = 2700 \, kg/m^3) \) in a vortex chamber. Vortex chamber: \( D = 30.5 \, cm, L = 6.3 \, cm, n \cdot s = 0.36 \, cm, \lambda = 0.00376 \). Operating conditions: total gas flow rate: 0.117 \( Nm^3/s \), solids loading: 0.05 - 0.8 kg. (a) Picture of the rotating particle bed; (b) Radial profiles of the axially averaged particle bed density at different solids loadings measured by x-ray absorption (100 kv, 15ma, typical exposure time: 1s); (c) Typical particle bed density contours deduced from x-ray absorption measurements for a solids loading of 0.4 kg. (From Anderson et al., 1972.)
HIGH SPEED CCD CAMERA TECHNIQUE:

- 1000 frames / second (up to 10000 possible)
- focus on gas inlet slot zone

FLOW PATTERN: INFLUENCE OF THE TYPE OF PARTICLES

HYDRODYNAMIC CHARACTERISTICS OF RFB-SGs: Experimental study

BUBBLING:

- MOTION
- INFLUENCE OF THE SOLIDS LOADING

0.8 kg solids, 4.5 rps

1G Geldart B-type particles, 36-cm diameter fluidization chamber
HYDRODYNAMIC CHARACTERISTICS OF RFB-SGs: Experimental study

FLOW PATTERN: INFLUENCE OF THE TYPE OF PARTICLES

HIGH SPEED CCD CAMERA TECHNIQUE:
- 1000 frames / second (up to 10000 possible)
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BUBBLING:
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HYDRODYNAMIC CHARACTERISTICS OF RFB-SGs: Experimental study

FLOW PATTERN: INFLUENCE OF THE TYPE OF PARTICLES

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HYDRODYNAMIC CHARACTERISTICS OF RFB-SGs: Experimental study

FLOW PATTERN: INFLUENCE OF THE TYPE OF PARTICLES

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BUBBLING:
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- INFLUENCE OF THE SOLIDS LOADING

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HYDRODYNAMIC CHARACTERISTICS OF RFB-SGs: Experimental study

FLOW PATTERN: INFLUENCE OF THE TYPE OF PARTICLES

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BUBBLING:
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1G Geldart B-type particles, 36-cm diameter fluidization chamber
HYDRODYNAMIC CHARACTERISTICS OF RFB-SGs: Experimental study

FLOW PATTERN: INFLUENCE OF THE TYPE OF PARTICLES

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- 1000 frames / second (up to 10000 possible)
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BUBBLING:
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- INFLUENCE OF THE SOLIDS LOADING

0.8 kg solids, 4.5 rps

1G Geldart B-type particles, 36-cm diameter fluidization chamber
HYDRODYNAMIC CHARACTERISTICS OF RFB-SGs: Experimental study

FLOW PATTERN: INFLUENCE OF THE TYPE OF PARTICLES

HIGH SPEED CCD CAMERA TECHNIQUE:
• 1000 frames / second (up to 10000 possible)
• focus on gas inlet slot zone

BUBBLING:
• MOTION
• INFLUENCE OF THE SOLIDS LOADING

1.1 kg solids, 3.5 rps

1G Geldart B-type particles, 36-cm diameter fluidization chamber
FLOW PATTERN: INFLUENCE OF THE TYPE OF PARTICLES

HIGH SPEED CCD CAMERA TECHNIQUE:
- 1000 frames / second (up to 10000 possible)
- focus on gas inlet slot zone

BUBBLING:
- MOTION
- INFLUENCE OF THE SOLIDS LOADING

1.1 kg solids, 3.5 rps

1G Geldart B-type particles, 36-cm diameter fluidization chamber
HYDRODYNAMIC CHARACTERISTICS OF RFB-SGs: Experimental study

FLOW PATTERN: INFLUENCE OF THE TYPE OF PARTICLES

HIGH SPEED CCD CAMERA TECHNIQUE:
- 1000 frames / second (up to 10000 possible)
- focus on gas inlet slot zone

BUBBLING:
- MOTION
- INFLUENCE OF THE SOLIDS LOADING

1.1 kg solids, 3.5 rps

1G Geldart B-type particles, 36-cm diameter fluidization chamber

\[ t = 16 \cdot 10^{-3} \text{ s} \]
**Main hydrodynamic characteristics of RFB-SGs:** (based on data with 1G-Geldart B and D type solids in identical reactor)

- Tangential fluidization particle bed, *also radial with smaller particles*
- Stable & large-scale-uniform bed at sufficiently high solids loadings
- Unique flexibility with respect to the process gas flow rate
- Pressure drop over the gas inlet slots important
- Particle bed well-mixed $\iff$ Gas behavior close to plug flow
- *Bubbling with smaller particles*, suppressed at high solids loadings

**Advantages of high-G operation confirmed:**
- Dense, more uniform particle bed at high slip velocities $\implies$ Intensified interfacial mass, heat & momentum transfer
- *Fluidization of smaller particles / fine powders ???*
- High particle bed width-to-height ratio
- Static geometry – facilitates continuous operation

$\Rightarrow$ Optimization reactor design, i.e. interfacial momentum transfer !
• Introduction
  • Process Intensification
  • Rotating fluidized beds

• Hydrodynamic characteristics of RFB-SGs
  • Experimental study
  • Theoretical and design considerations

• Potential & applications
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  • Experimental study of biomass drying and particle coating/granulation
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HYDRO_DYNAMIC CHARACTERISTICS OF RFB-SGs: Experimental study

FLOW PATTERN: INFLUENCE OF THE TYPE OF PARTICLES

Identical reactor design & gas and solids feeding rates

1mm HDPE pellets (1G Geldart D)
300µm salt particles (1G Geldart B)
85µm FCC catalyst (1G Geldart A)

Particle bed:
• Stability
• Density
• Uniformity
  • Tangential
  • Axial
• Gas-solids separation

Criteria:
• $F(\text{centrifugal}) \geq F(\text{drag, radial})$
• $\Delta P(\text{gas inlet slots}) > \Delta P(\text{bed})$

Reactor design:
• Number of gas inlet slots
• Size gas inlet slots
HYDRODYNAMIC CHARACTERISTICS OF RFB-SGs: Theor. considerations

FLOW PATTERN: INFLUENCE OF THE TYPE OF PARTICLES
INTERFACIAL MOMENTUM TRANSFER

(1) Maximize tangential momentum injected for a given gas flow rate:

- Flow rate injected \( \sim \rho_g u_{inj} \)
- Momentum injected \( \sim \rho_g u^2_{inj} \)

\( \Rightarrow \) Decrease gas inlet surface area
  - Number of slots \( \downarrow \)
  - Slot width \( \downarrow \)

(2) Optimize particle bed uniformity for a given gas flow rate:

- Tangential \( \rightarrow \) Number of slots \( \uparrow \)
- Axial \( \rightarrow \) Increase pressure drop over the slots

\( \Rightarrow \) Decrease gas inlet surface area
  - Number of slots \( \downarrow \)
  - Slot width \( \downarrow \)
HYDRODYNAMIC CHARACTERISTICS OF RFB-SGs: Theor. considerations

FLOW PATTERN: INFLUENCE OF THE TYPE OF PARTICLES

INTERFACIAL MOMENTUM TRANSFER

Theoretical case study:
- 24 cm diameter reactor
- 72 slots
- $\rho_g$: 1 kg/m$^3$
- $\rho_s$: 1500 kg/m$^3$

Model assumptions:
- $v_t = \eta \cdot u_{inj}$
- $\eta = f(\text{reactor design})$
- uniform, dense turbulent bed

- Radial drag force $\sim \rho_g(d_p)^2(u_r)^2$
- Centr. Force $\sim \eta^2(u_{inj})^2 \rho_s(d_p)^3/D$

![Graphs showing forces vs. particle diameter and slot size]
HYDRODYNAMIC CHARACTERISTICS OF RFB-SGs: Experimental study

DESIGN CONSIDERATIONS

- Reactor diameter = 24 cm
- 70 µm FCC catalyst (1G Geldart A)
- $F_g = 700 \text{ Nm}^3/\text{h}$
- $F_s = 8.35 \text{ g/s}$

Different reactor designs, given gas and solids feeding rates

- 24 slots
  - slot width = 3 mm
  - $u_{inj} = 54 \text{ m/s}$

- 72 slots
  - slot width = 0.5 mm
  - $u_{inj} = 108 \text{ m/s}$

- 36 slots
  - slot width = 0.5 mm
  - $u_{inj} = 216 \text{ m/s}$

$u_{inj} \uparrow \Rightarrow \text{Solids retention} \uparrow$
HYDRODYNAMIC CHARACTERISTICS OF RFB-SGs: Experimental study

**DESIGN CONSIDERATIONS**

- Reactor diameter = 24 cm
- 70 µm FCC catalyst (1G Geldart A type)
- 36 or 72, 0.5 mm gas inlet slots
- $F_g = 600 \text{Nm}^3/\text{h}$

**INTERFACIAL MOMENTUM TRANSFER DESIGN CONSIDERATIONS**

- Solids retention
- Improved bed uniformity (tangential & axial !)

$u_{\text{inj}} \uparrow$ => - Solids retention $\uparrow$

$\Delta P_{\text{inj}} \uparrow$ => - Improved bed uniformity (tangential & axial !)

$F_s = 13.5 \text{ g/s}$

**72 gas inlet slots, $u_{\text{inj}} = 93 \text{ m/s}$**

Rapid camera: 1 kHz

**36 gas inlet slots, $u_{\text{inj}} = 185 \text{ m/s}$**

Denser + Improved **axial** bed uniformity
Figure 3.6.4. Illustration of boundary layer flow. Experimentally measured axial profiles of the radial gas velocity. 1. In the absence of particles; 2. In the presence of particles. Vortex chamber: D = 20 cm, L = 2.6 cm, D_c = 10 cm, n > 20, λ = 0.0518. Operating conditions: solids loading: 0.15 kg of wheat grain particles (ρ_s = 1200 kg/m^3, d_p = 2-5 mm). [Adapted from Volchkov et al., 1993.]
Behavior at higher solids feeding rates / solids loadings:

\[ F_s = 8.35 \text{ g/s} \]

36 gas inlet slots, \( u_{inj} = 185 \text{ m/s} \)

\[ F_s = 20.08 \text{ g/s} \]
HYDRODYNAMIC CHARACTERISTICS OF RFB-SGs: Design considerations

Other aspects: • Chimney design
• Solids feeding and removal design

CFD study:
• 24 cm diameter reactor
• chimney diameter: 3, 6, 12 cm
• \( \rho_g \): 1 kg/m\(^3\), \( \rho_s \) = 1500 kg/m\(^3\)
• \( d_p \) = 60 \( \mu m \)
• \( \Xi \) solids loading & gas flow rate

• Free vortex type flow pattern destroyed in the presence of solids
• Free vortex type flow pattern in the particle bed freeboard region with sufficiently small chimney

=> Beneficial for gas-solids separation (Coriolis effect)

(Kuzmin et al., 2005)
HYDRODYNAMIC CHARACTERISTICS OF RFB-SGs: Design considerations

Other aspects: • Chimney design
• Solids feeding and removal design

Dual-chimney design with cyclone flow exit tube with a guide slot. Gas-liquid flow with specific liquid outlet design. (From Loftus et al., 1992.)

Profiled end wall and concentric ring. (From Kuzmin et al., 2005.)
HYDRODYNAMIC CHARACTERISTICS OF RFB-SGs: Design considerations

Other aspects:

- Chimney design
- Solids feeding and removal design

Figure 4.3.4. Vortex chamber with secondary gas injection via additional nozzles positioned concentric to the central gas outlet at the end of a tapered annex. (a) Schematic representation; (b) Rate coefficient for particle losses via the gas outlet (chimney) as a function of the normalized secondary gas flow rate for different total gas flow rates. \( \dot{m}_{EW} \): secondary (End Wall) gas flow rate; \( \dot{m} \): total gas flow rate. (Adapted from Anderson et al., 1972.)
HYDRODYNAMIC CHARACTERISTICS OF RFB-SGs: Design considerations

Other aspects:
- Chimney design
- Solids feeding and removal design

Figure 4.5.1. (a) Vortex chamber with a cyclone type system for the recovery of the solids. 1. Gas distribution chamber (helix); 2. vortex chamber; 3. end walls; 4. solids feeder; 5. hopper. (From Volchkov et al., 1993.) (b) Different configurations for combining in- and outflow via the slots. (From Goldshtik et al., 1997.)
HYDRODYNAMIC CHARACTERISTICS OF RFB-SGs: Design considerations

Other aspects: • Chimney design
• Solids feeding and removal design
HYDRODYNAMIC CHARACTERISTICS OF RFB-SGs: Design considerations

- Gas inlet design to be adapted to the type of particles to be fluidized
  Smaller / lighter particles
  => - Higher gas inlet velocity
      - Higher pressure drop over the gas inlet slots

- Hydrodynamics in the particle bed freeboard region important
  Smaller / lighter particles
  => - Smaller chimney diameter (free vortex, Coriolis effect)
      - Separate and carefully designed solids outlet
FULL PI POTENTIAL: MULTI-ZONE OPERATION: RFB-SG AND CRFB TECHNOLOGIES

- Integrated reaction and catalyst regeneration zones
- Integrated exothermic and endothermic reaction zones
- Short contact time between particles and a very hot gas

HYDRODYNAMIC CHARACTERISTICS OF RFB-SGs: Design considerations
HYDRODYNAMIC CHARACTERISTICS OF RFB-SGs: Experimental study

ATTRITION

36-cm DIAMETER FLUIDIZATION CHAMBER

• 1G GELDART D PARTICLES
  • 1.8 kg solids
  • 2 h 45 min residence time
  \[\text{losses (fines): 0.3 - 0.5 g}\]

• 1G GELDART B PARTICLES (SALT)
  • 2.5 kg solids
  • 10 min residence time
  \[\text{losses: coating detached}\]
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Opportunities: Process Intensification potential:

• Dense bed at high gas(-solid slip) velocities

• Improved bed uniformity (reduced bubbling, temperature)
  ⇒ Increased gas-solid mass and heat transfer coefficients
  ⇒ Improved gas-solid contact

• Unique flexibility in the fluidization gas flow rate

• High particle bed width-to-height ratio
  ⇒ Short gas phase residence times
  ⇒ Higher reaction temperatures, more active catalysts

• Multi-zone operation
  ⇒ Higher catalyst circulation rates
POTENTIAL APPLICATIONS OF RFB-SGs:

Challenges:
- Small bed height (order of cm)
- High gas velocities (radial)

\[\text{Small gas phase residence time}\]
\[\Rightarrow \text{Conversion limited?}\]

- Gas phase density variations due to reactions
  \[\Rightarrow \text{Effect on stability and density of the bed?}\]

- Process Intensification factor:
  - Intrinsic:
    - Optimization geometry
  - Full potential:
    - Higher reaction temperatures, more active catalysts
    - Multi-zone operation
- Particle bed mixing: for reacting solids
COMPUTATIONAL FLUID DYNAMICS STUDY OF GAS-SOLID HEAT TRANSFER

- RESPONSE OF PARTICLE BED TEMPERATURE TO STEP CHANGE IN THE FLUIDIZATION GAS TEMPERATURE FROM 300 K TO 400 K AT TIME $t_0$
- EULERIAN-EULERIAN APPROACH WITH KINETIC THEORY OF GRANULAR FLOW
- PARTICLES: 700 µm, 2500 kg/m$^3$
- RESTITUTION COEFFICIENT: PARTICLE-PARTICLE: 0.95
- RESTITUTION COEFFICIENT: PARTICLE-WALL: 0.9
- SPECULARITY COEFFICIENT: 0.5
- SOLIDS LOADING: 33.75 kg/m$^3_{\text{length fluid. chamber}}$
- COMPARISON CONVENTIONAL FLUIDIZED BED AND ROTATING FLUIDIZED BED IN A STATIC GEOMETRY

(de Broqueville & De Wilde, 2009)
POTENTIAL APPLICATIONS OF RFB-SGs: CFD study interfacial heat transfer

**FLUIDIZATION GAS FLOW RATE**

- **Conventional Fluidized Bed**
  - Fluidization gas flow rate:
    - 540 m$^3$/h
    - 1080 m$^3$/h

- **Rotating Fluidized Bed in a Static Geometry**
  - Fluidization gas flow rate:
    - Rotating fluidized bed in a static geometry: 29800 m$^3$/h
    - Rotating fluidized bed in a static geometry: 59600 m$^3$/h

**SOLIDS VOLUME FRACTION**

- **Conventional Fluidized Bed**
  - Fluidization gas flow rate:
    - 195 m$^3$/h
    - 540 m$^3$/h
    - 1080 m$^3$/h

**CONVENTIONAL FLUIDIZED BED**

**PARTICLE BED TEMPERATURE RESPONSE**

- **Average particle bed temperature [K]**
  - Time [s]

- **Particle bed temperature [K]**
  - Rotating fluidized bed in a static geometry
  - Fluidization gas flow rate:
    - 59600 m$^3$/h
    - 29800 m$^3$/h

**PARTICLE BED UNIFORMITY**

- Conventional fluidized bed
  - Fluidization gas flow rate:
    - 1080 m$^3$/h
    - 540 m$^3$/h

**ROUNDED OFF TOometry (RFB-SGs)**

- Particles: 700 µm, 2500 kg/m$^3$
- Solids loading: 33.75 kg/m$^3$
**POTENTIAL APPLICATIONS OF RFB-SGs:** Exp. study of biomass drying

**BATCH AND CONTINUOUS OPERATION**

<table>
<thead>
<tr>
<th>Continuous operation</th>
<th>Conventional fluidized bed</th>
<th>Rotating fluidized bed in a static geometry</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Dimensions</strong></td>
<td>$D = 0.10 \text{ m}$</td>
<td>$D = 0.43 \text{ m}$</td>
</tr>
<tr>
<td></td>
<td>$H = 2.00 \text{ m}$</td>
<td>$D(\text{chimney}) = 0.10 \text{ m}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$L = 0.05 \text{ m}$</td>
</tr>
<tr>
<td><strong>Gas distribution</strong></td>
<td>Cone and perforated plate</td>
<td>72, $30^\circ$ inclined gas inlet slots</td>
</tr>
<tr>
<td><strong>Solids feeding</strong></td>
<td>Via side wall at $h = \text{ m}$</td>
<td>Via end plate</td>
</tr>
<tr>
<td><strong>Particle characteristics</strong></td>
<td>Pelletized wood, cylindrically shaped, $d_p = 4 \text{ mm}$, $h_p = 4 \text{ mm}$</td>
<td>(no intra-particle diffusion limitations)</td>
</tr>
<tr>
<td><strong>Operating conditions</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$T \ [\text{K}]$</td>
<td>318</td>
<td></td>
</tr>
<tr>
<td>$P_{\text{out}} \ [\text{Pa}]$</td>
<td>101300</td>
<td></td>
</tr>
<tr>
<td>Gas mass flow rate [$\text{Nm}^3/\text{h}$]</td>
<td>110</td>
<td>700</td>
</tr>
<tr>
<td>Solids mass flow rate [g wet solids / s]</td>
<td>1, 2, 3, 6, 9</td>
<td>3, 6, 9, 12, 15, 18</td>
</tr>
<tr>
<td>Solids inlet humidity [g water / kg dry solids]</td>
<td>850</td>
<td></td>
</tr>
</tbody>
</table>
POTENTIAL APPLICATIONS OF RFB-SGs: Exp. study of biomass drying

CONTINUOUS OPERATION

Process Intensification by a factor > 7:
- Increased bed density
- Improved bed uniformity
- Increased slip velocity and related coefficients of mass & heat transfer

\[
P_{IF} = \frac{Q_{\text{feed}-RFB}}{Q_{\text{feed}-CFB}} \cdot \frac{V_{CFB}}{V_{RFB}} \cdot \frac{\left(H_{\text{feed}} - H_{\text{chim}} \right)_{RFB}}{\left(H_{\text{feed}} - H_{\text{chim}} \right)_{CFB}}
\]

Mean biomass feed humidity

Conventional Fluidized Bed

Intra-particle diffusion limitations

Biomass feed mass flow rate/Volume of reactor [kg\(_{\text{dry biomass}}/m^3\cdot s\)]

(\sim 1/\text{biomass residence time})
POTENTIAL APPLS. OF RFB-SGs: Coating/granulation of cohesive particles

<table>
<thead>
<tr>
<th>Operating variable</th>
<th>Units</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air flow rate</td>
<td>Nm³/h</td>
<td>250</td>
</tr>
<tr>
<td>Pressure before air distributor</td>
<td>mbar</td>
<td>300-370</td>
</tr>
<tr>
<td>Air inlet temperature</td>
<td>°C</td>
<td>55</td>
</tr>
<tr>
<td>Powder feeding rate</td>
<td>g/s</td>
<td>2</td>
</tr>
<tr>
<td>Air atomisation pressure</td>
<td>bar</td>
<td>1.5</td>
</tr>
<tr>
<td>Coating solution feeding rate</td>
<td>g/s</td>
<td>1</td>
</tr>
<tr>
<td>Droplets mean size</td>
<td>µm</td>
<td>70</td>
</tr>
<tr>
<td>Coating solution feeding time</td>
<td>s</td>
<td>5, 15, 30, 60</td>
</tr>
<tr>
<td>Temperature of the water in the double casing of the coating solution</td>
<td>°C</td>
<td>90</td>
</tr>
<tr>
<td>Weight percent of coating material in the coating solution</td>
<td>wt.-%</td>
<td>50</td>
</tr>
</tbody>
</table>

Measurements:
- Operating conditions (P, T, Fg, ...)
- Quantity of coated particles produced
- Agglomeration: Particle size distribution
- Coating quality:
  - Active component release test
  - SEM pictures
POTENTIAL APPLS. OF RFB-SGs: Coating/granulation of cohesive particles

Other operating conditions: atomising air pressure of 1.5 bar, solids feeding rate of 2 g/s

Visual inspection (SEM):
- Limited agglomeration (< 4 particles)
- Low level considering droplet size & relatively low T
POTENTIAL APPLS. OF RFB-SGs: Coating/granulation of cohesive particles

Particles morphology & Coating quality: Active component release test

<table>
<thead>
<tr>
<th>Powder</th>
<th>Core material component</th>
<th>Active component release</th>
<th>Coating (g/g)</th>
<th>Active component release reduction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Original powder</td>
<td>73.7</td>
<td>0.6</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>250 Nm3/h coated powder</td>
<td>46.4</td>
<td>0.24</td>
<td>0.59</td>
<td>60%</td>
</tr>
<tr>
<td>400 Nm3/h coated powder</td>
<td>46.6</td>
<td>0.24</td>
<td>0.58</td>
<td>60%</td>
</tr>
</tbody>
</table>

- 60% reduction release active component
  → few cracks & cavities

- $58 \text{g}_{\text{coating}} / 100 \text{g}_{\text{uncoated}}$
  → on average 1.22 µm coating
  (assuming 70µm spherical uncoated particles)
### Simulation set-up: Model

<table>
<thead>
<tr>
<th>Hydrodynamics:</th>
<th>Reaction kinetics:</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Two-fluid model</td>
<td>• 10-lump model</td>
</tr>
<tr>
<td>• Kinetic Theory of Granular Flow</td>
<td>• C-lump split (LG and coke)</td>
</tr>
<tr>
<td>• k-( \varepsilon ) turbulence model</td>
<td>• Heavy aromatics adsorption</td>
</tr>
<tr>
<td>• Solid walls B.C.:</td>
<td>• Catalyst deactivation (coke)</td>
</tr>
<tr>
<td>• Gas phase: no slip</td>
<td></td>
</tr>
<tr>
<td>• Solid phase: partial slip</td>
<td></td>
</tr>
</tbody>
</table>

**Grid independency:**
- Verify bubble formation
- Grid size < 0.2 mm
- Time step < 1 x 10^{-5} s
• Feasibility and intrinsic process intensification (conventional cracking catalyst & temperature):
  • Conversion with typical RFB-SG reactor dimensions
  • Influence gas phase density variations on hydrodynamics
  • Intrinsic Process Intensification factor (comparison with riser technology)
  • Cat-to-Oil ratio and multi-zone operation

• Full process intensification potential:
  • Higher cracking temperatures
  • More active catalysts
POTENTIAL APPLICATIONS OF RFB-SGs: CFD study of FCC

- Conversion not as high as in a CFB riser (non-optimized geometry) but sufficiently high
- PI factor between 7 and 16, depending on the GO conversion
POTENTIAL APPLICATIONS OF RFB-SGs: CFD study of FCC

**Full PI potential: Higher cracking temperatures**

- **Gasoline mass fraction**
- **LG mass fraction**
- **Gas Oil conversion**
- **Gasoline selectivity**
POTENTIAL APPLICATIONS OF RFB-SGs: CFD study of FCC

**Full PI potential: Higher cracking temperatures**

<table>
<thead>
<tr>
<th>T</th>
<th>$\chi_G$ [%]</th>
<th>$\chi_{GO}$ [%]</th>
<th>$\chi_G/\chi_{GO}$ [%]</th>
<th>$\chi_{LG}$ [%]</th>
<th>$\left&lt; \Re_e \right&gt;$ [kmol/(m$^3$s)]</th>
<th>$\left&lt; \Re^* \right&gt; \times 10^4$ [kg$<em>{coke}$/kg$</em>{cat}$s]</th>
<th>$\tau_{cat}$ [s]</th>
<th>N [-]</th>
<th>$\dot{m}_{cat}$ [kg/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>775</td>
<td>23.38</td>
<td>32.14</td>
<td>72.75</td>
<td>7.09</td>
<td>0.0016</td>
<td>0.93</td>
<td>0.81</td>
<td>4.03</td>
<td>181.4</td>
</tr>
<tr>
<td>800</td>
<td>25.12</td>
<td>35.85</td>
<td>70.07</td>
<td>8.68</td>
<td>0.0019</td>
<td>1.16</td>
<td>0.64</td>
<td>3.22</td>
<td>222.2</td>
</tr>
<tr>
<td>820</td>
<td>26.16</td>
<td>38.55</td>
<td>67.84</td>
<td>10.03</td>
<td>0.0022</td>
<td>1.38</td>
<td>0.54</td>
<td>2.70</td>
<td>256.9</td>
</tr>
<tr>
<td>840</td>
<td>27.13</td>
<td>41.38</td>
<td>65.55</td>
<td>11.53</td>
<td>0.0025</td>
<td>1.63</td>
<td>0.46</td>
<td>2.28</td>
<td>295.1</td>
</tr>
<tr>
<td>860</td>
<td>28.38</td>
<td>45.02</td>
<td>63.03</td>
<td>13.46</td>
<td>0.0030</td>
<td>1.89</td>
<td>0.40</td>
<td>2.01</td>
<td>344.7</td>
</tr>
<tr>
<td>880</td>
<td>28.83</td>
<td>47.63</td>
<td>60.53</td>
<td>15.21</td>
<td>0.0034</td>
<td>2.20</td>
<td>0.34</td>
<td>1.71</td>
<td>389.3</td>
</tr>
</tbody>
</table>

Based on a cat. coke content increase from 0.15 to 0.1575 wt%
POTENTIAL APPLICATIONS OF RFB-SGs: CFD study of FCC

Full PI potential: More active catalyst

- **Gasoline mass fraction**
- **LG mass fraction**
- **Gas Oil conversion**
- **Gasoline selectivity**
## POTENTIAL APPLICATIONS OF RFB-SGs: CFD study of FCC

### Full PI potential: More active catalyst

<table>
<thead>
<tr>
<th>Act [-]</th>
<th>$\chi_G$ [%]</th>
<th>$\chi_{GO}$ [%]</th>
<th>$\chi_G/\chi_{GO}$ [%]</th>
<th>$\chi_{LG}$ [%]</th>
<th>$\langle \mathcal{R}_C \rangle$ [kmol/(m$^3$s)]</th>
<th>$\langle R' \rangle \times 10^4$ [kg$<em>{coke}$/kg$</em>{cat}$s]</th>
<th>$\tau_{cat}$ [s]</th>
<th>N [-]</th>
<th>$\dot{m}_{cat}$ [kg/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1a</td>
<td>23.38</td>
<td>32.14</td>
<td>72.75</td>
<td>7.09</td>
<td>0.0016</td>
<td>0.93</td>
<td>0.81</td>
<td>4.03</td>
<td>181.4</td>
</tr>
<tr>
<td>1.5a</td>
<td>27.33</td>
<td>37.81</td>
<td>72.28</td>
<td>8.47</td>
<td>0.0019</td>
<td>1.24</td>
<td>0.60</td>
<td>2.97</td>
<td>218.3</td>
</tr>
<tr>
<td>2a</td>
<td>31.17</td>
<td>43.41</td>
<td>71.82</td>
<td>9.90</td>
<td>0.0022</td>
<td>1.51</td>
<td>0.50</td>
<td>2.39</td>
<td>253.0</td>
</tr>
<tr>
<td>3a</td>
<td>38.47</td>
<td>54.78</td>
<td>70.23</td>
<td>13.20</td>
<td>0.0029</td>
<td>1.88</td>
<td>0.40</td>
<td>2.08</td>
<td>337.1</td>
</tr>
<tr>
<td>4a</td>
<td>41.21</td>
<td>59.69</td>
<td>69.05</td>
<td>14.94</td>
<td>0.0033</td>
<td>2.29</td>
<td>0.33</td>
<td>1.69</td>
<td>383.2</td>
</tr>
<tr>
<td>5a</td>
<td>43.02</td>
<td>63.38</td>
<td>67.88</td>
<td>16.46</td>
<td>0.0037</td>
<td>2.67</td>
<td>0.28</td>
<td>1.44</td>
<td>422.9</td>
</tr>
<tr>
<td>6a</td>
<td>44.67</td>
<td>67.01</td>
<td>66.66</td>
<td>18.06</td>
<td>0.0040</td>
<td>3.01</td>
<td>0.25</td>
<td>1.28</td>
<td>464.3</td>
</tr>
</tbody>
</table>

### Diagrams

- **Solids volume fraction**
  - Time [s]
  - Act 1a and 5a

- **PI Factor**
  - GO Conversion
  - Act 1a, 1.5a, 2a, 3a, 4a, 5a, 6a
POTENTIAL APPLICATIONS OF RFB-SGs: CFD study of FCC

- PI POTENTIAL OF RFB-SGs FOR FCC CONFIRMED
- PI BY ABOUT ONE ORDER OF MAGNITUDE WHEN USING THE EQUAL CATALYST AND CRACKING TEMPERATURE THAN IN A CONVENTIONAL CFB RISER
- ADDITIONAL PI BY USING MORE ACTIVE CATALYST OR HIGHER CRACKING TEMPERATURE
- OF INTEREST FOR OTHER HETEROGEOUS CATALYTIC PROCESSES (MTO)
- CFD STUDY:
  - DESIGN ASPECTS: IMPORTANCE CONFIRMED
  - OPERATING CONDITIONS: THINKING OUT OF THE BOX!
- FULL PI POTENTIAL:
  - HIGHER CRACKING TEMPERATURES
  - MORE ACTIVE CATALYST
  - INCREASED CATALYST CIRCULATION
  => MAY REQUIRE MULTI-ZONE OPERATION
POTENTIAL APPLICATIONS OF RFB-SGs: Multi-zone operation

- Integrated reaction and catalyst regeneration zones
- Integrated exothermic and endothermic reaction zones
- Short contact time between particles and a very hot gas
• Introduction
  • Process Intensification
  • Rotating fluidized beds

• Hydrodynamic characteristics of RFB-SGs
  • Experimental study
  • Theoretical and design considerations

• Potential & applications of RFB-SGs
  • Theoretical and CFD study on interfacial mass and heat transfer
  • Experimental study of biomass drying and particle coating/granulation
  • Numerical study of biomass pyrolysis and Fluid Catalytic Cracking
  • Multi-zone operation

• Conclusions and perspectives
CONCLUSIONS AND PERSPECTIVES

NOVEL REACTOR CONCEPTS
- ROTATING FLUIDIZED BED IN A STATIC GEOMETRY (USING VORTEX CHAMBER)

HYDRODYNAMIC CHARACTERISTICS STUDIED
- EXPERIMENTALLY
- COMPUTATIONAL FLUID DYNAMICS

PI POTENTIAL AND POTENTIAL APPLICATIONS STUDIED
- NUMERICALLY
- EXPERIMENTALLY
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Thank you for your interest

Juray.DeWilde@UCLouvain.be


REFERENCES


