ROTATING FLUIDIZED BEDS

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Process Intensification, MSc course 2012-2013, TUDelft

OUTLINE

- **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**

Remove limitations of chemical reactors introduced by:

Intrinsic reaction rates (e.g. using more active catalyst)
Thermodynamics

Transport phenomena:

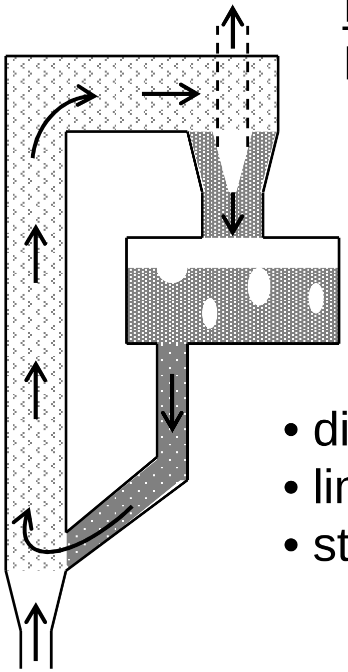
- Inter-phase mass- and heat transfer
- Inter-phase momentum transfer
- Intra-particle mass transfer

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



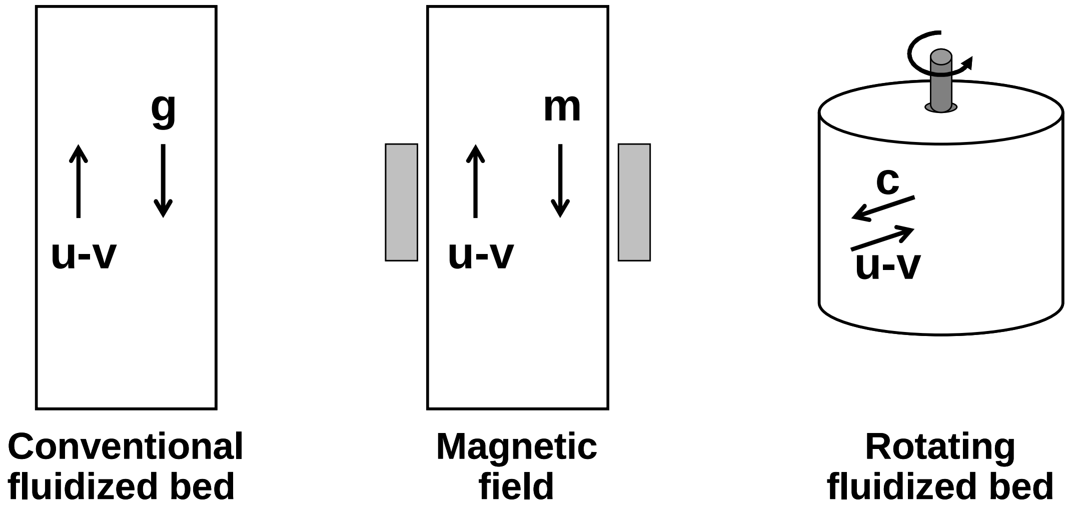
Example:
Riser reactor (FCC):

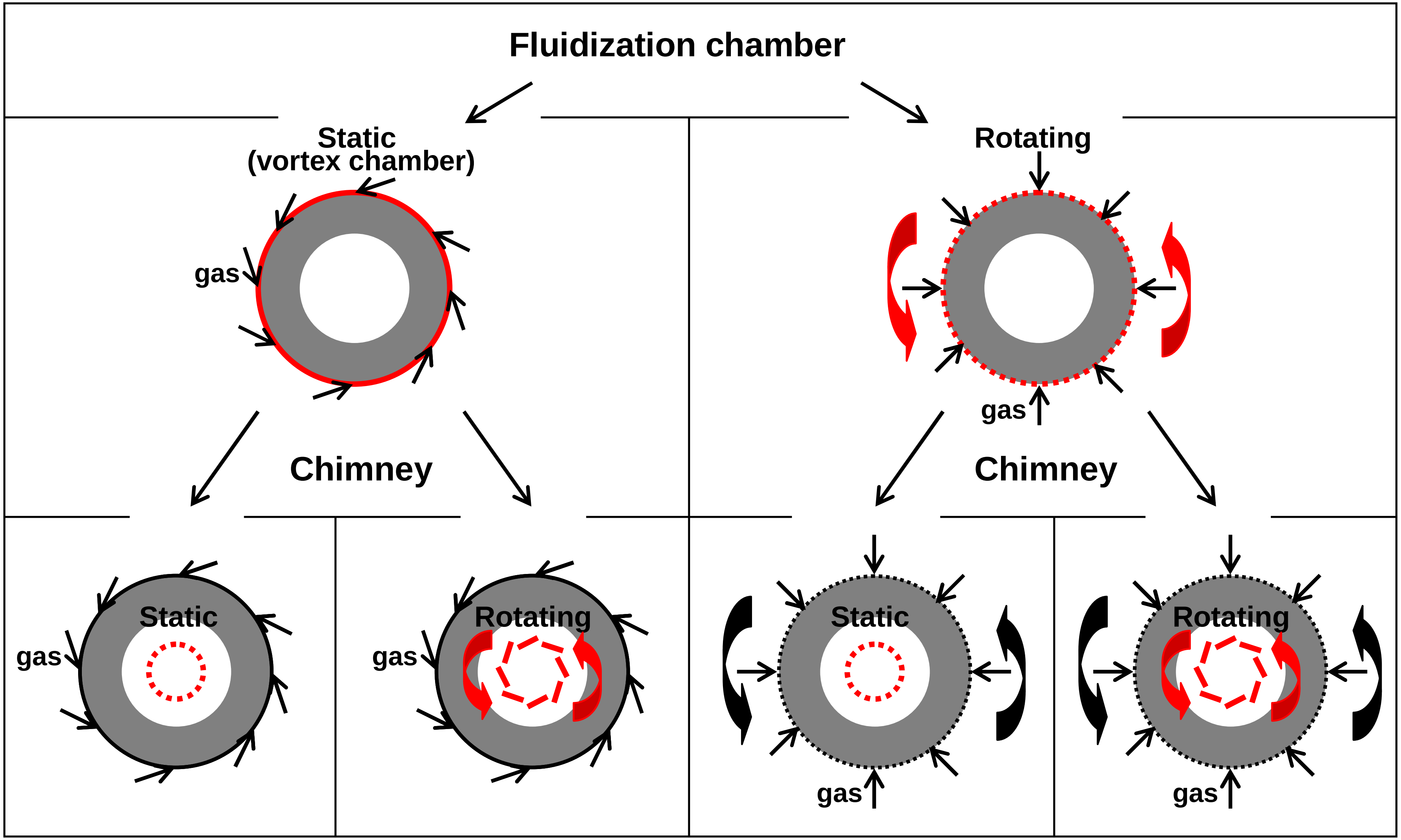
- dilute riser
- limited slip velocity
- stand pipe height

Role of earth gravity !

⬇

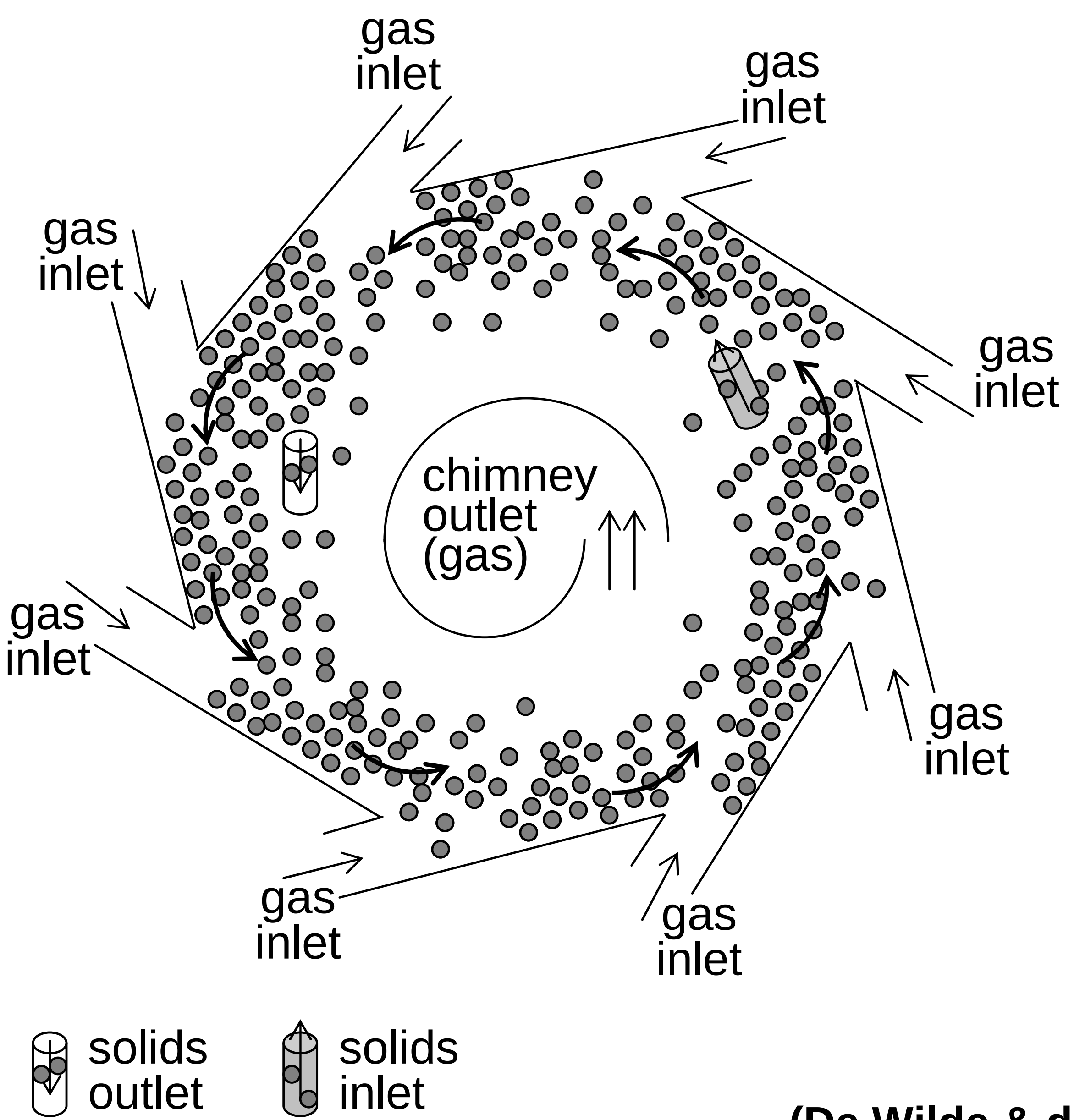
High-G operation !

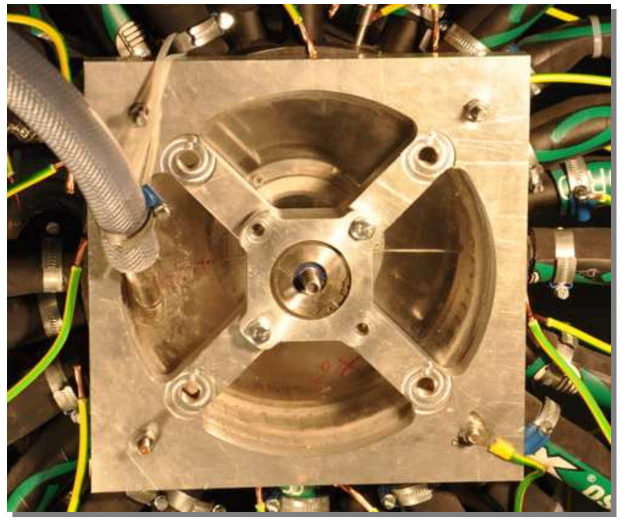



Fluidization chamber
Static
(vortex chamber)
gas
Rotating
gas
Chimney
Chimney
Static
gas
Rotating
gas
Static
gas
Rotating
gas

INTRODUCTION: Rotating Fluidized Beds

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





(De Wilde & de Broqueville, AIChE J., 2007)

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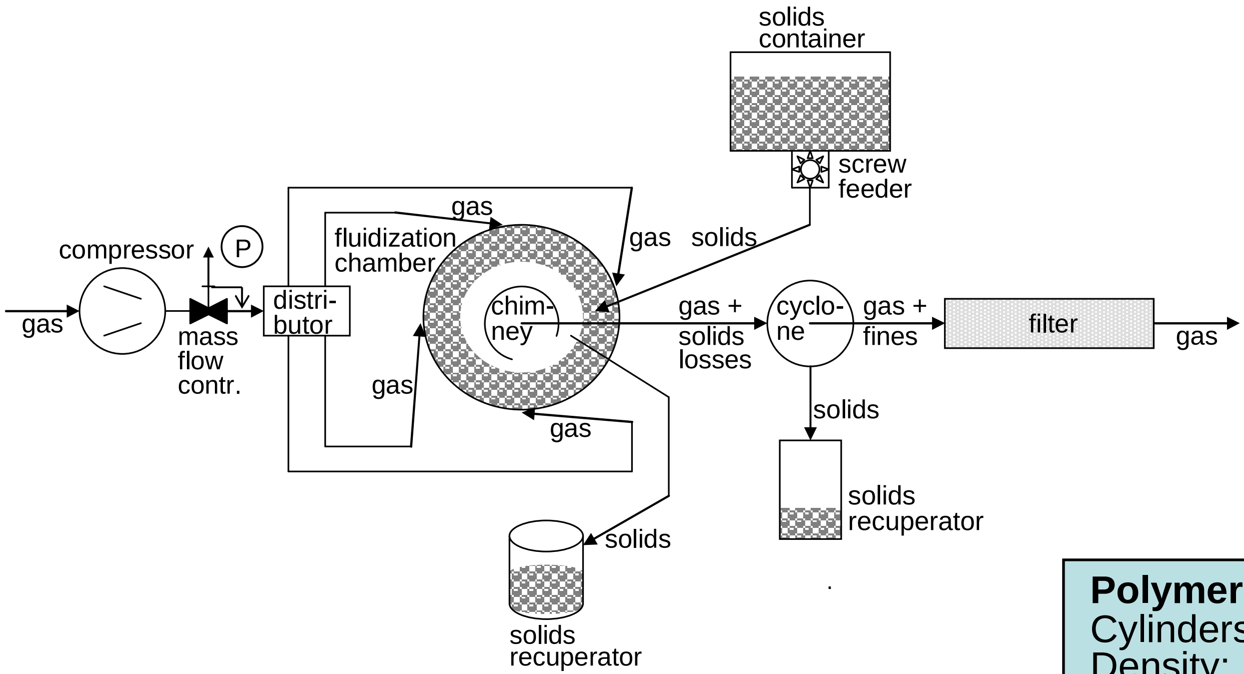
- **Hydrodynamic characteristics of RFB-SGs**
  - Experimental study
  - Theoretical and desi
- **Potential & app**
  - Theoretical and CFD
  - Experimental study o
  - Numerical study of b
  - Multi-zone operation
- **Conclusions and perspectives**

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/m^3

Biomass granules: 1G Geldart D
Average size: 4 mm
Density: 600 kg/m^3

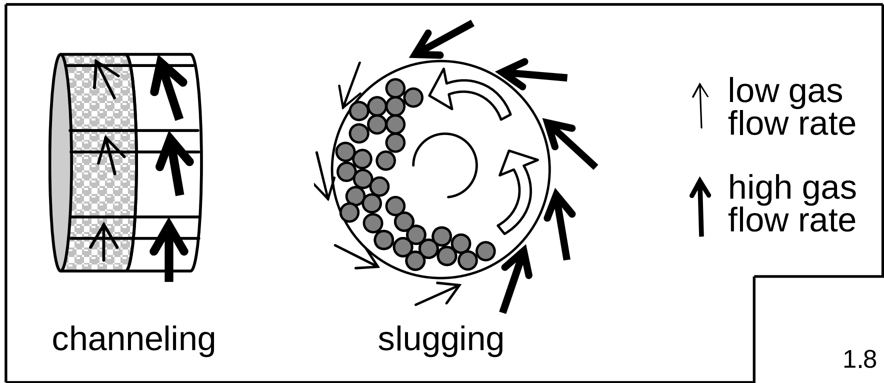
Alumina / salt particles: 1G Geldart B
Average size: 350 µm
Density: 2100 kg/m^3

FCC catalyst powder: 1G Geldart A
Average size: 60 µm
Density: 1500 kg/m^3

Organic powder: 1G Geldart C
Average size: 70 µm
Density: 260 kg/m^3

HYDRODYNAMIC CHARACTERISTICS OF RFB-SGs: Experimental study

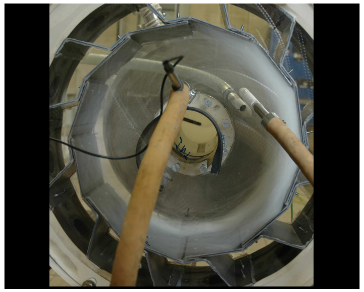
BED STABILITY AND LARGE-SCALE UNIFORMITY



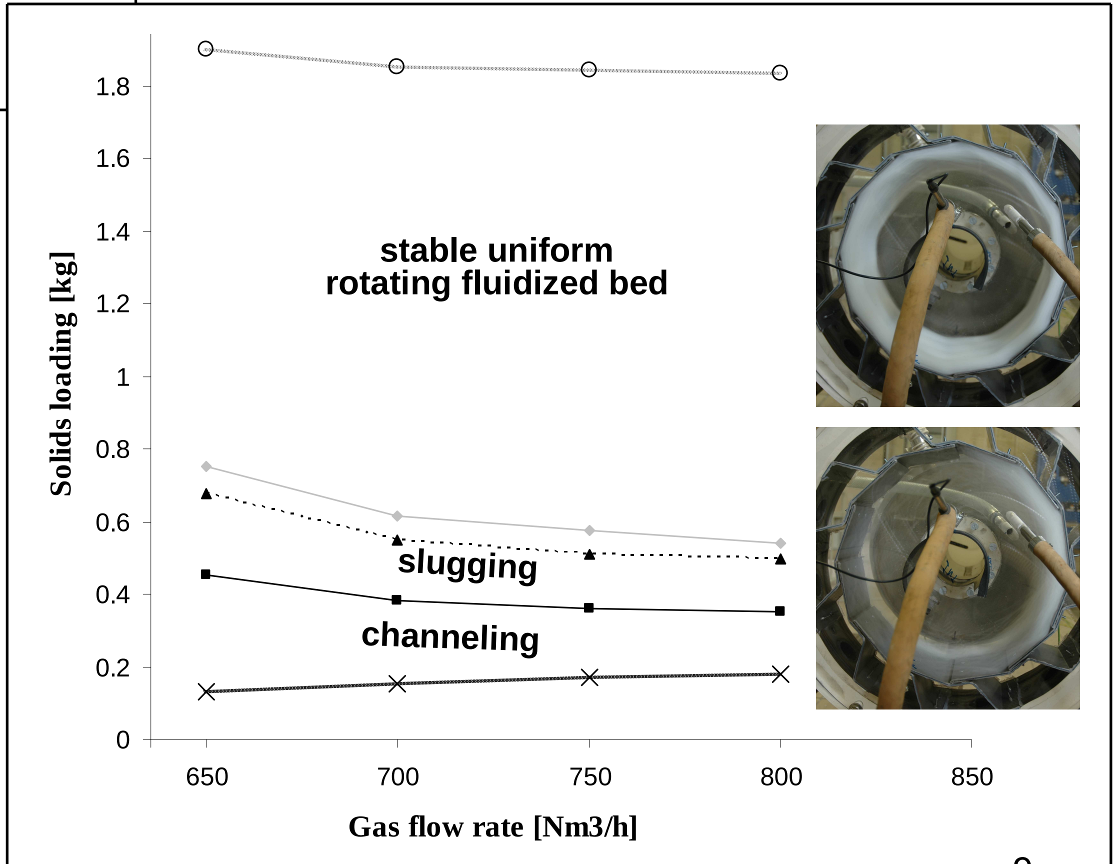
Process gas bypassing the particles
⇒ Poor gas-solid contact !

- **1G Geldart D-type particles**
- **24-cm diameter fluid. chamb.**

Stable bed



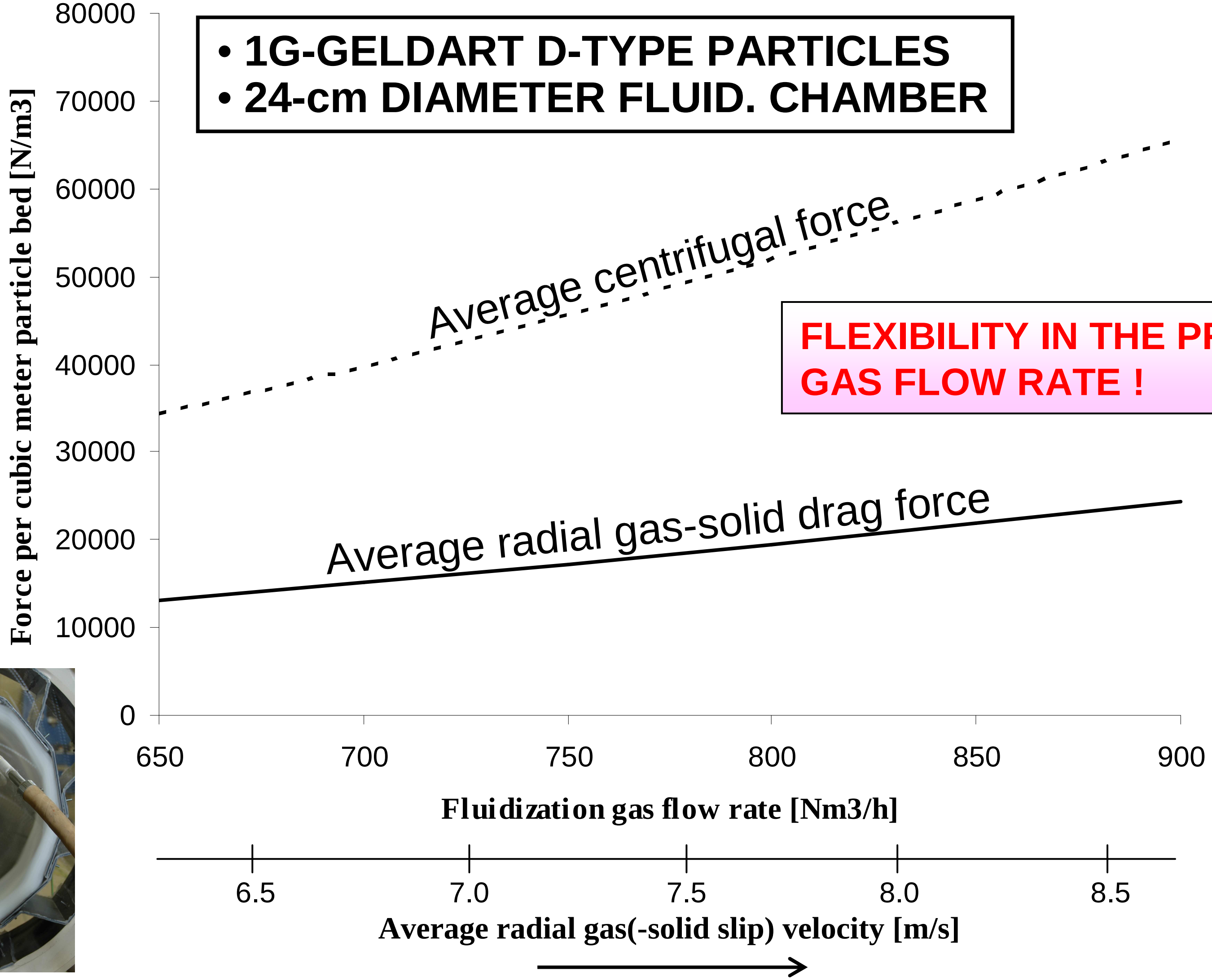
Slugging



(De Wilde & de Broqueville, 2008)

HYDRODYNAMIC CHARACTERISTICS OF RFB-SGs: Experimental study

OPERATING CONDITIONS: GAS AND SOLIDS FLOW RATES

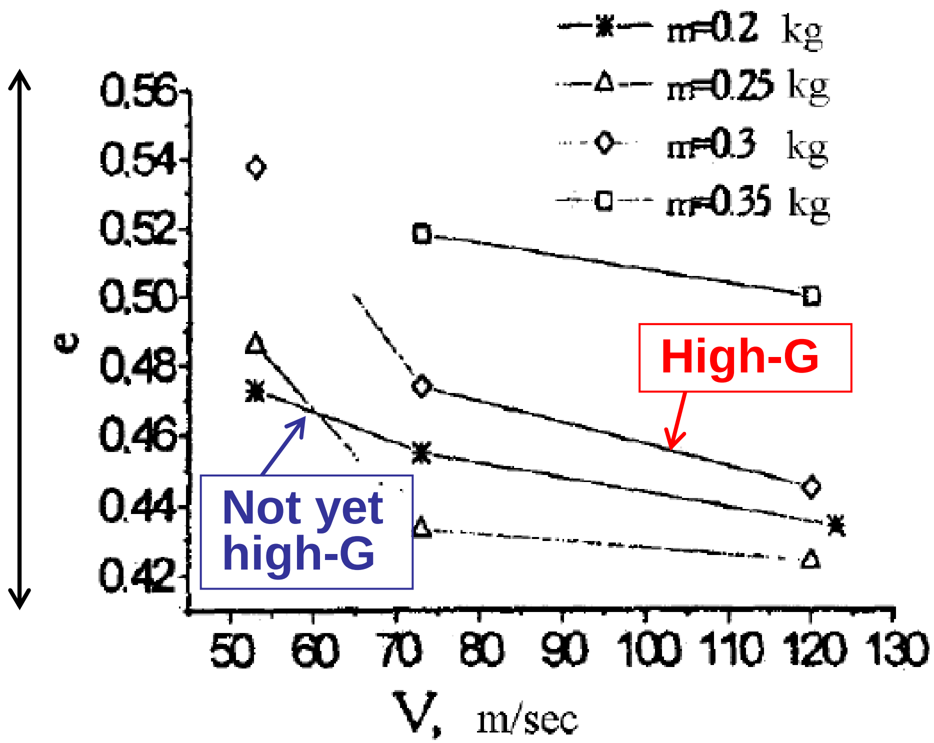


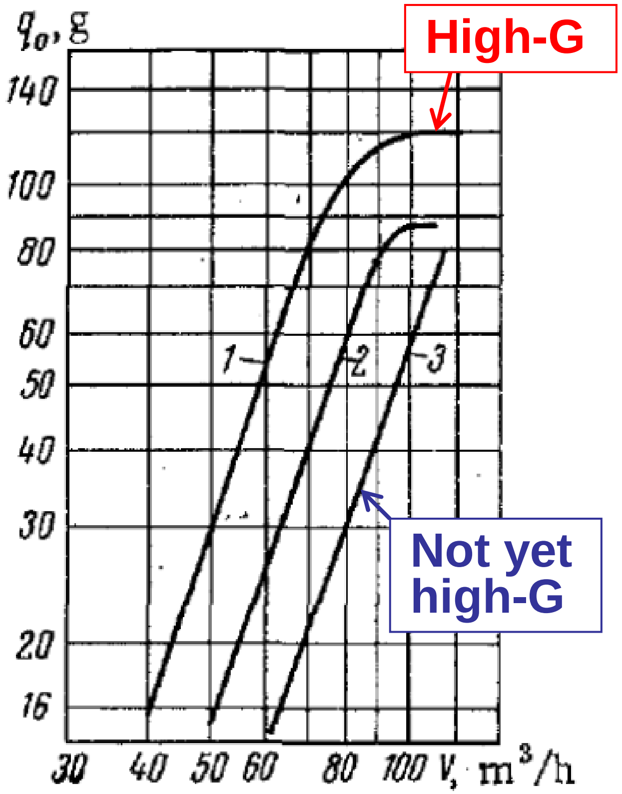
FLEXIBILITY IN THE PROCESS GAS FLOW RATE !

LIMITED RADIAL BED EXPANSION, EVEN RADIAL BED CONTRACTION

OPERATING CONDITIONS: GAS AND SOLIDS FLOW RATES

Relatively small effect





(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.)

OPERATING CONDITIONS: GAS AND SOLIDS FLOW RATES

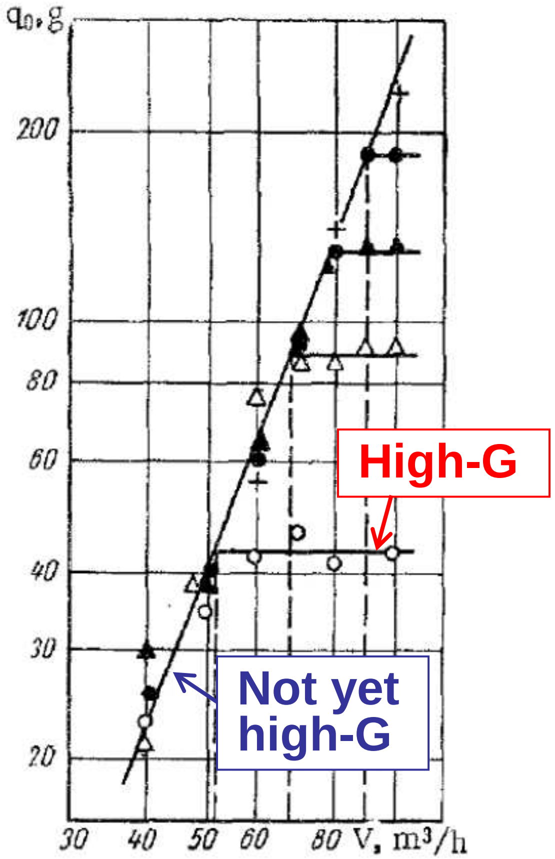
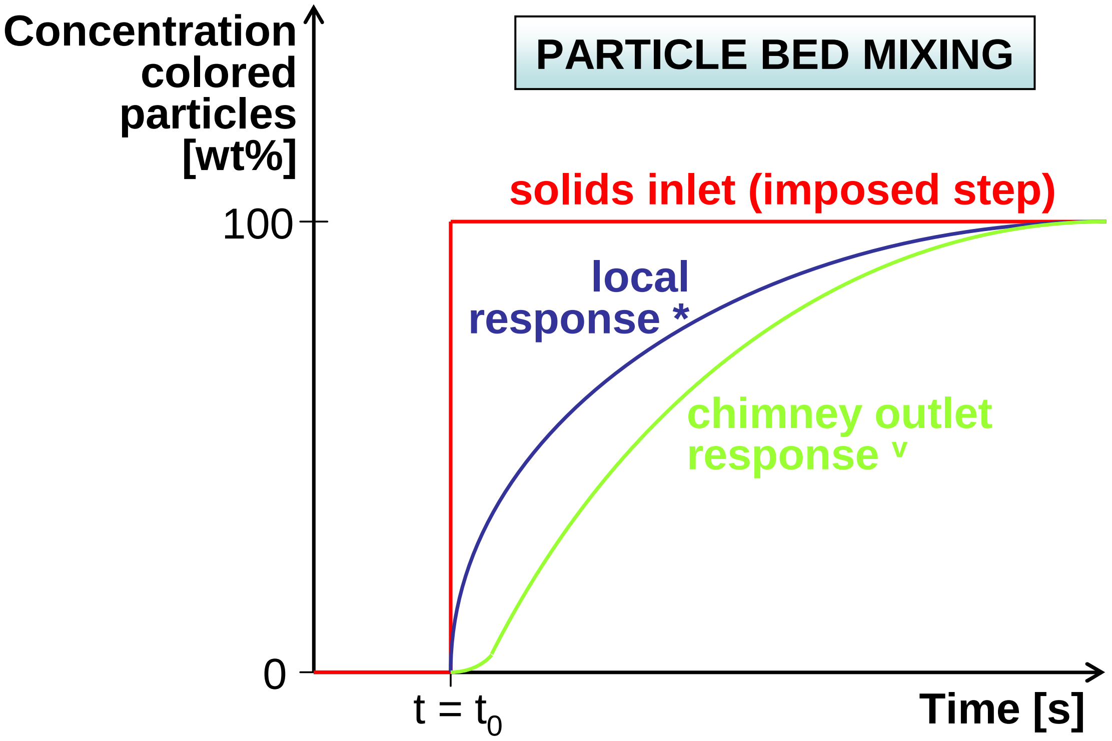


Figure 4.2.2. Fluidization of different types of particles in a vortex chamber of given design. (a) Solids retention capacity (zero solids feeding rate) as a function of the air flow rate. Polystyrene particles: ○ d_p = 0.25-0.5 mm; Δ d_p = 0.5-1.0 mm; ▲ d_p = 1.2-1.5 mm; ● d_p = 1.5-2.0 mm. Vortex chamber: D = 24 cm, L = 3.5 cm, n·s = 1.5 cm, λ = 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, λ = 0.096. (From Trujillo and De Wilde, 2012b.)

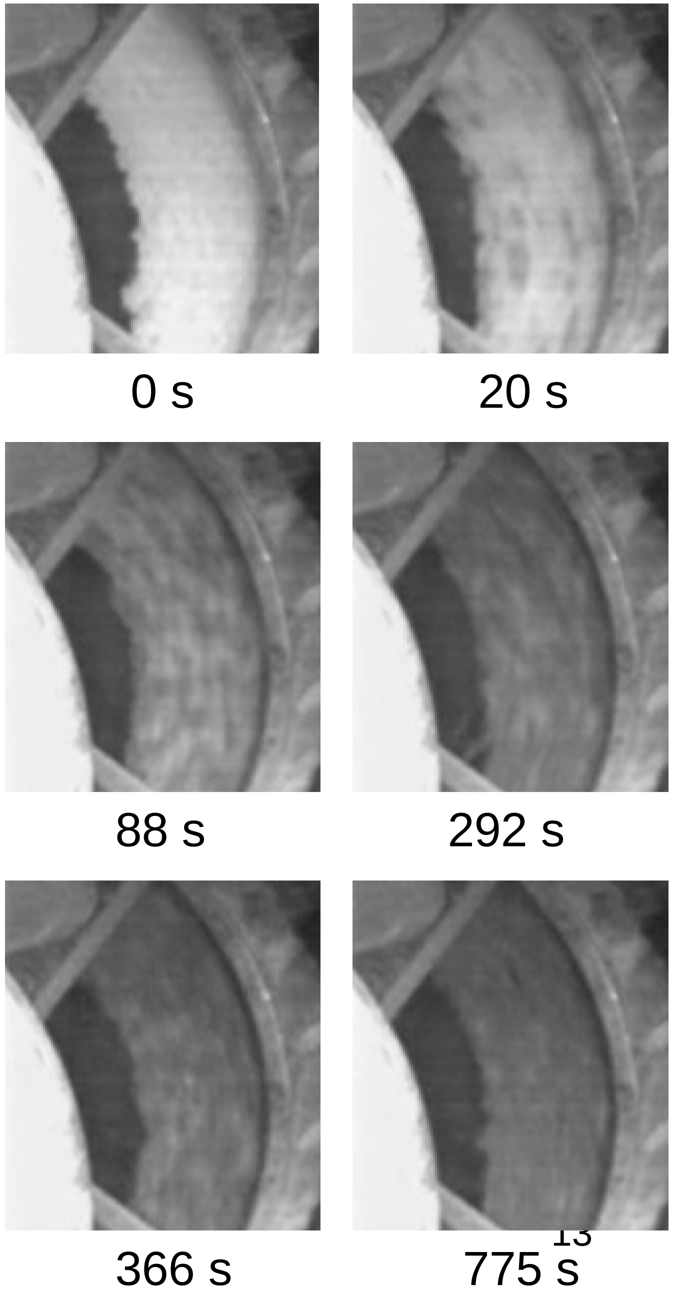
HYDRODYNAMIC CHARACTERISTICS OF RFB-SGs: Experimental study

FLOW PATTERN: GAS AND PARTICLES



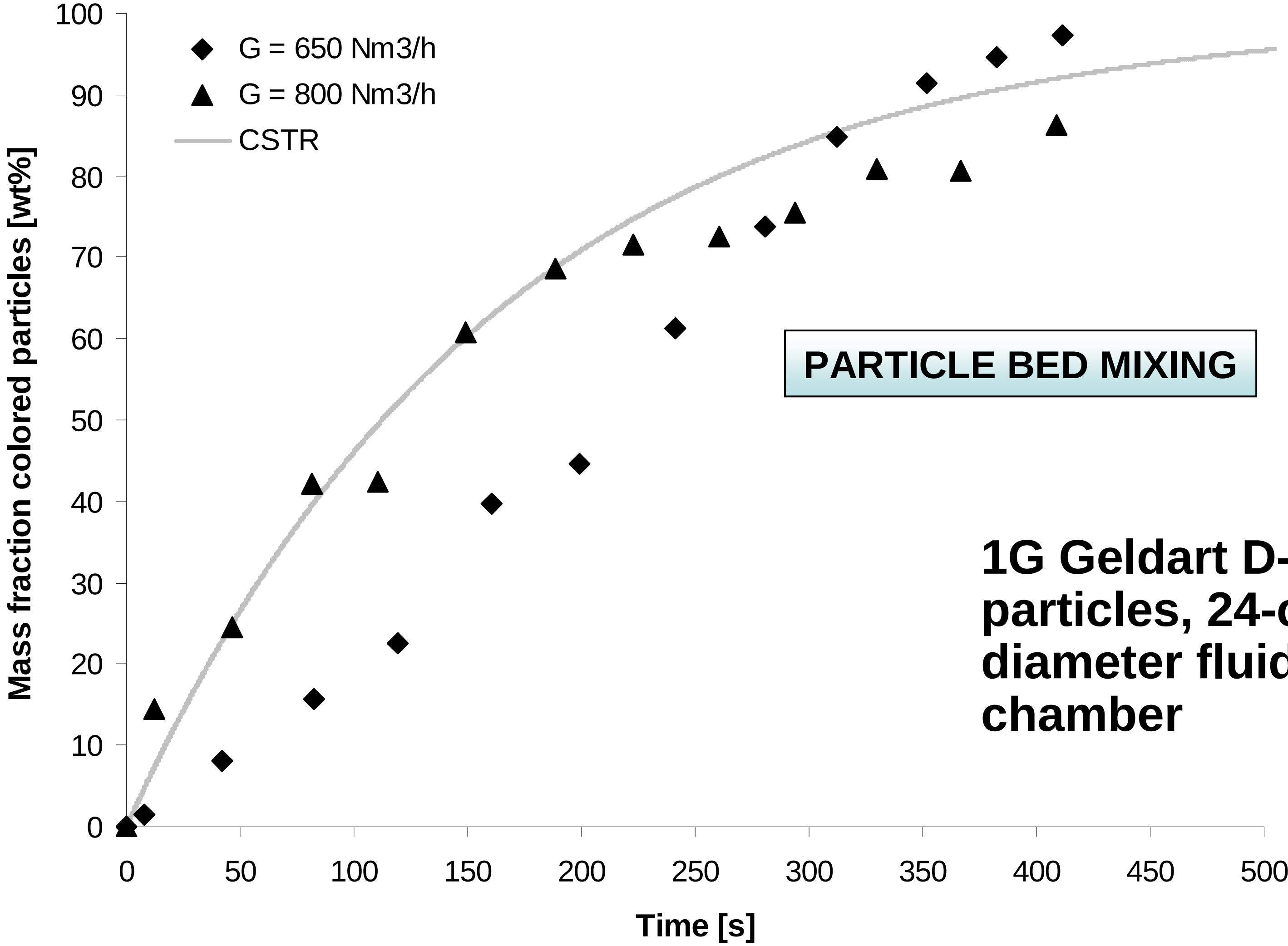
*** local fluidization chamber response measured at the end plate opposite the solids inlet by rapid camera**

v chimney outlet response measured between the chimney and the cyclone by sampling



HYDRODYNAMIC CHARACTERISTICS OF RFB-SGs: Experimental study

FLOW PATTERN: GAS AND PARTICLES



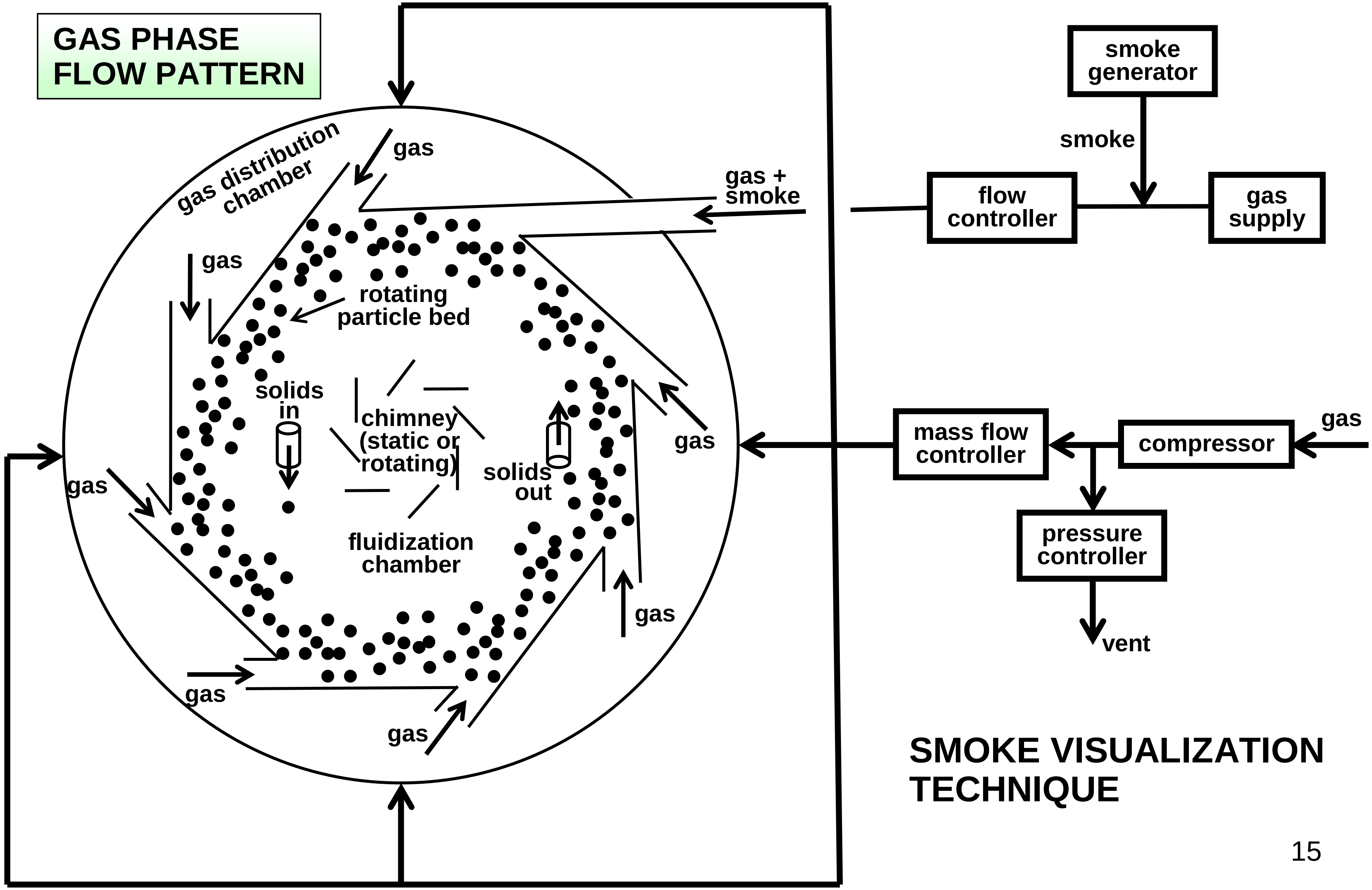
1G Geldart D-type particles, 24-cm diameter fluidization chamber

CSTR AT SUFFICIENTLY HIGH PARTICLE BED ROTATIONAL SPEEDS

HYDRODYNAMIC CHARACTERISTICS OF RFB-SGs: Experimental study

FLOW PATTERN: GAS AND PARTICLES

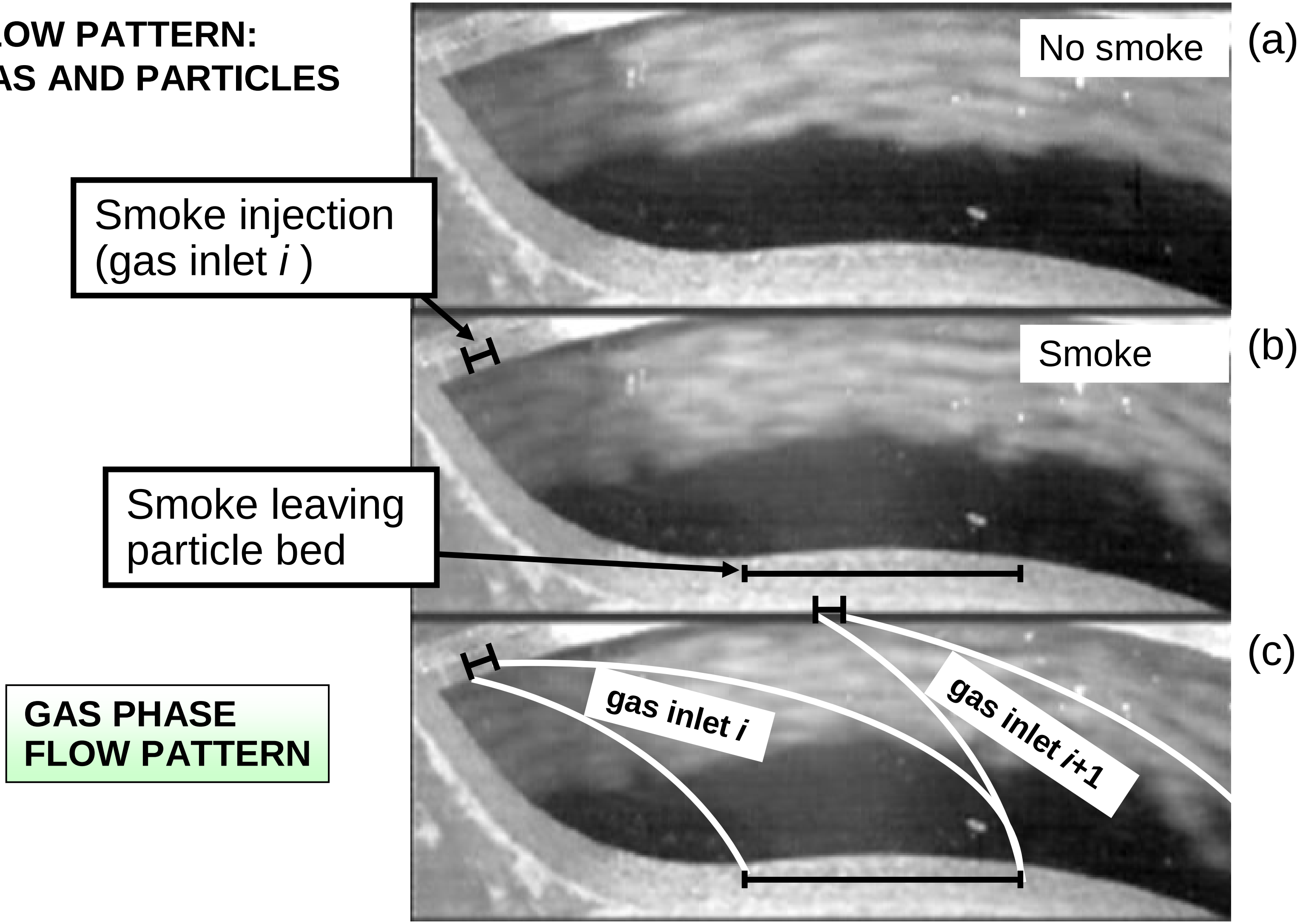
GAS PHASE FLOW PATTERN



SMOKE VISUALIZATION TECHNIQUE

HYDRODYNAMIC CHARACTERISTICS OF RFB-SGs: Experimental study

FLOW PATTERN:
GAS AND PARTICLES

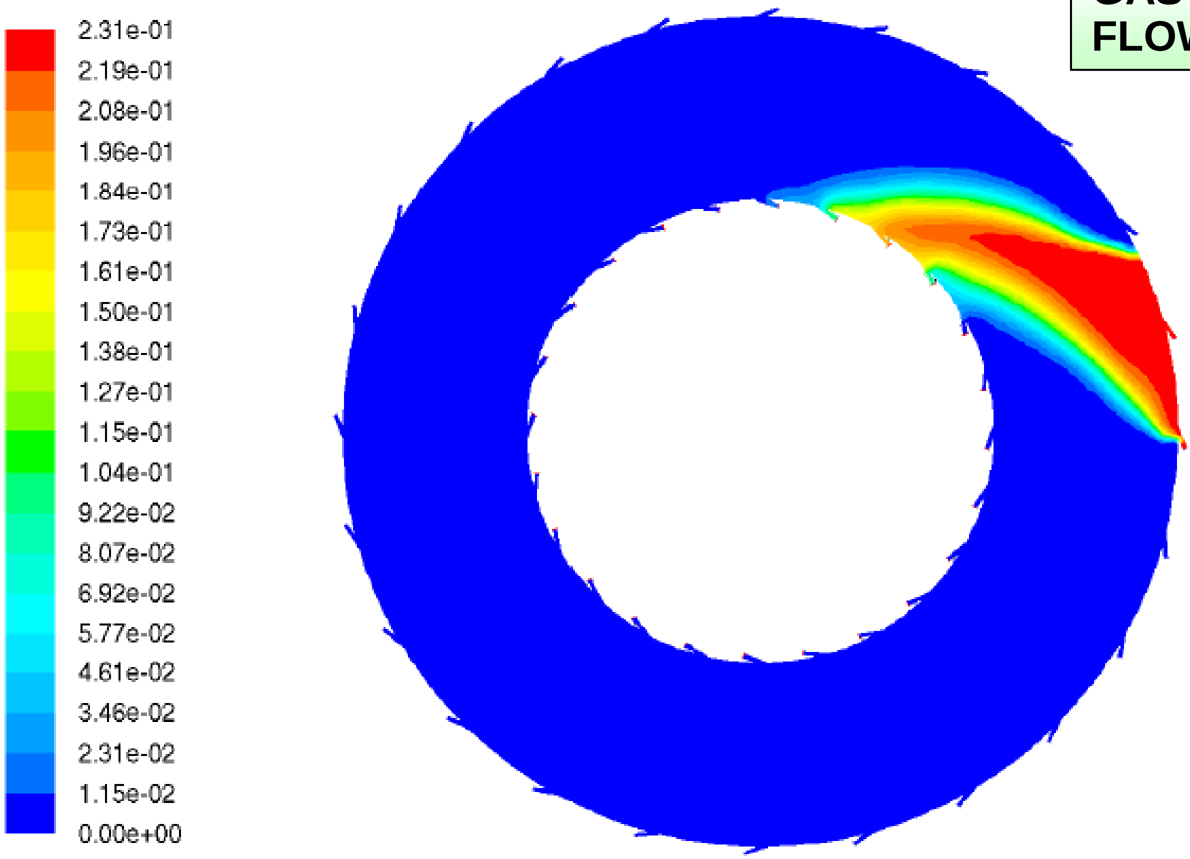


- **GASES INJECED VIA SUCCESSIVE GAS INLETS HARDLY MIXED**
- **PLUG FLOW TYPE PATTERN FOR THE FLUIDIZATION GAS**
- **RTD GAS DETERMINED BY THE RADIAL VELOCITY COMPONENT**

HYDRODYNAMIC CHARACTERISTICS OF RFB-SGs: Experimental study

FLOW PATTERN: GAS AND PARTICLES

GAS PHASE FLOW PATTERN

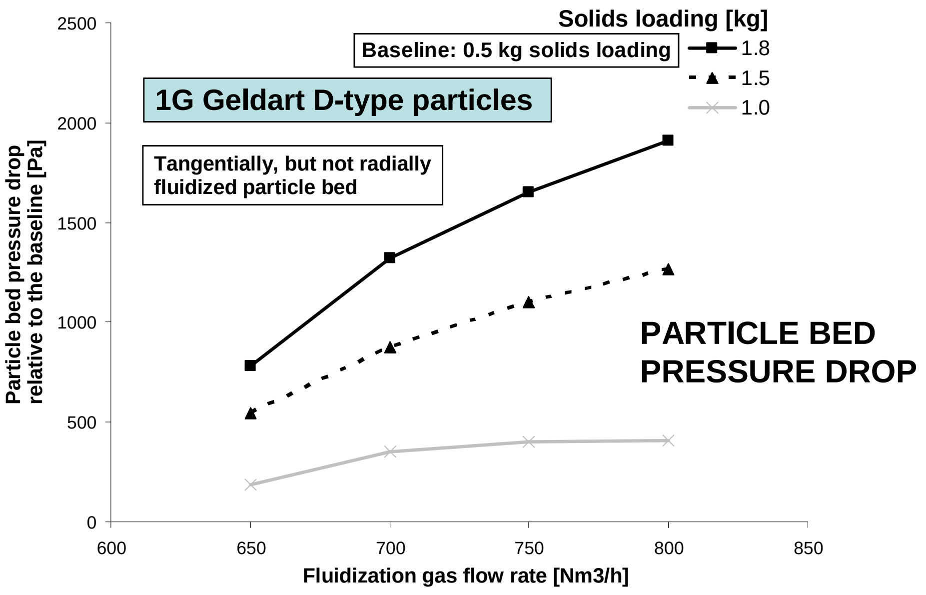


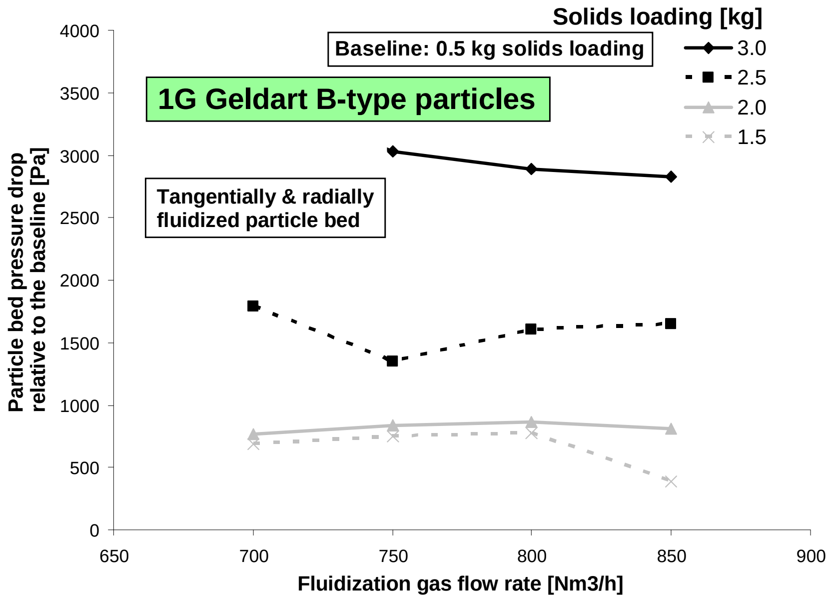
- GASES INJECED VIA SUCCESSIVE GAS INLETS HARDLY MIXED
- PLUG FLOW TYPE PATTERN FOR THE FLUIDIZATION GAS
- RTD GAS DETERMINED BY THE RADIAL VELOCITY COMPONENT

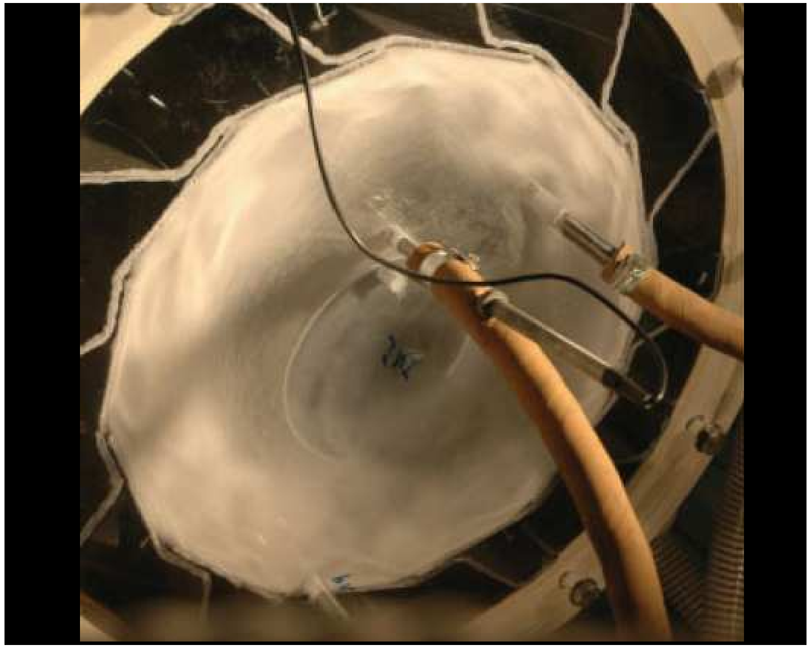
HYDRODYNAMIC CHARACTERISTICS OF RFB-SGs: Experimental study

FLOW PATTERN: INFLUENCE OF THE TYPE OF PARTICLES

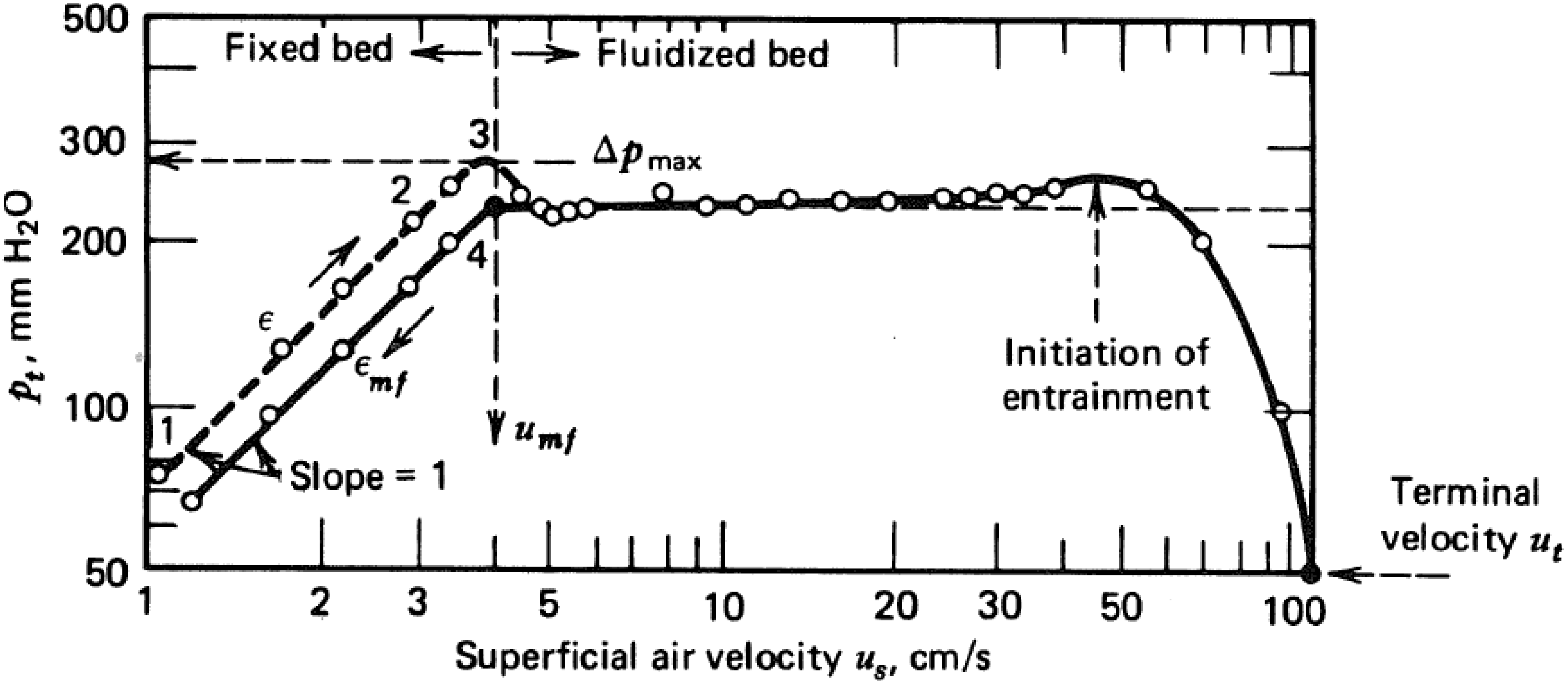
24-cm diameter fluidization chamber





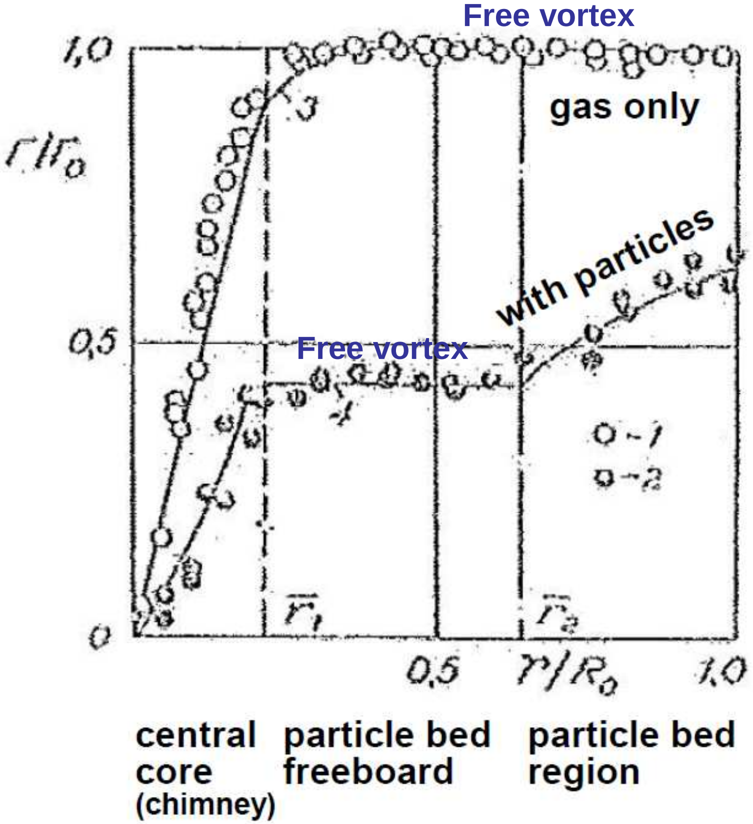


COMPARE TO PRESSURE DROP OVER THE PARTICLE BED AS A FUNCTION OF THE SUPERFICIAL AIR VELOCITY IN A CONVENTIONAL FLUIDIZED BED



(Froment, Bischoff and De Wilde, 2010)

FLOW PATTERN: INFLUENCE OF THE SOLIDS LOADING



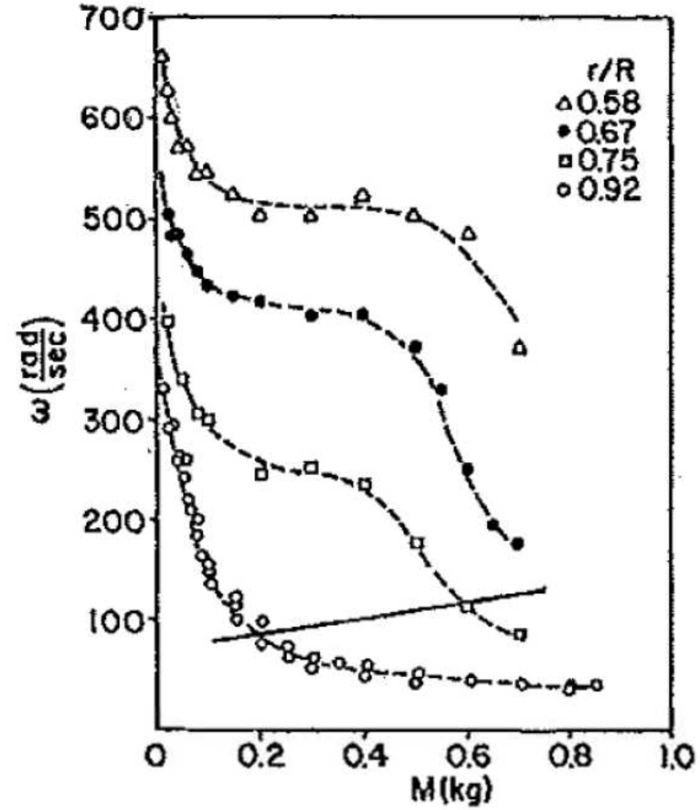
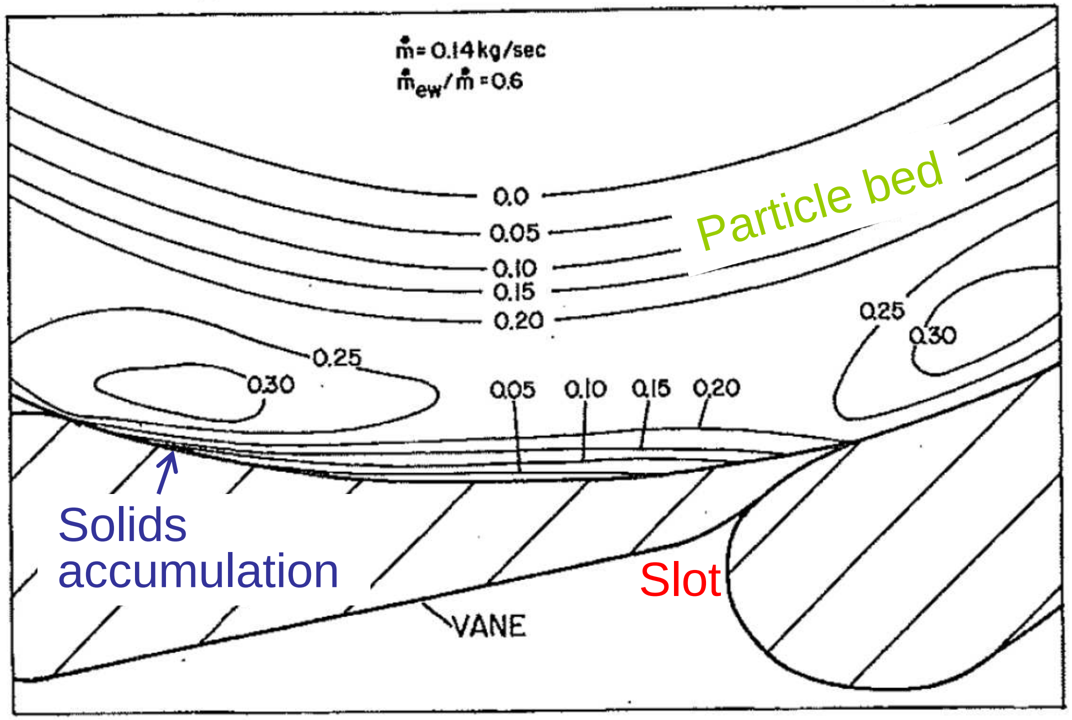


Figure 3.2.1. (a) Normalized circulation ($\Gamma = v_t \cdot r$) as a function of the normalized radial position in the vortex chamber (subscript $_0$ indicates at the chamber outer wall) in the absence and presence of particles. Vortex chamber: D = 36 cm, L = 6 cm, D_c = 8 cm, n > 20, λ = 0.099. Operating conditions: solids loading: 1 kg of sand particles (ρ_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 → 8 cm (convergent), n = 12, s = 0.3 mm, λ = 0.00376. Operating conditions: talc particles (ρ_s = 2700 kg/m^3, d_p = 20 μm). (From Anderson et al., 1972.)

FLOW PATTERN: SOLIDS DISTRIBUTION



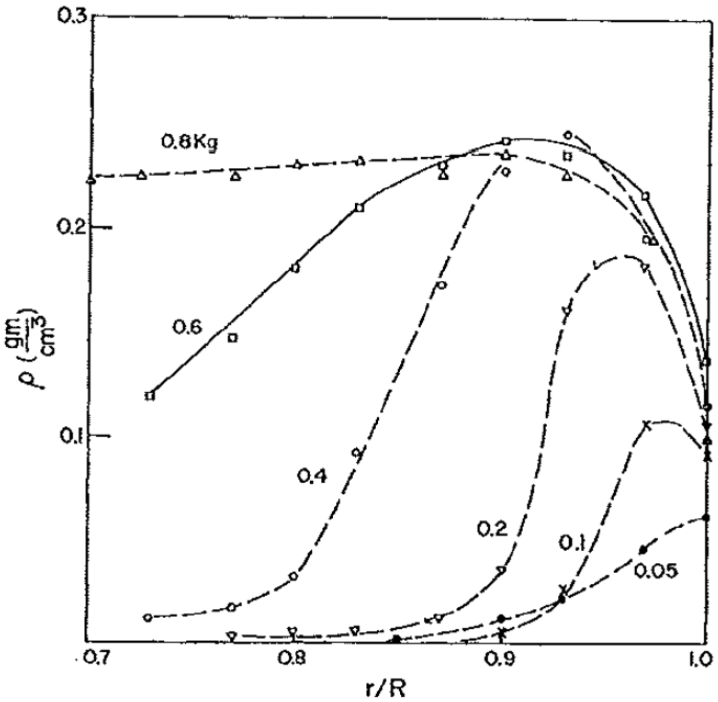


Figure 3.6.3. Fluidization of fine talc powder (d_p = 20 μm, ρ_s = 2700 kg/m^3) in a vortex chamber. Vortex chamber: D = 30.5 cm, L = 6.3 cm, n·s = 0.36 cm, λ = 0.00376. Operating conditions: total gas flow rate: 0.117 Nm^3/s, solids loading: 0.05 - 0.8 kg. (a) Picture of the rotating particle bed; (b) 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.)

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**

0.8 kg solids, 4.5 rps

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

FLOW PATTERN: INFLUENCE OF THE TYPE OF PARTICLES

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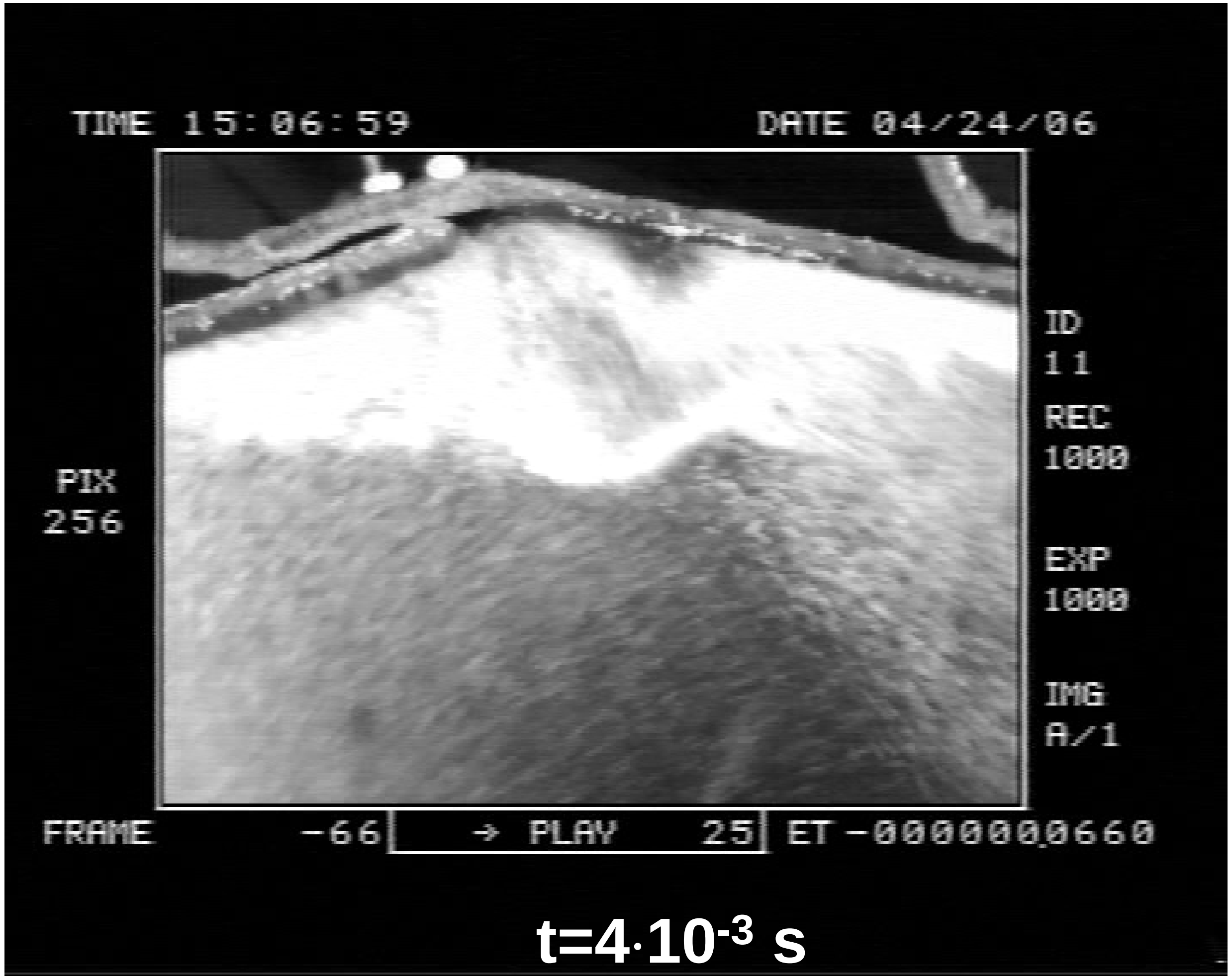

1G Geldart B-type particles, 36-cm diameter fluidization chamber

HYDRODYNAMIC CHARACTERISTICS OF RFB-SGs: Experimental study

FLOW PATTERN: INFLUENCE OF THE TYPE OF PARTICLES

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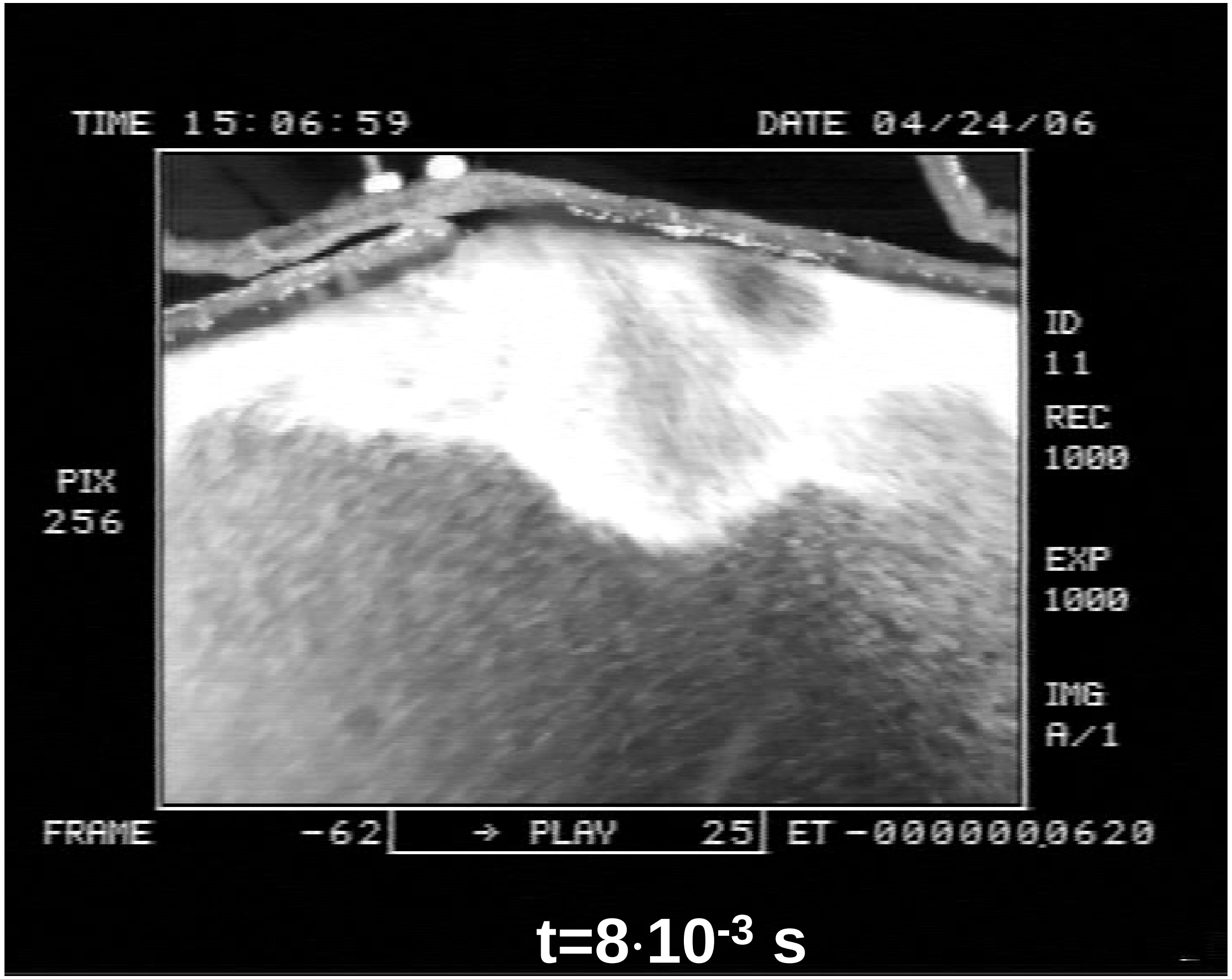

1G Geldart B-type particles, 36-cm diameter fluidization chamber

FLOW PATTERN: INFLUENCE OF THE TYPE OF PARTICLES

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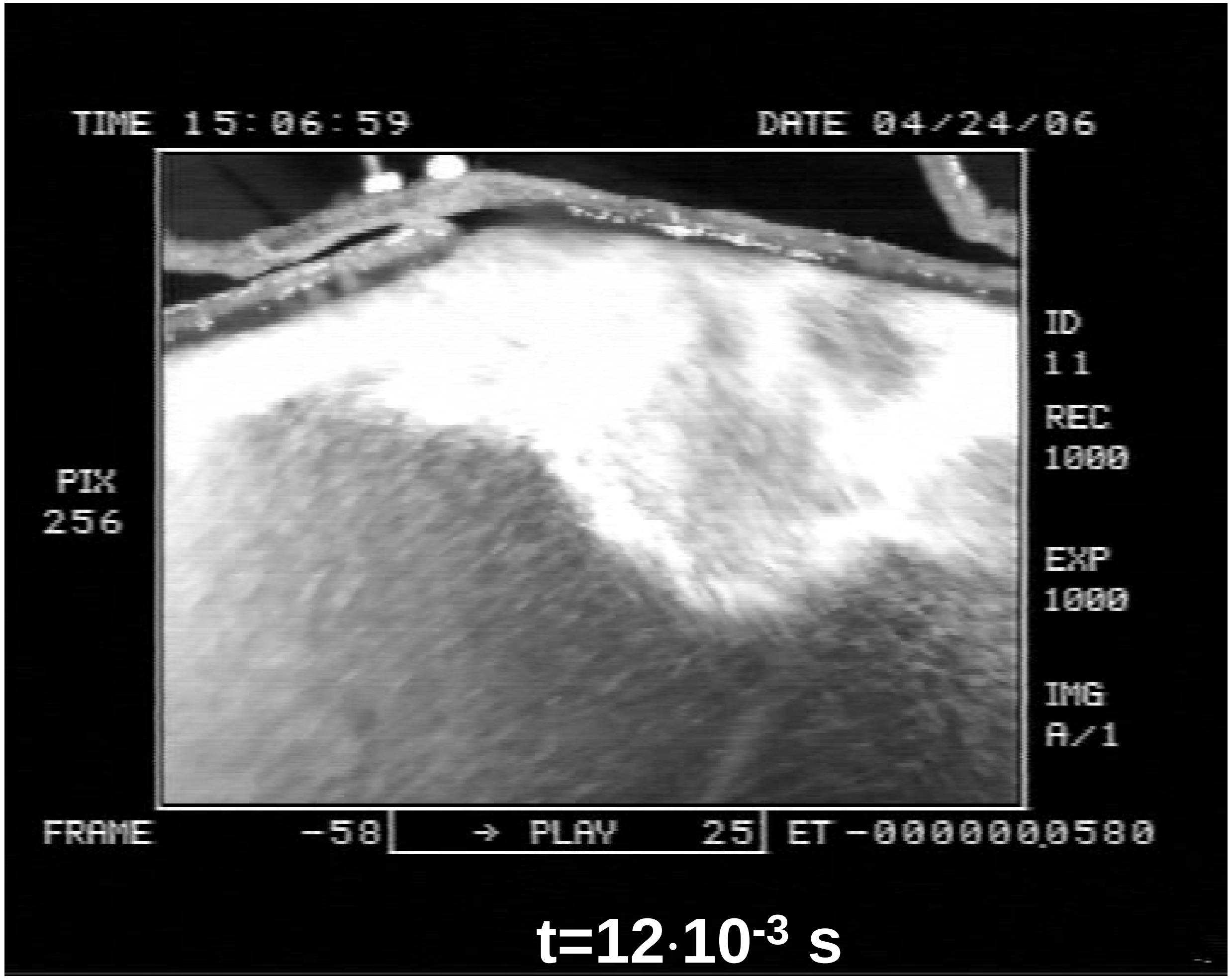

1G Geldart B-type particles, 36-cm diameter fluidization chamber

FLOW PATTERN: INFLUENCE OF THE TYPE OF PARTICLES

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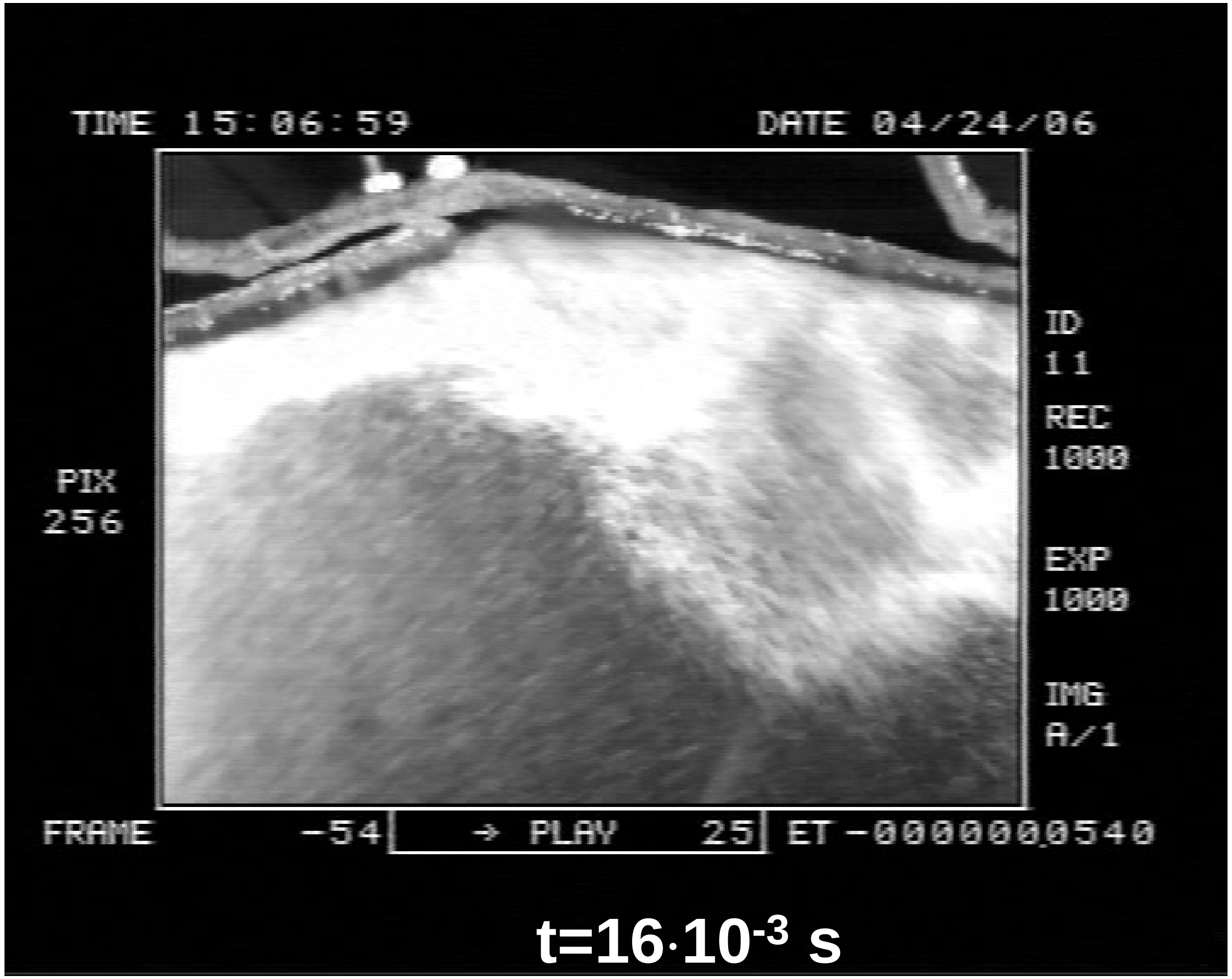

1G Geldart B-type particles, 36-cm diameter fluidization chamber

HYDRODYNAMIC CHARACTERISTICS OF RFB-SGs: Experimental study

FLOW PATTERN: INFLUENCE OF THE TYPE OF PARTICLES

HIGH SPEED CCD CAMERA TECHNIQUE:

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- focus on gas inlet slot zone

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)
- 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

FLOW PATTERN: INFLUENCE OF THE TYPE OF PARTICLES

HIGH SPEED CCD CAMERA TECHNIQUE:

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BUBBLING:

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1.1 kg solids, 3.5 rps

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

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 <=> 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
      => Intensified interfacial mass, heat & momentum transfer
    - Fluidization of smaller particles / fine powders ???
- High particle bed width-to-height ratio
- Static geometry – facilitates continuous operation

⇒ Optimization reactor design, i.e. interfacial momentum transfer !

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- **Potential & app**
  - Theoretical and CFD
  - Experimental study c
  - Numerical study of b
  - Multi-zone operation
- **Conclusions and perspectives**

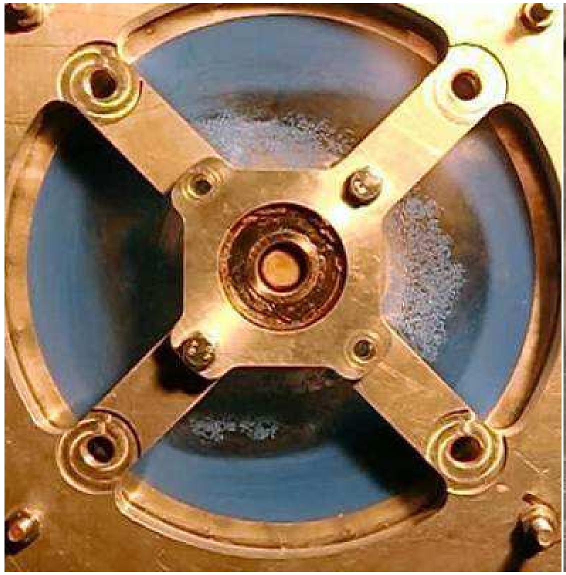
Aspects:

- Influence of the type of particles
  - Forces, bed expansion & solids losses, bubbling
- Theoretical and design considerations
  - Gas inlets
  - Chimney (gas outlet)
  - Solids feeding & removal

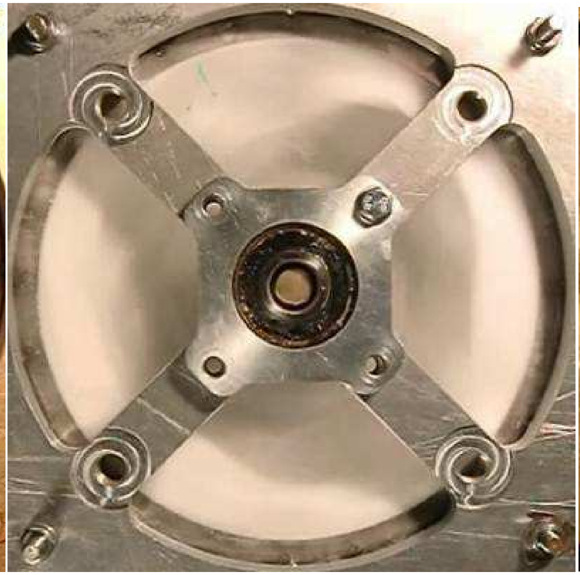
HYDRODYNAMIC CHARACTERISTICS OF RFB-SGs: Experimental study

FLOW PATTERN: INFLUENCE OF THE TYPE OF PARTICLES

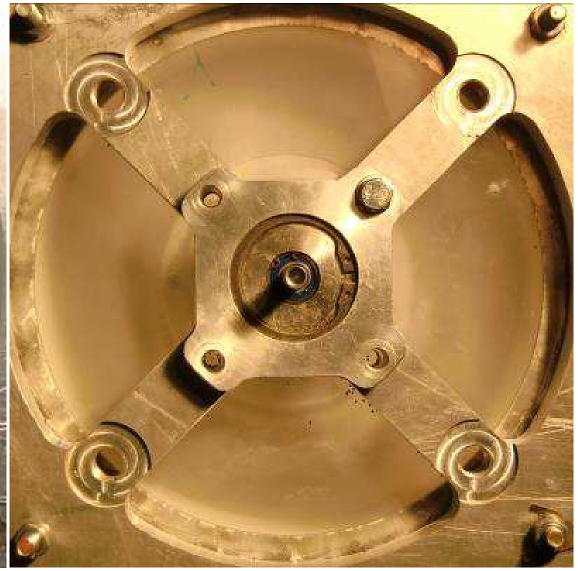
Identical reactor design & gas and solids feeding rates



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

⬌

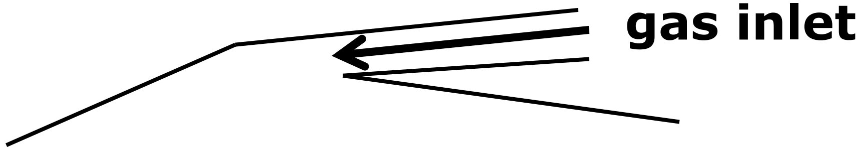
Criteria:
- F(centrifugal) ≥ F(drag, radial)
- ΔP(gas inlet slots) > ΔP(bed) !

⬍

Reactor design:
- Number of gas inlet slots
- Size gas inlet slots

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 ~ $\rho_g u_{inj}$
- Momentum injected ~ $\rho_g u^2_{inj}$

- Increase u_{inj}

=> Decrease gas inlet surface area
- Number of slots ↓
- Slot width ↓

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

- Tangential → Number of slots ↑; Increase pressure drop over the slots
- Axial → Increase pressure drop over the slots

- Number of slots ↑
- Increase pressure drop over the slots

=> Decrease gas inlet surface area
- Number of slots ↓
- Slot width ↓

HYDRODYNAMIC CHARACTERISTICS OF RFB-SGs: Theor. considerations

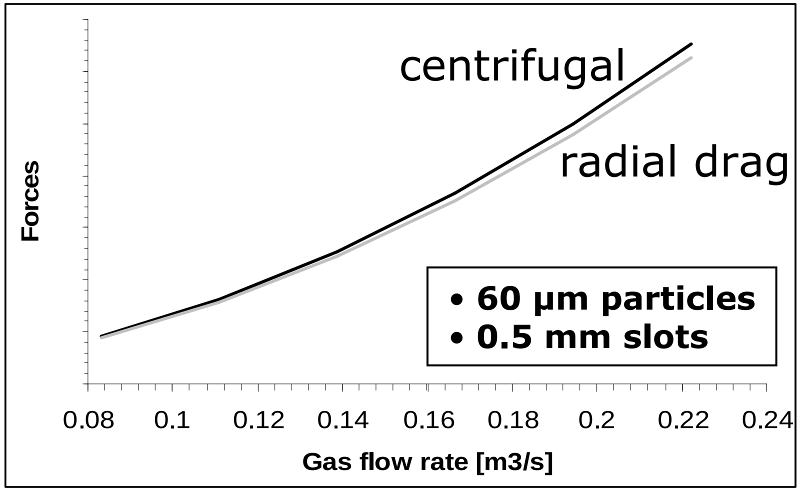
FLOW PATTERN: INFLUENCE OF THE TYPE OF PARTICLES

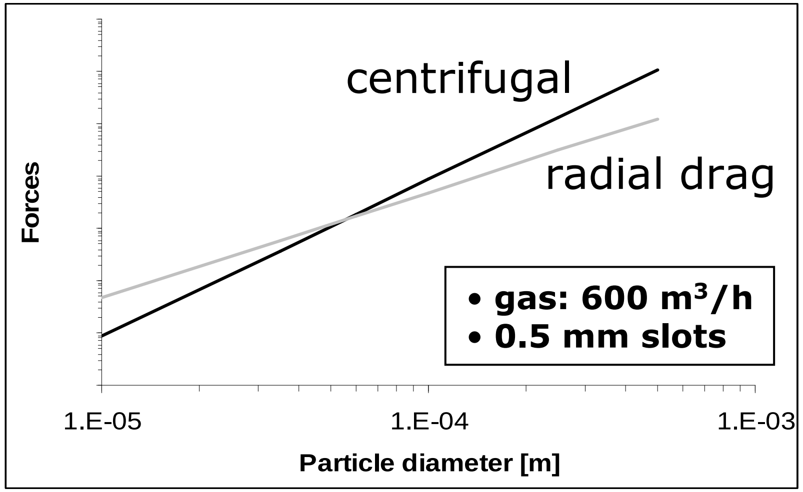
INTERFACIAL MOMENTUM TRANSFER

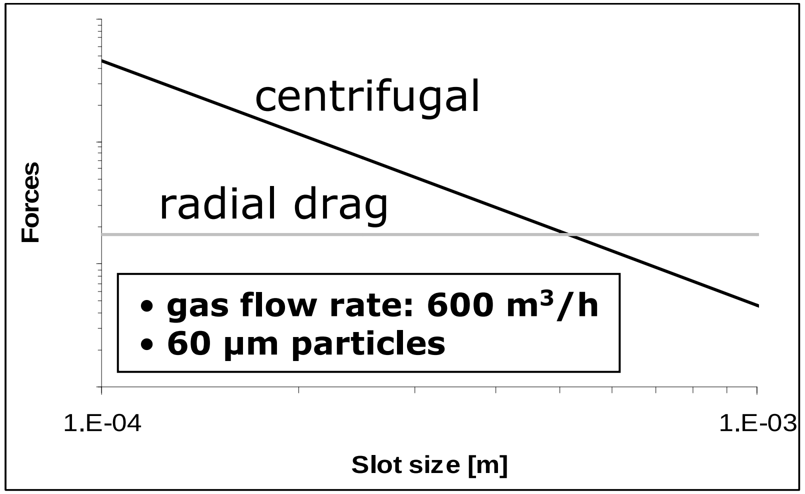
Theoretical case study:
- 24 cm diameter reactor
- 72 slots
- ρ_g: 1 kg/m^3
- ρ_s: 1500 kg/m^3

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

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





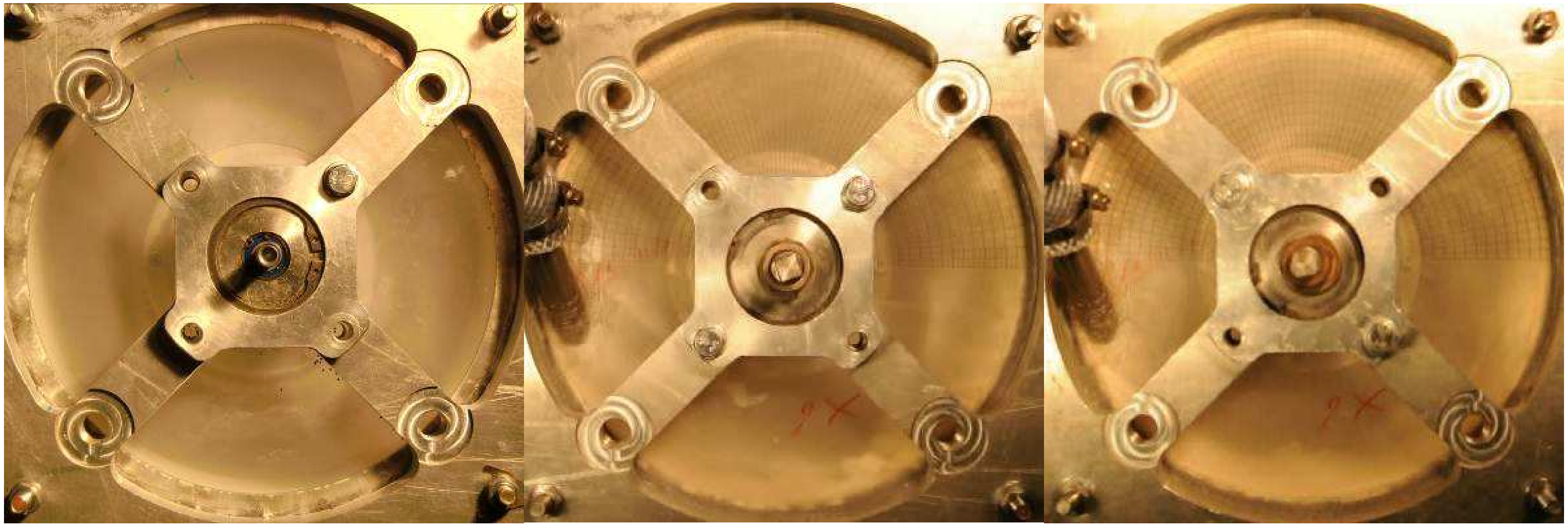


HYDRODYNAMIC CHARACTERISTICS OF RFB-SGs: Experimental study

DESIGN CONSIDERATIONS

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

Different reactor designs, given gas and solids feeding rates

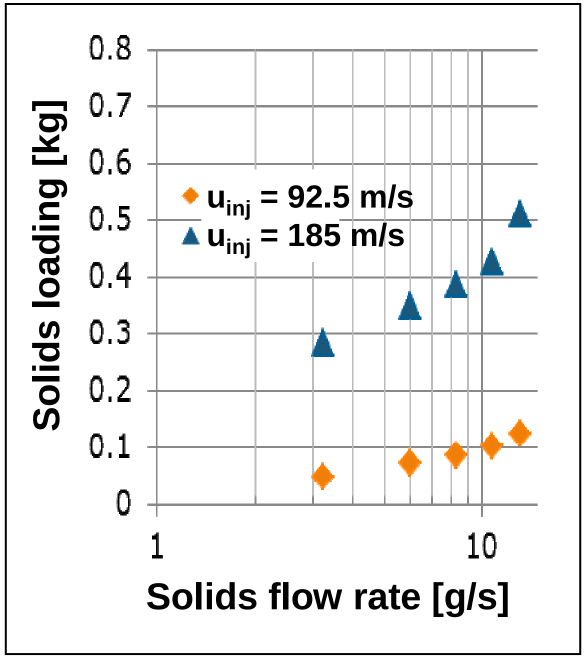


24 slots	72 slots	36 slots
slot width=3mm	slot width=0.5mm	slot width=0.5mm
u_{inj} = 54 m/s	u_{inj} = 108 m/s	u_{inj} = 216 m/s

u_{inj} ↑ => Solids retention ↑

HYDRODYNAMIC CHARACTERISTICS OF RFB-SGs: Experimental study

DESIGN CONSIDERATIONS



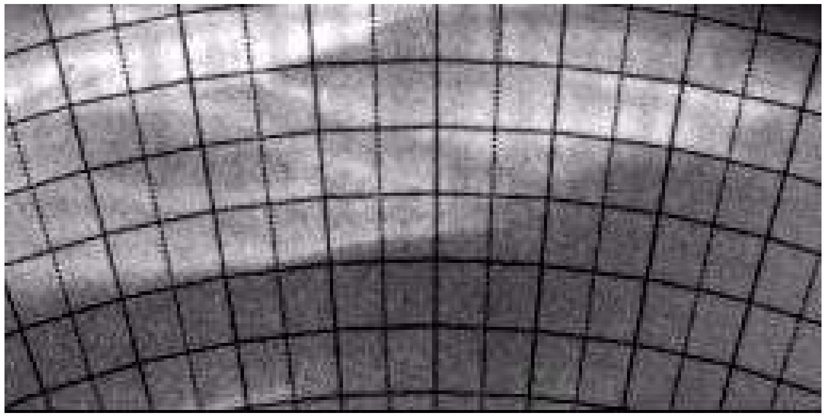
INTERFACIAL MOMENTUM TRANSFER

- Reactor diameter = 24 cm
- 70 µm FCC catalyst (1G Geldart A type)
- 36 or 72, 0.5 mm gas inlet slots
- F_g = 600 Nm³/h

u_{inj} ↑ => - Solids retention ↑
ΔP_{inj} ↑ => - Improved bed uniformity
(tangential & axial !)

F_s = 13.5 g/s

72 gas inlet slots, u_{inj} = 93 m/s



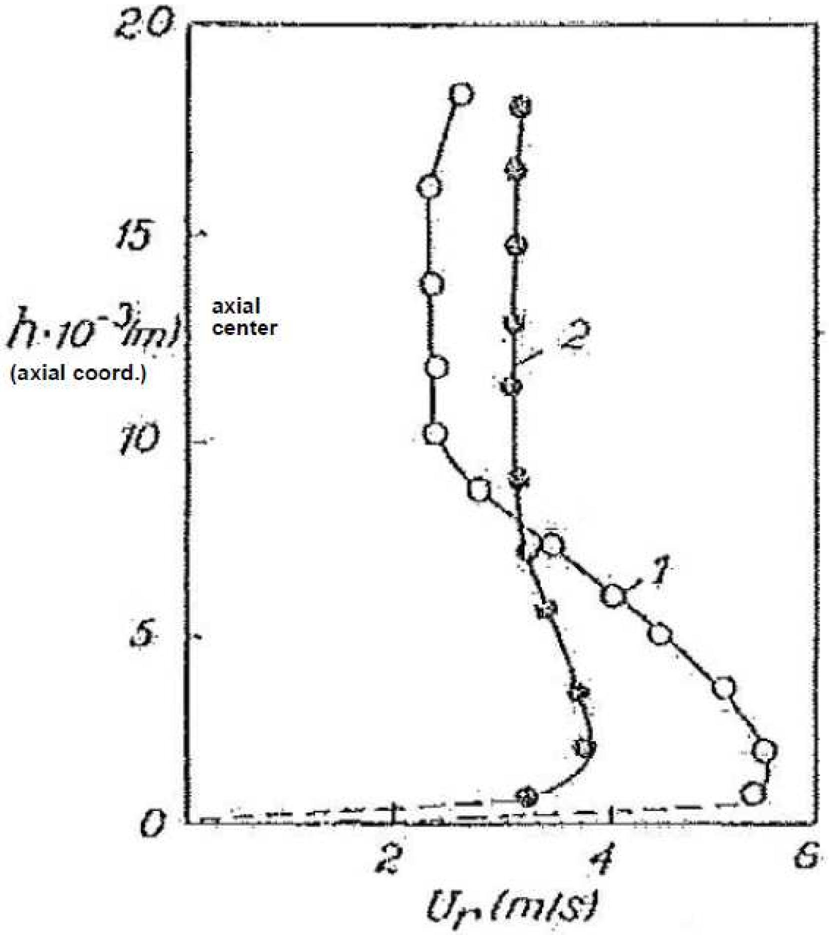
Rapid camera: 1 kHz

36 gas inlet slots, u_{inj} = 185 m/s

Denser + Improved **axial** bed uniformity

DESIGN CONSIDERATIONS

AXIAL BED UNIFORMITY



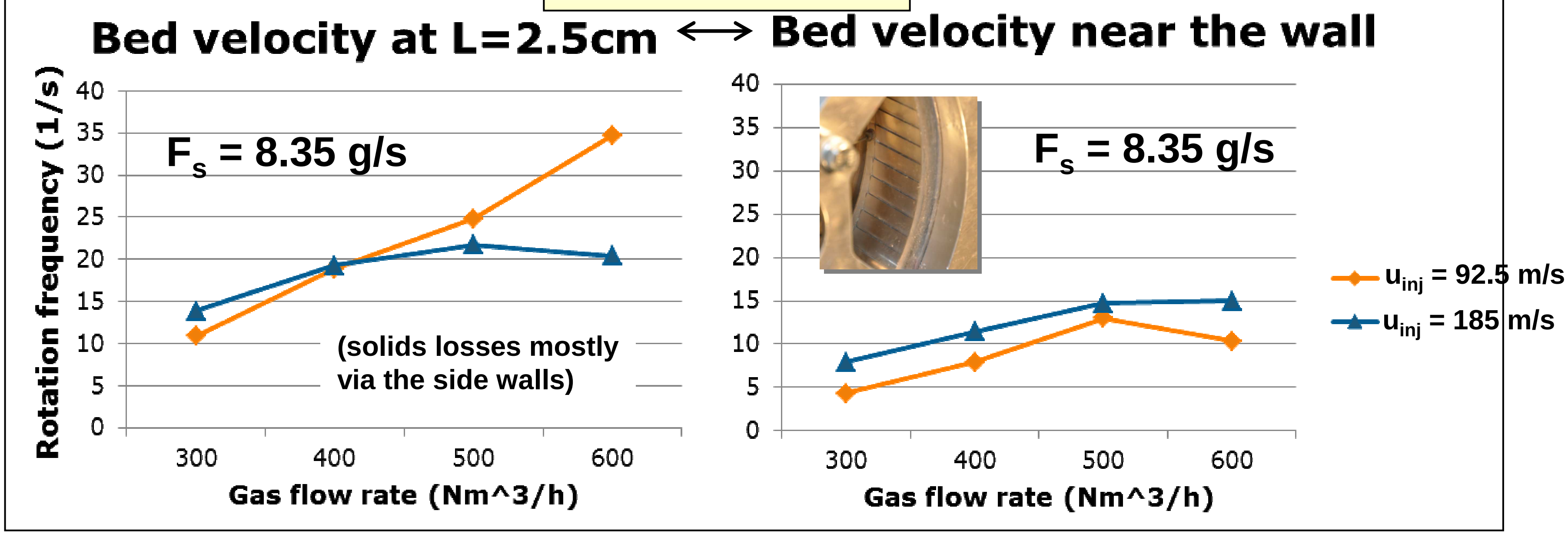
Problem of boundary layer flow

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.]

HYDRODYNAMIC CHARACTERISTICS OF RFB-SGs: Experimental study

DESIGN CONSIDERATIONS

AXIAL BED UNIFORMITY

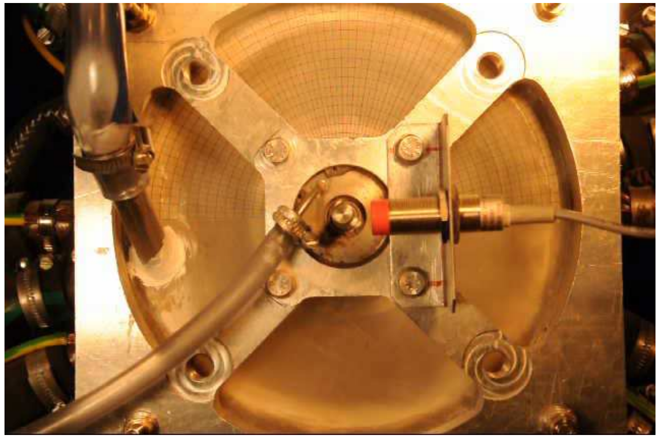


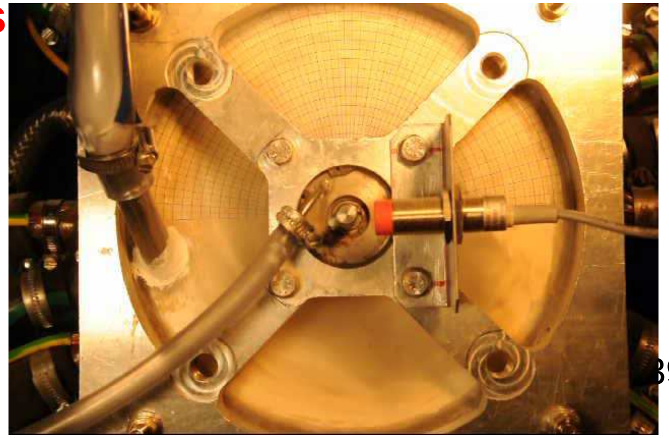
Behavior at higher solids feeding rates / solids loadings:

F_s = 8.35 g/s

36 gas inlet slots,
u_{inj} = 185 m/s

F_s = 20.08 g/s





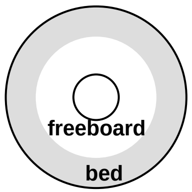
Other aspects:
- Chimney design
- Solids feeding and removal design

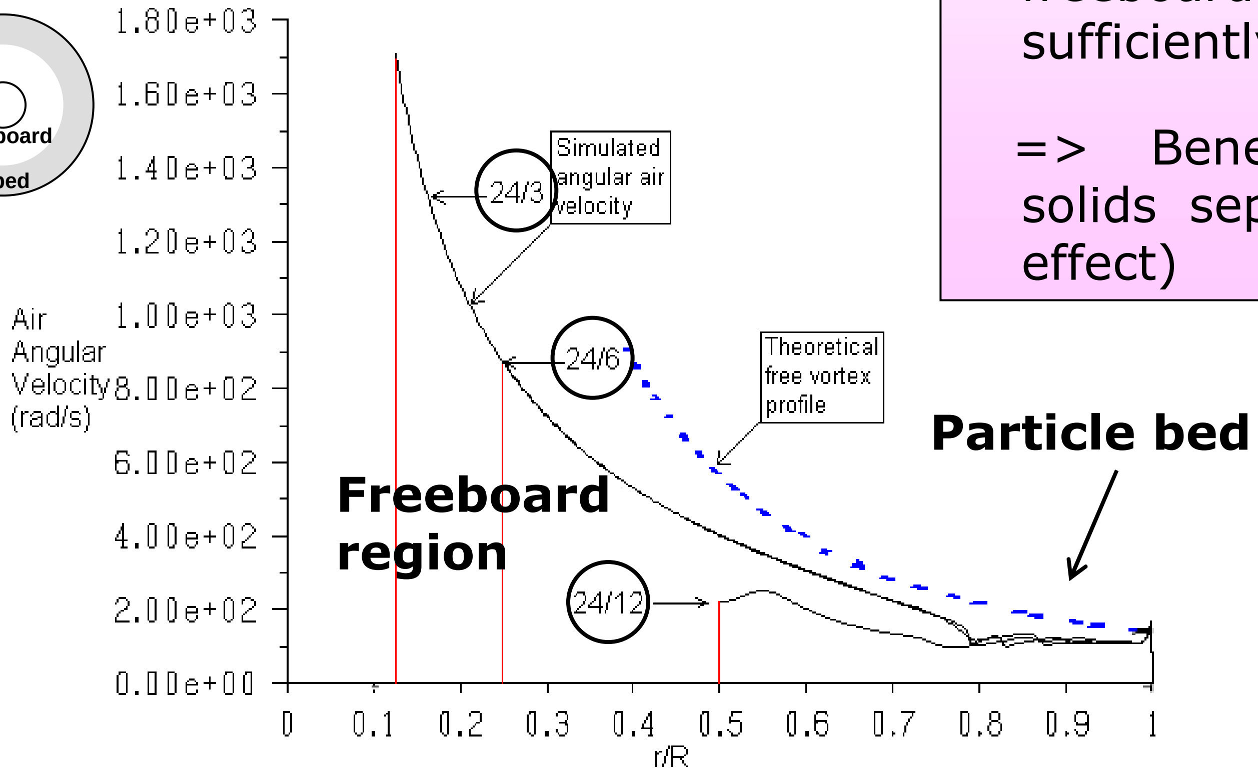
CFD study:
- 24 cm diameter reactor
- chimney diameter: 3, 6, 12 cm
- ρ_g: 1 kg/m³, ρ_s = 1500 kg/m³
- d_p = 60 μm
- Ξ solids loading & gas flow rate

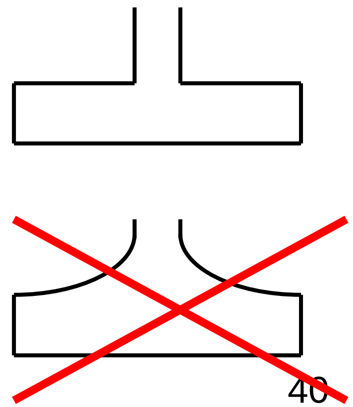
- Free vortex type flow pattern destroyed in the presence of solids

- Free vortex type flow pattern in the particle bed freeboard region with sufficiently small chimney

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



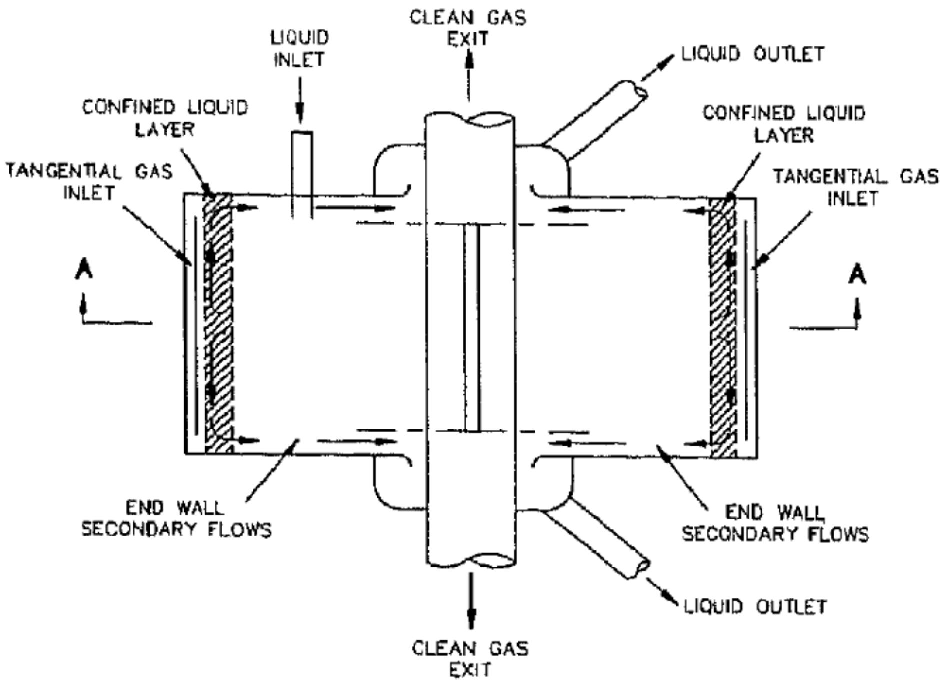




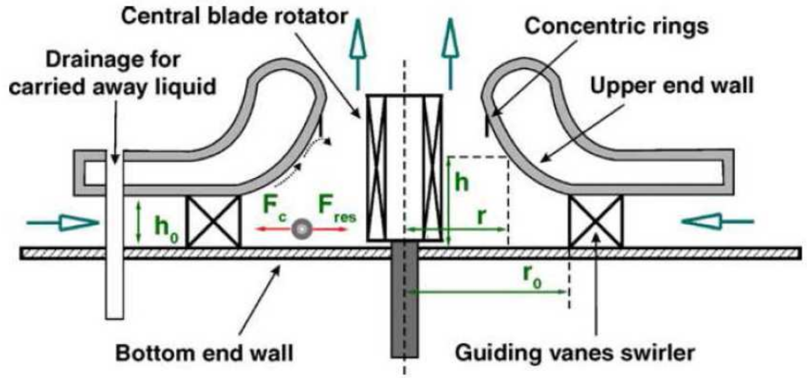
(Kuzmin et al., 2005)

HYDRODYNAMIC CHARACTERISTICS OF RFB-SGs: Design considerations

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



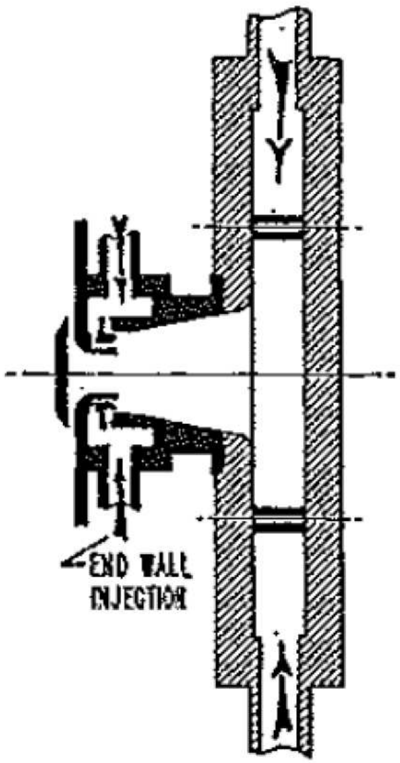
Dual-chimney design with cyclone flow exit tube with a guide slot. Gas-liquid flow with specific liquid outlet design. (From Loftus et al., 1992.)



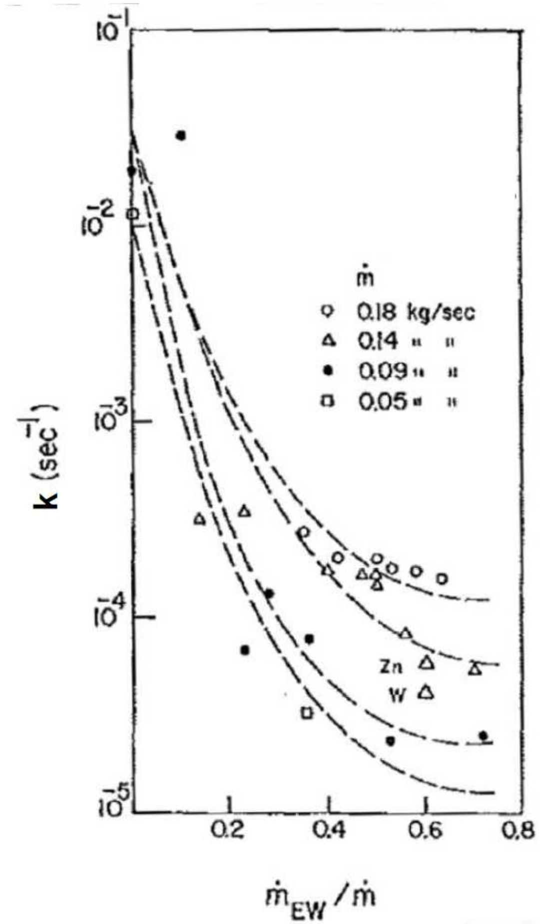
Profiled end wall and concentric ring. (From Kuzmin et al., 2005.)

HYDRODYNAMIC CHARACTERISTICS OF RFB-SGs: Design considerations

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



(a)



(b)

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.)

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

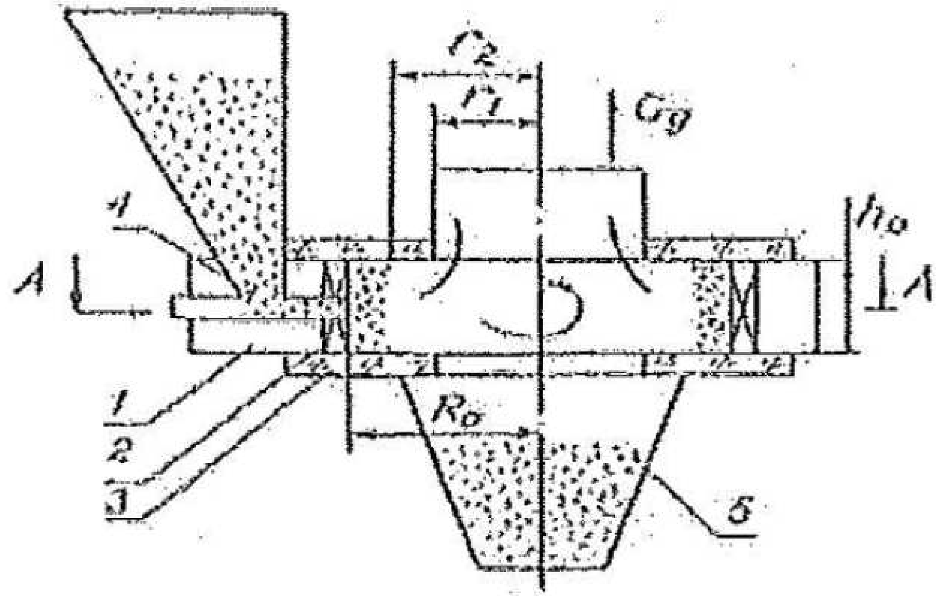
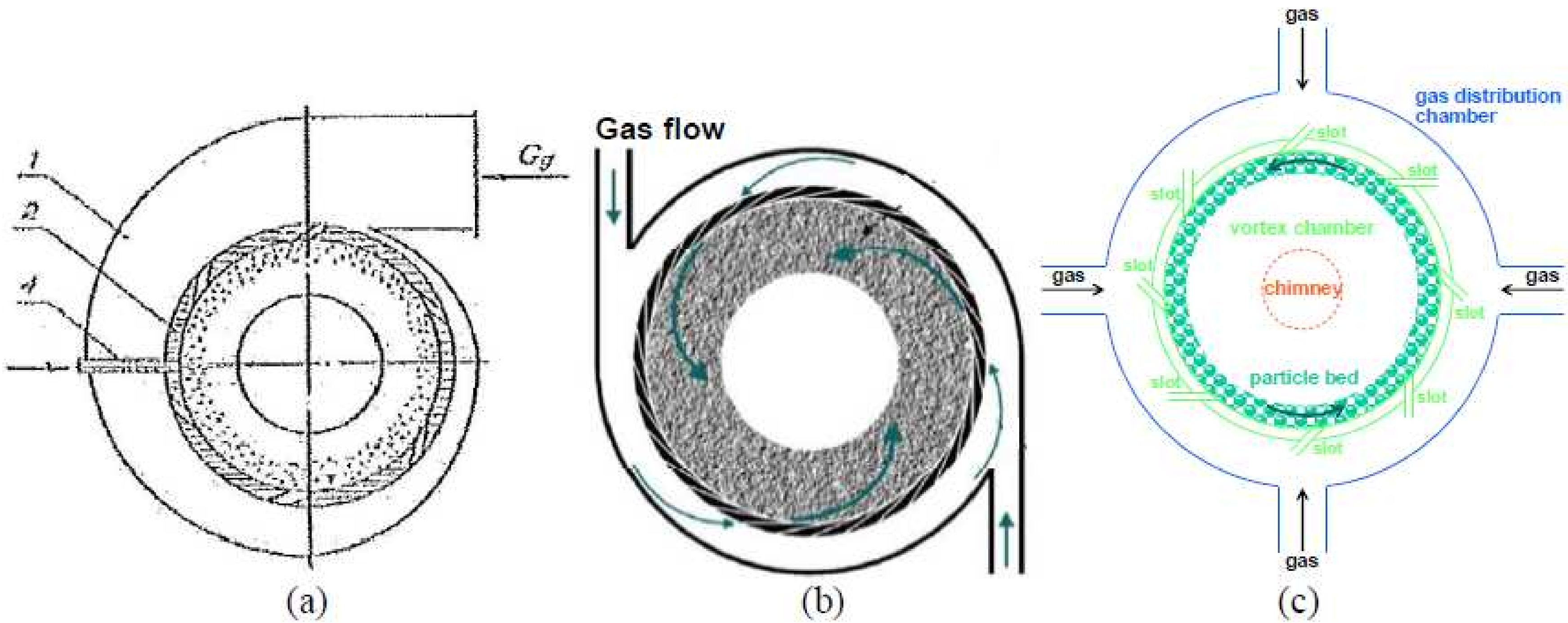


Figure 4.5.1. (a) Vortex chamber with a cyclone type system for the recovery of the solids. 1. Gas distribution chamber (helix); 2. vortex chamber; 3. end walls; 4. solids feeder; 5. hopper. (From Volchkov et al., 1993.) (b) Different configurations for combining in- and outflow via the slots. (From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

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



- **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

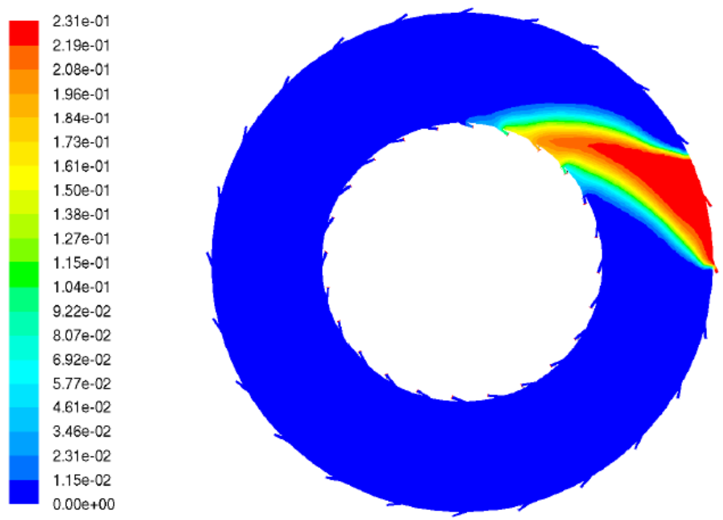
- **Hydrodynamics in the particle bed freeboard region important**

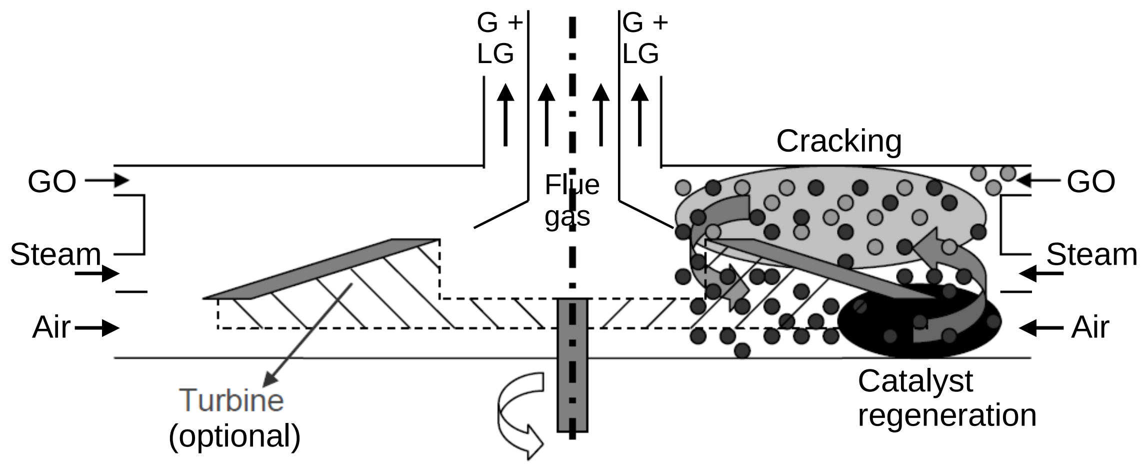
  Smaller / lighter particles

  => - Smaller chimney diameter (free vortex, Coriolis effect)

  - Separate and carefully designed solids outlet

FULL PI POTENTIAL: MULTI-ZONE OPERATION: RFB-SG AND CRFB TECHNOLOGIES





CRFB technology

Tangential

Longitudinal

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

ATTRITION

36-cm DIAMETER FLUIDIZATION CHAMBER

- **1G GELDART D PARTICLES**

• 1.8 kg solids
• 2 h 45 min residence time

⬇

losses (fines): 0.3 - 0.5 g

- **1G GELDART B PARTICLES (SALT)**

• 2.5 kg solids
• 10 min residence time

⬇

losses: coating detached

OUTLINE

- **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**

POTENTIAL APPLICATIONS OF RFB-SGs:

Opportunities: Process Intensification potential:

- Dense bed at high gas(-solid slip) velocities
- Improved bed uniformity (reduced bubbling, temperature)
  - $\Rightarrow$ Increased gas-solid mass and heat transfer coefficients
  - $\Rightarrow$ Improved gas-solid contact
- Unique flexibility in the fluidization gas flow rate
- High particle bed width-to-height ratio
  - $\Rightarrow$ Short gas phase residence times
  - $\Rightarrow$ Higher reaction temperatures, more active catalysts
- Multi-zone operation
  - $\Rightarrow$ Higher catalyst circulation rates

POTENTIAL APPLICATIONS OF RFB-SGs:

Challenges:

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

Small gas phase residence time

➡ Conversion limited ?

- Gas phase density variations due to reactions

➡ 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

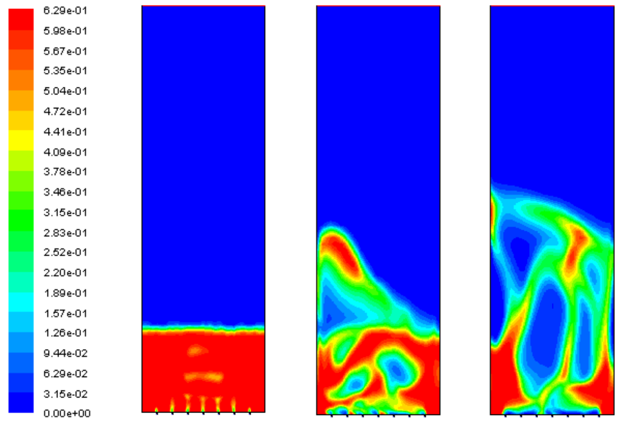
- **RESPONSE OF PARTICLE BED TEMPERATURE TO STEP CHANGE IN THE FLUIDIZATION GAS TEMPERATURE FROM *300 K* TO *400 K* AT TIME t_0**
- **EULERIAN-EULERIAN APPROACH WITH KINETIC THEORY OF GRANULAR FLOW**
- **PARTICLES: 700 µm, 2500 kg/m^3**
- **RESTITUTION COEFFICIENT: PARTICLE-PARTICLE: 0.95**
- **RESTITUTION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

PARTICLE BED UNIFORMITY

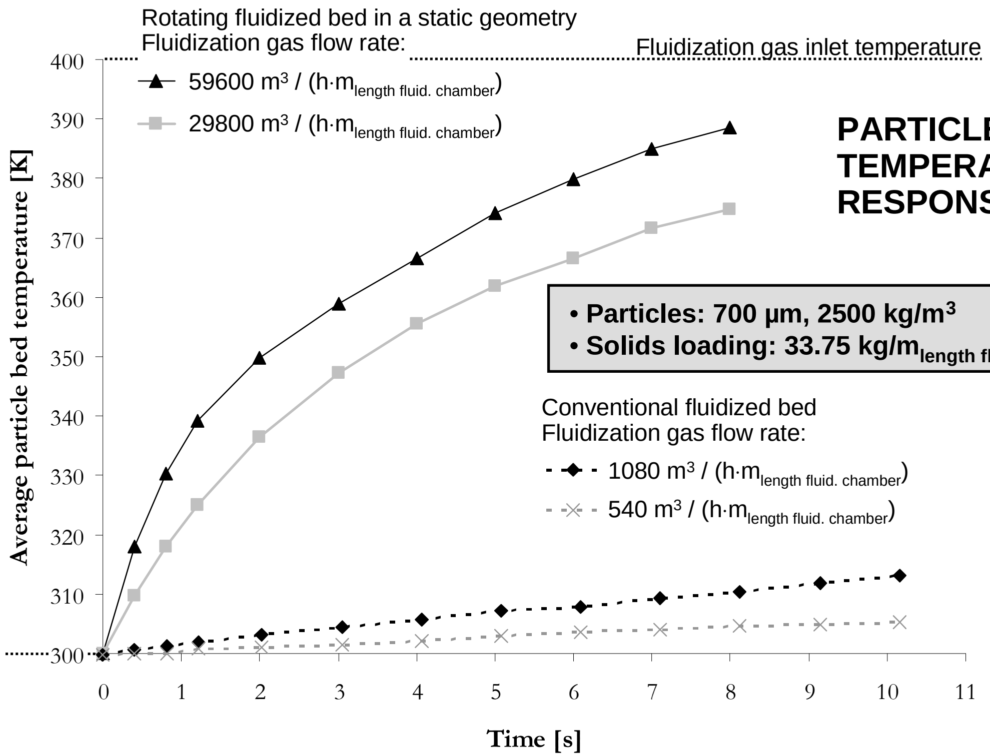
CONVENTIONAL FLUIDIZED BED



SOLIDS VOLUME FRACTION

195 m²/h — 540 m²/h — 1080 m²/h

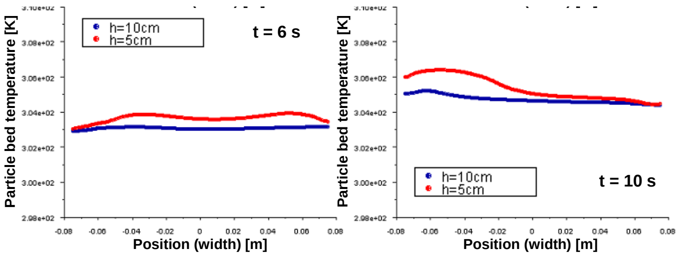
FLUIDIZATION GAS FLOW RATE



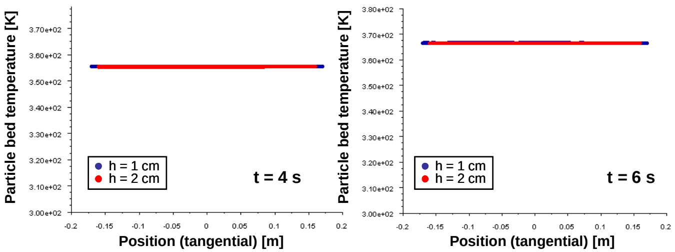
PARTICLE BED TEMPERATURE RESPONSE

- **Particles: 700 μm, 2500 kg/m³**
- **Solids loading: 33.75 kg/m$_{\text{length fluid. cham.}}$**

PARTICLE BED TEMPERATURE UNIFORMITY

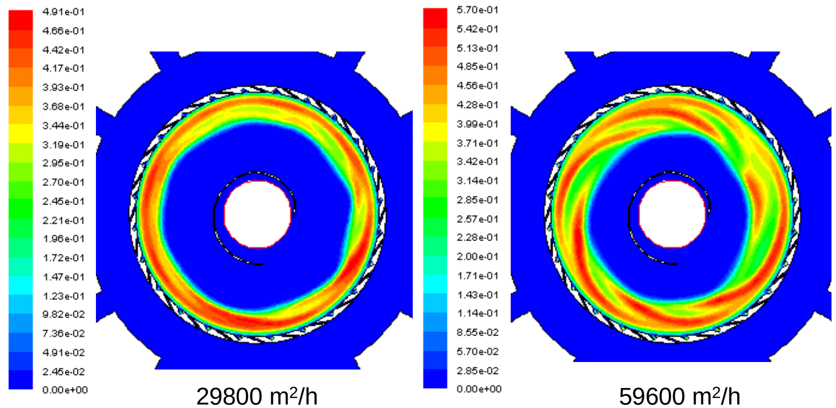


Conventional fluidized bed
Fluidization gas flow rate = 540 m³ / (h·m$_{\text{length fluid. chamber}}$)



Rotating fluidized bed in a static geometry
Fluidization gas flow rate = 29800 m³ / (h·m$_{\text{length fluid. chamber}}$)

ROTATING FLUIDIZED BED IN A STATIC GEOMETRY



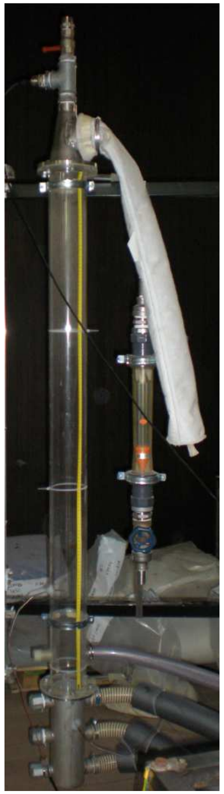
SOLIDS VOLUME FRACTION

29800 m²/h — 59600 m²/h

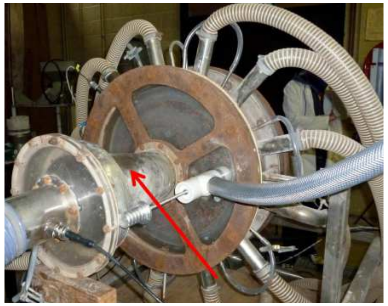
FLUIDIZATION GAS FLOW RATE

POTENTIAL APPLICATIONS OF RFB-SGs: Exp. study of biomass drying

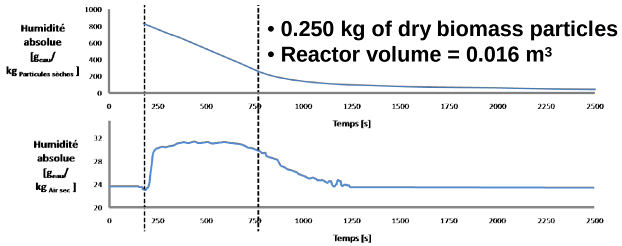
BATCH AND CONTINUOUS OPERATION



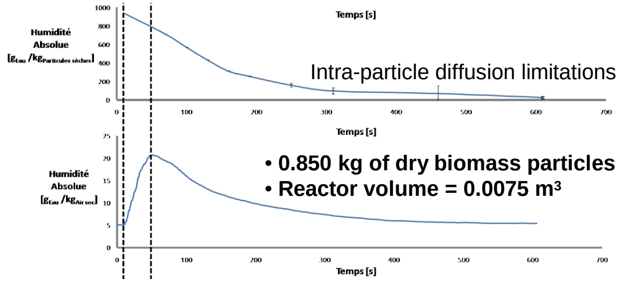
Conv. FB



RFB-SG



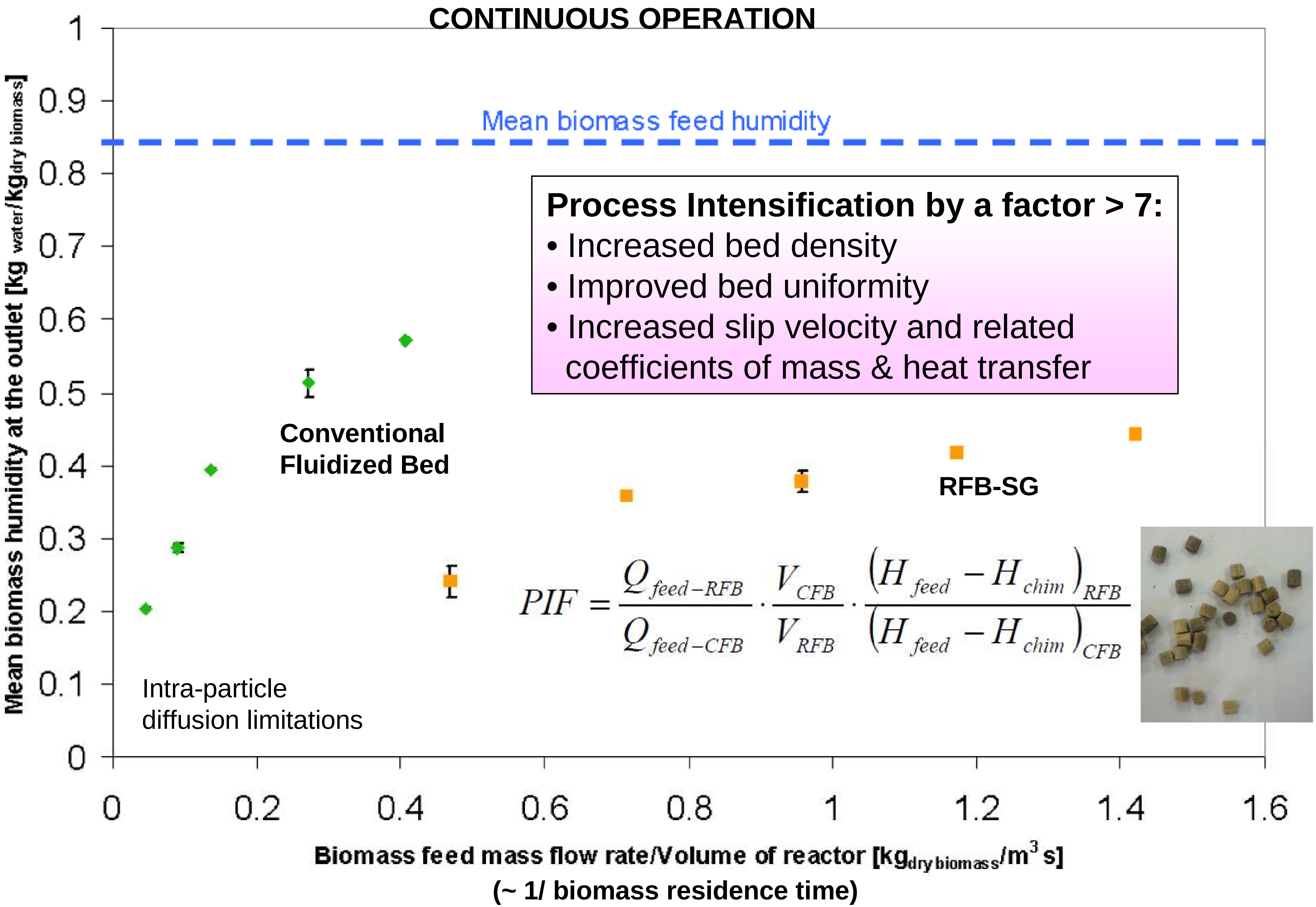
Conv. FB



RFB-SG

Continuous operation	Conventional fluidized bed	Rotating fluidized bed in a static geometry
Dimensions	D = 0.10 m H = 2.00 m	D = 0.43 m D(chimney) = 0.10 m L = 0.05 m
Gas distribution	Cone and perforated plate	72, 30° inclined gas inlet slots
Solids feeding	Via side wall at h = m	Via end plate
Particle characteristics	Pelletized wood, cylindrically shaped, d_p = 4 mm, h_p = 4 mm (no intra-particle diffusion limitations)	
Operating conditions		
T [K]	318	
P_{out} [Pa]	101300	
Gas mass flow rate [Nm^3/h]	110	700
Solids mass flow rate [g wet solids / s]	1, 2, 3, 6, 9	3, 6, 9, 12, 15, 18
Solids inlet humidity [g water / kg dry solids]	850	

POTENTIAL APPLICATIONS OF RFB-SGs: Exp. study of biomass drying

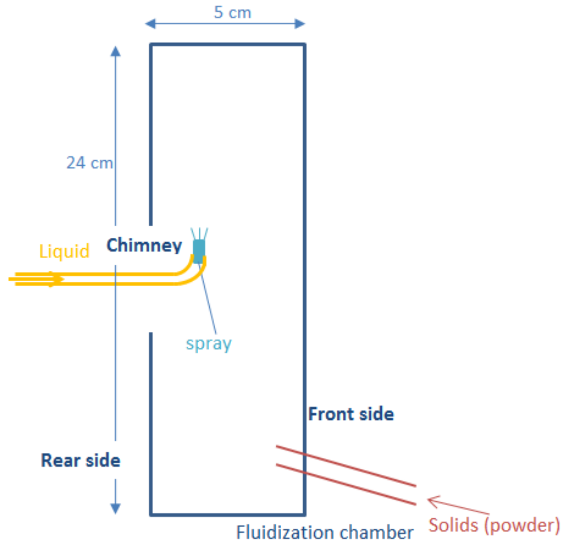


POTENTIAL APPLS. OF RFB-SGs: Coating/granulation of cohesive particles

Operating variable	Units	Value		
Air flow rate	Nm^3/h	250	400	
Pressure before air distributor	mbar	300-370	540-650	
Air inlet temperature	°C	55		
Powder feeding rate	g/s	2	2	2, 3.72, 6.17
Air atomisation pressure	bar	1.5	1.5	3
Coating solution feeding rate	g/s	1	1	1.63
Droplets mean size	µm	70	70	60
Coating solution feeding time	s	5, 15, 30, 60	3, 5, 15, 30, 60	5
Temperature of the water in the double casing of the coating solution tank	°C	90		
Weight percent of coating material in the coating solution	wt.-%	50		

Measurements:

- Operating conditions (P, T, Fg, …)
- Quantity of coated particles produced
- Agglomeration: Particle size distribution
- Coating quality:
    - Active component release test
    - SEM pictures



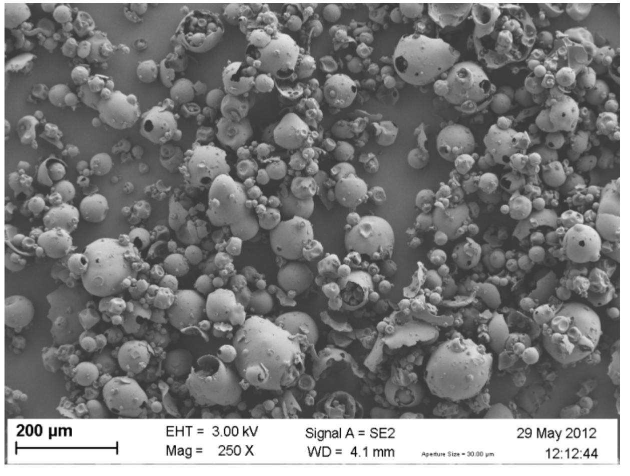
POTENTIAL APPLS. OF RFB-SGs: Coating/granulation of cohesive particles

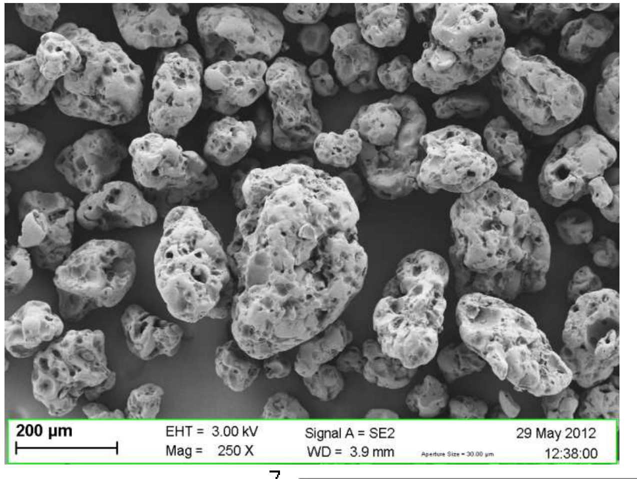
Other operating conditions: atomising air pressure of 1.5 bar, solids feeding rate of 2 g/s

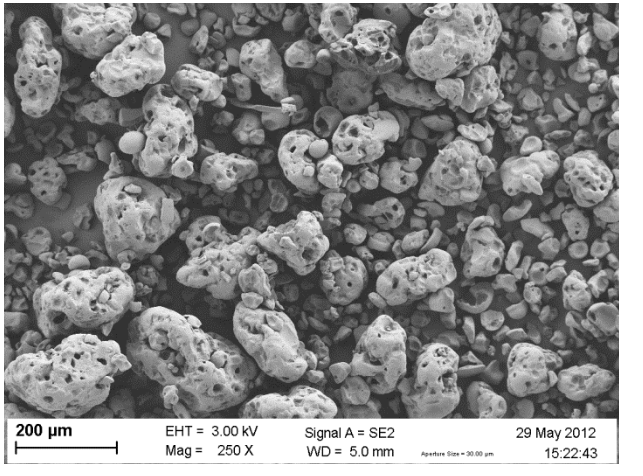
original powder

coated powder
t_{inj} = 5 s
250 Nm^3/h

coated powder
t_{inj} = 5 s
400 Nm^3/h

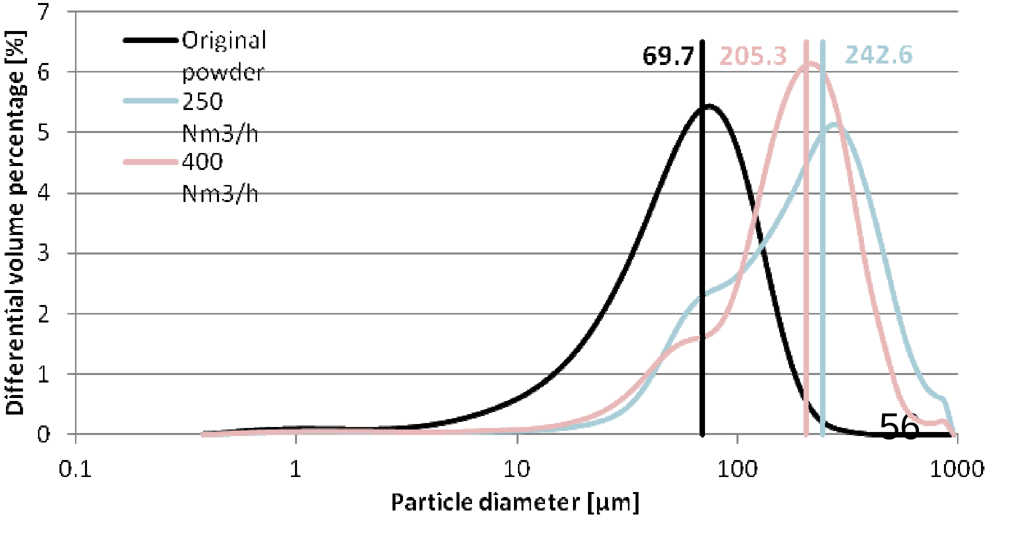






Visual inspection (SEM):

- Limited agglomeration (< 4 particles)
- Low level considering droplet size & relatively low T

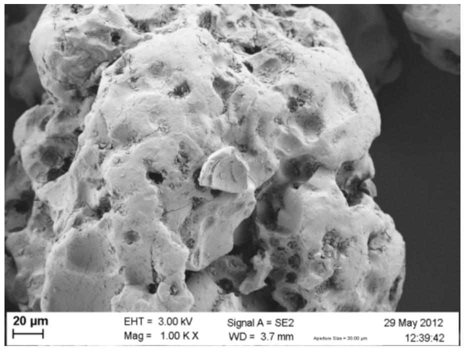


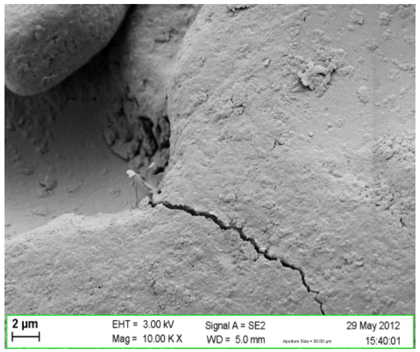
POTENTIAL APPLS. OF RFB-SGs: Coating/granulation of cohesive particles

Particles morphology & Coating quality: Active component release test

Powder	Core material component %	Active component release	Coating (g/g)	Active component release reduction
Original powder	73.7	0.6	-	-
250 Nm3/h coated powder	46.4	0.24	0.59	**60%**
400 Nm3/h coated powder	46.6	0.24	0.58	**60%**

- 60% reduction release active component
  → few cracks & cavities
- 58 $g_{coating}$ /100 $g_{uncoated}$
  → on average 1.22 µm coating
  (assuming 70µm spherical uncoated particles)





few cracks

Simulation set-up: Model

Fluid Catalytic Cracking

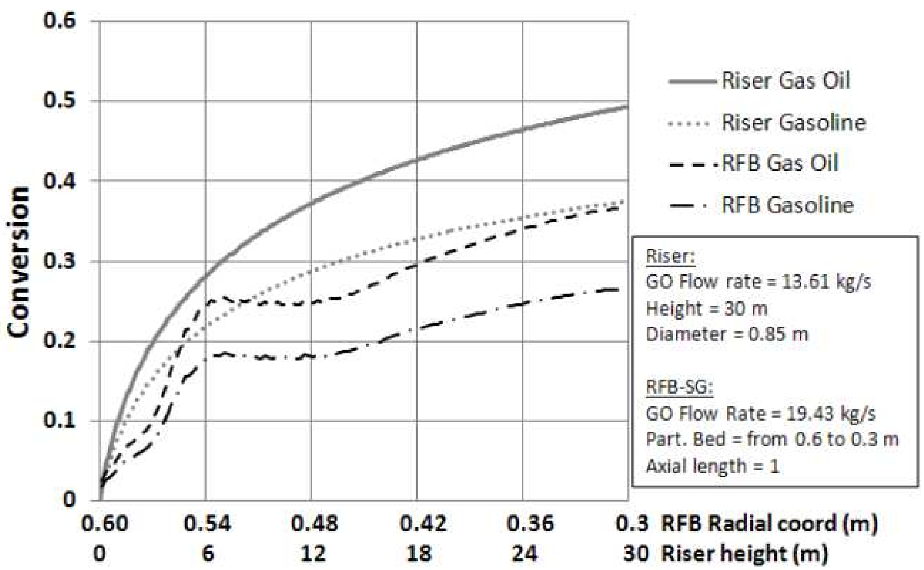
Hydrodynamics:	Reaction kinetics:
• Two-fluid model	• 10-lump model
• Kinetic Theory of Granular Flow	• C-lump split (LG and coke)
• k-ε turbulence model	• Heavy aromatics adsorption
• Solid walls B.C.:	• Catalyst deactivation (coke)
• Gas phase: no slip	
• Solid phase: partial slip	

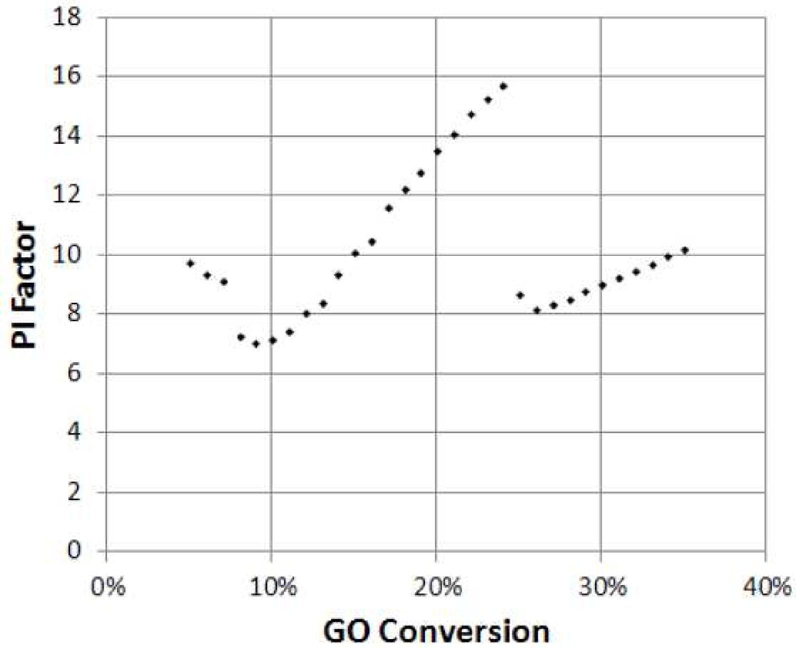
Grid independency:

- 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

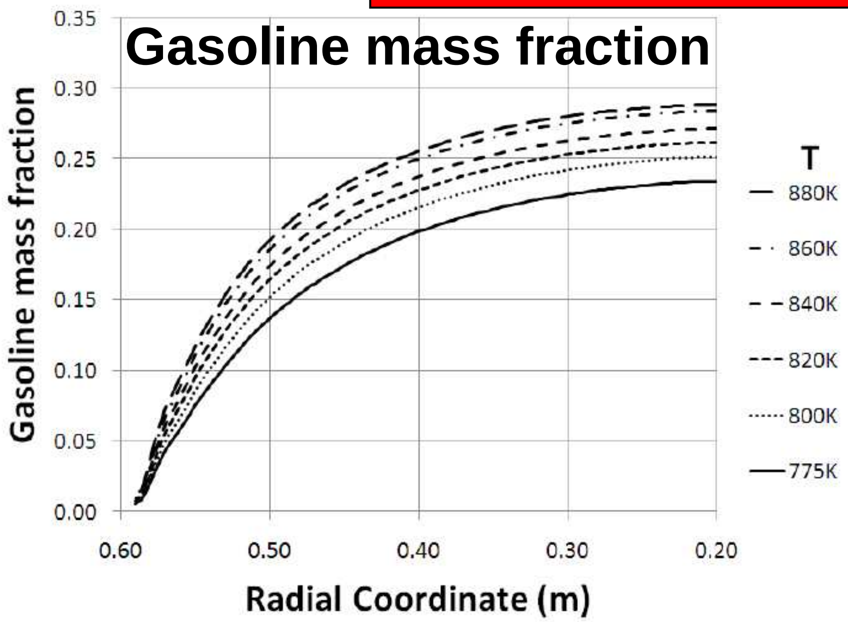


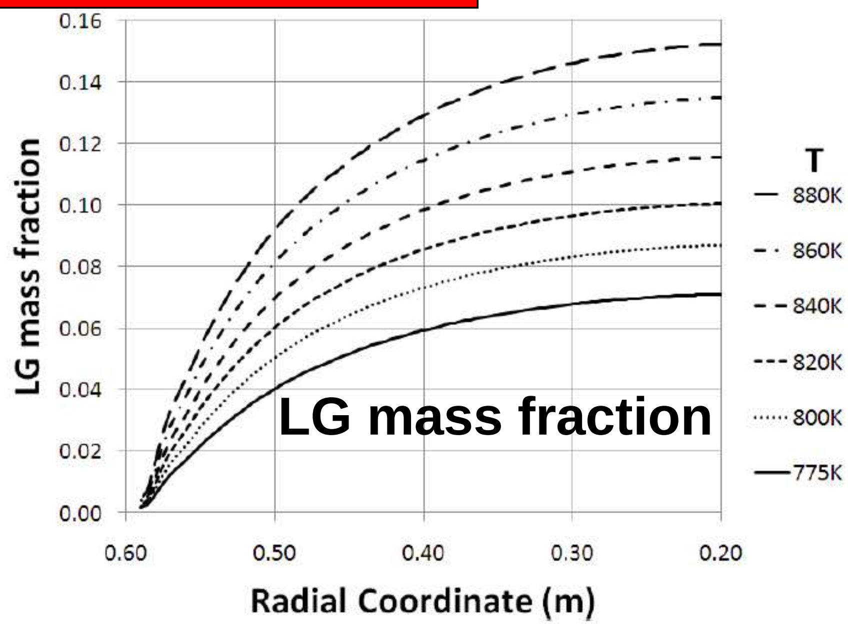


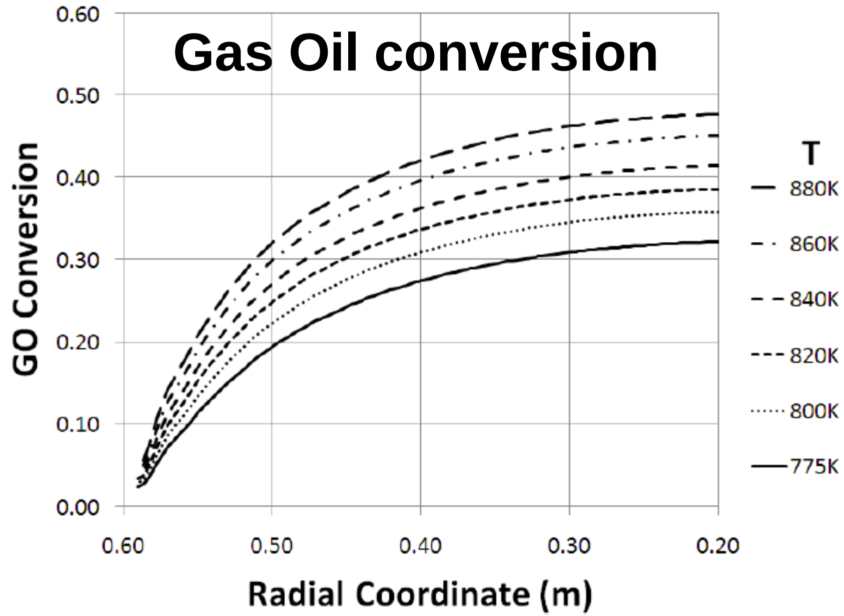
- Conversion not as high as in a CFB riser (non-optimized geometry) but sufficiently high
- PI factor between 7 and 16, depending on the GO conversion

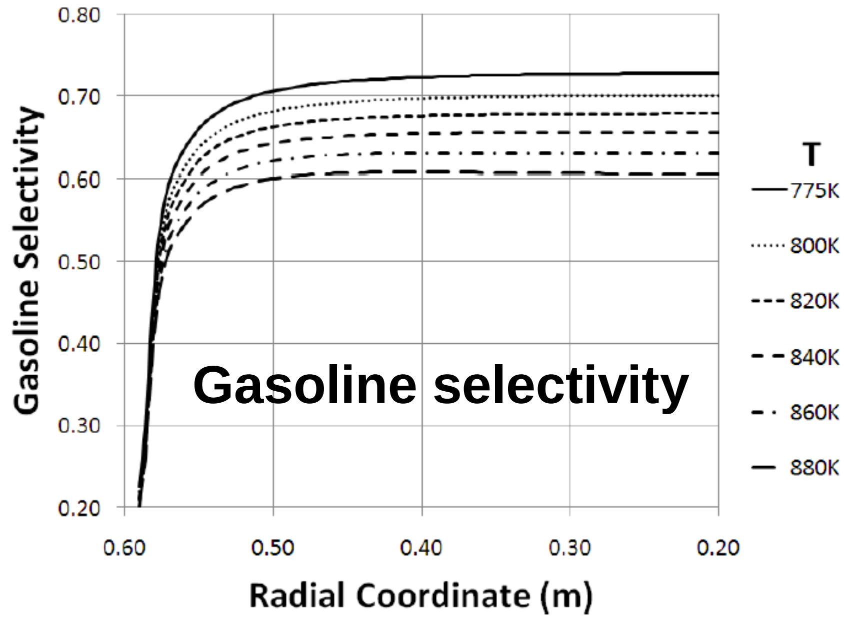
POTENTIAL APPLICATIONS OF RFB-SGs: CFD study of FCC

Full PI potential: Higher cracking temperatures





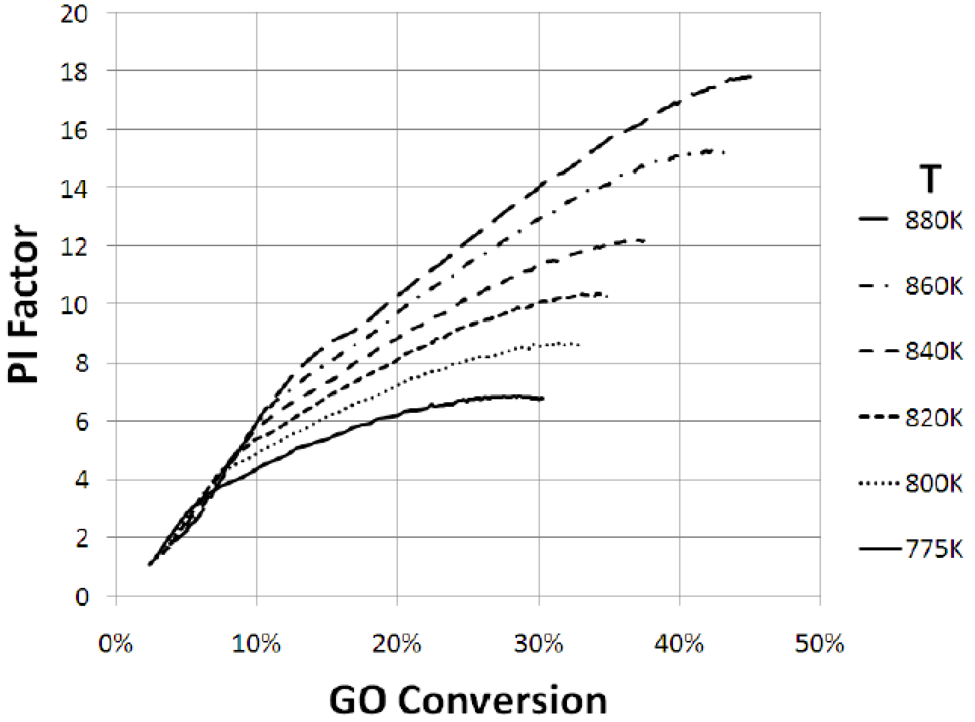




POTENTIAL APPLICATIONS OF RFB-SGs: CFD study of FCC

Full PI potential: Higher cracking temperatures

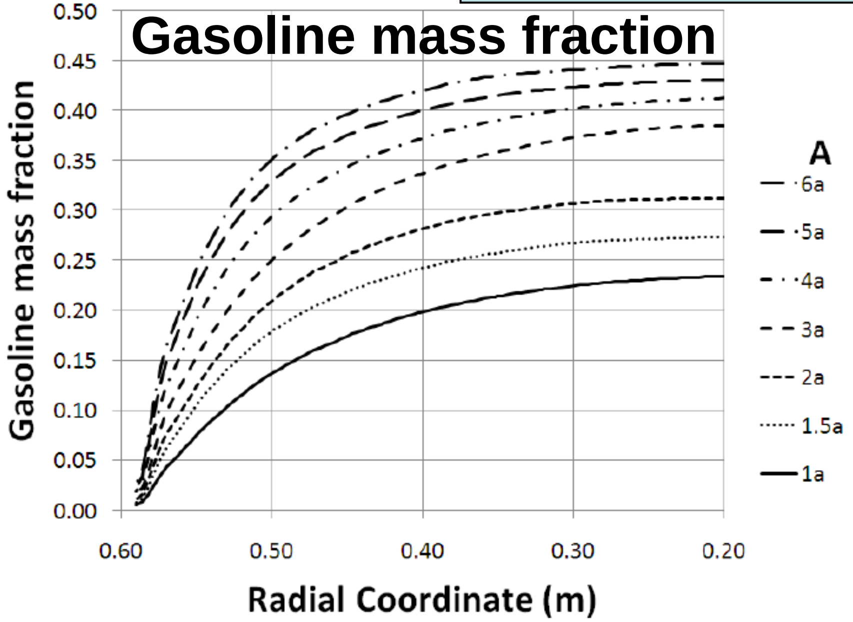
T [K]	χ_G [%]	χ_{GO} [%]	χ_G/χ_{GO} [%]	χ_{LG} [%]	$\langle \Re_c \rangle$ [kmol/(m^{3}s)]	$\langle R' \rangle \times 10^4$ [kg$_{coke}$/(kg$_{cat}$s)]	τ_{cat} [s]	N [-]	$\dot{m}_{cat}$ [kg/s]
775	23.38	32.14	72.75	7.09	0.0016	0.93	0.81	4.03	181.4
800	25.12	35.85	70.07	8.68	0.0019	1.16	0.64	3.22	222.2
820	26.16	38.55	67.84	10.03	0.0022	1.38	0.54	2.70	256.9
840	27.13	41.38	65.55	11.53	0.0025	1.63	0.46	2.28	295.1
860	28.38	45.02	63.03	13.46	0.0030	1.89	0.40	2.01	344.7
880	28.83	47.63	60.53	15.21	0.0034	2.20	0.34	1.71	389.3

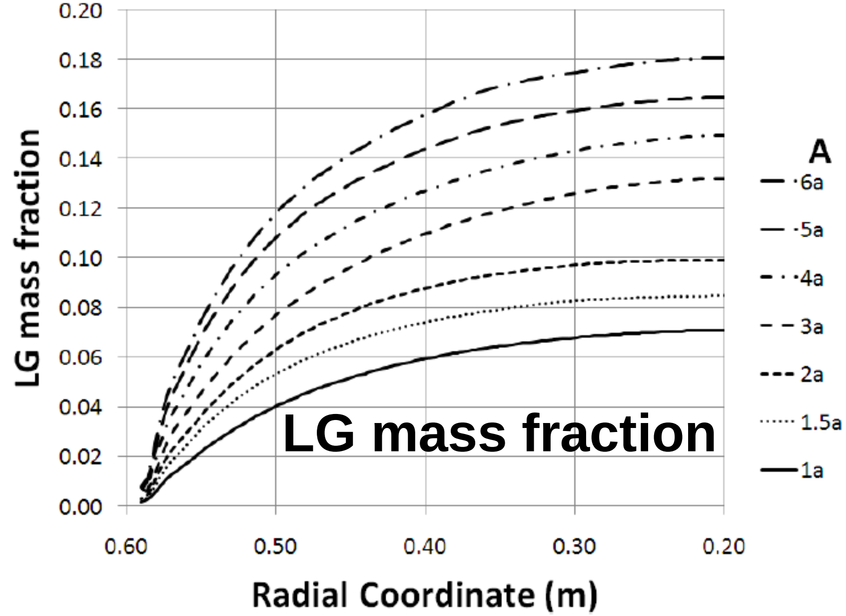


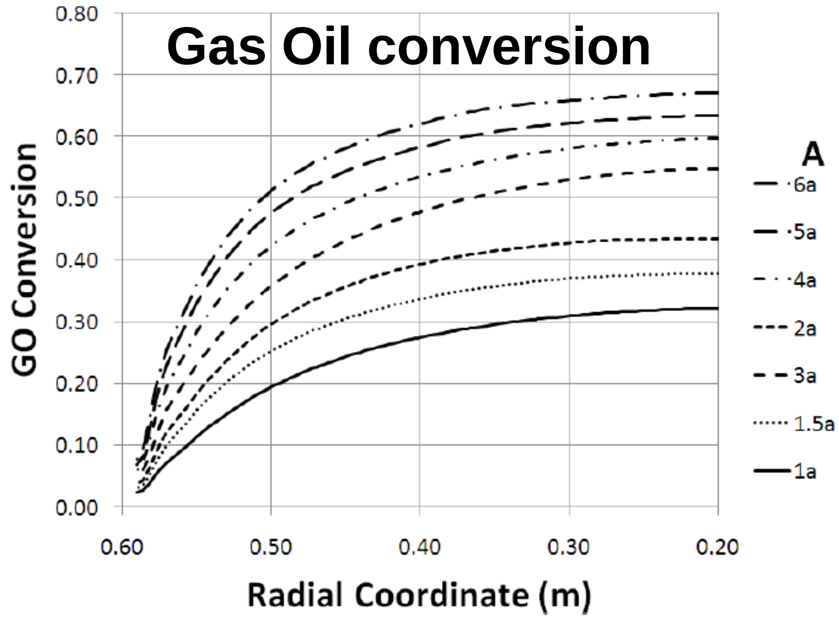
Based on a cat. coke content increase from 0.15 to 0.1575 wt%

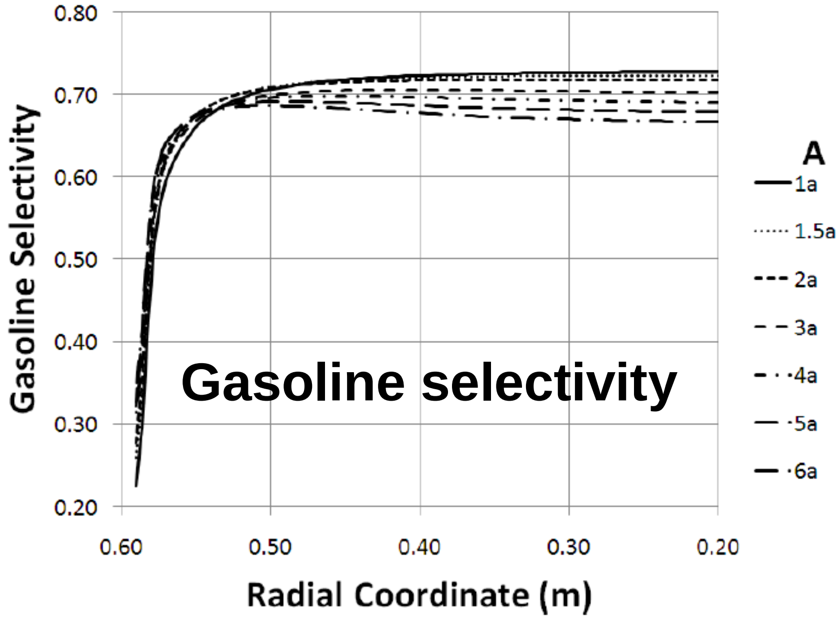
POTENTIAL APPLICATIONS OF RFB-SGs: CFD study of FCC

Full PI potential: More active catalyst





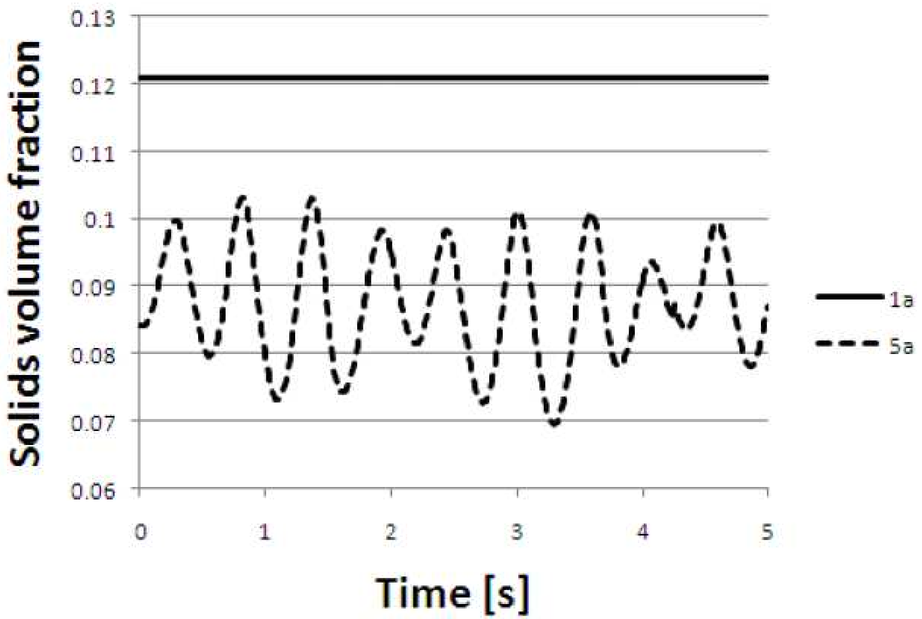


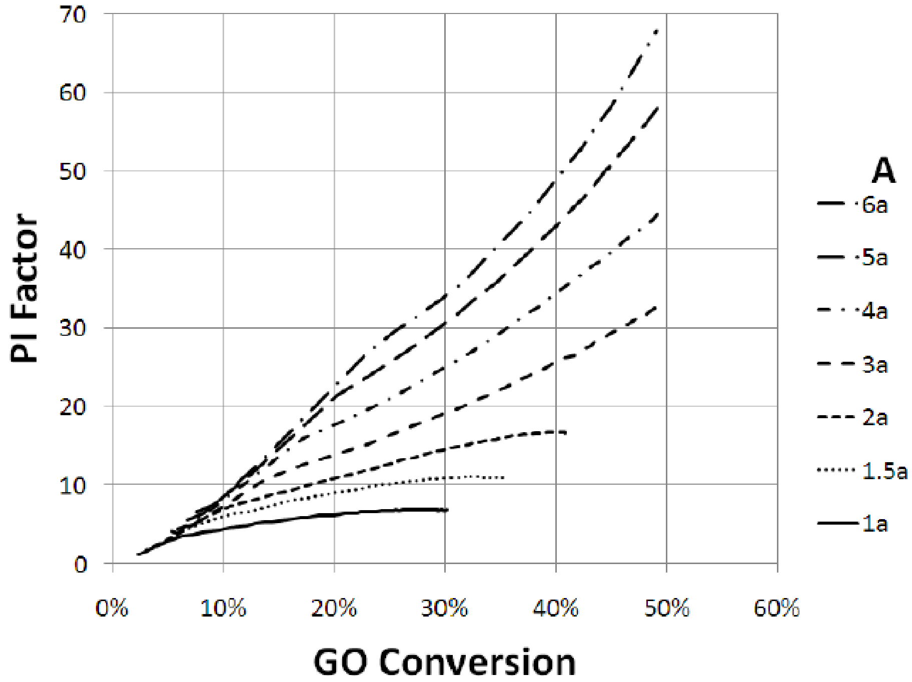


POTENTIAL APPLICATIONS OF RFB-SGs: CFD study of FCC

Full PI potential: More active catalyst

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



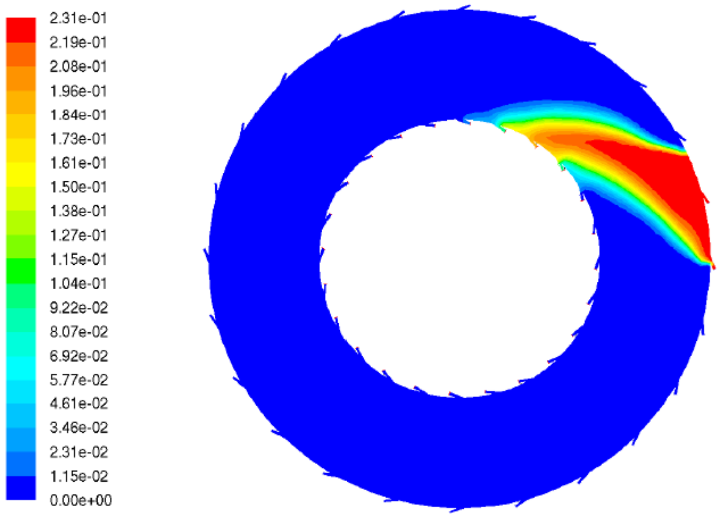


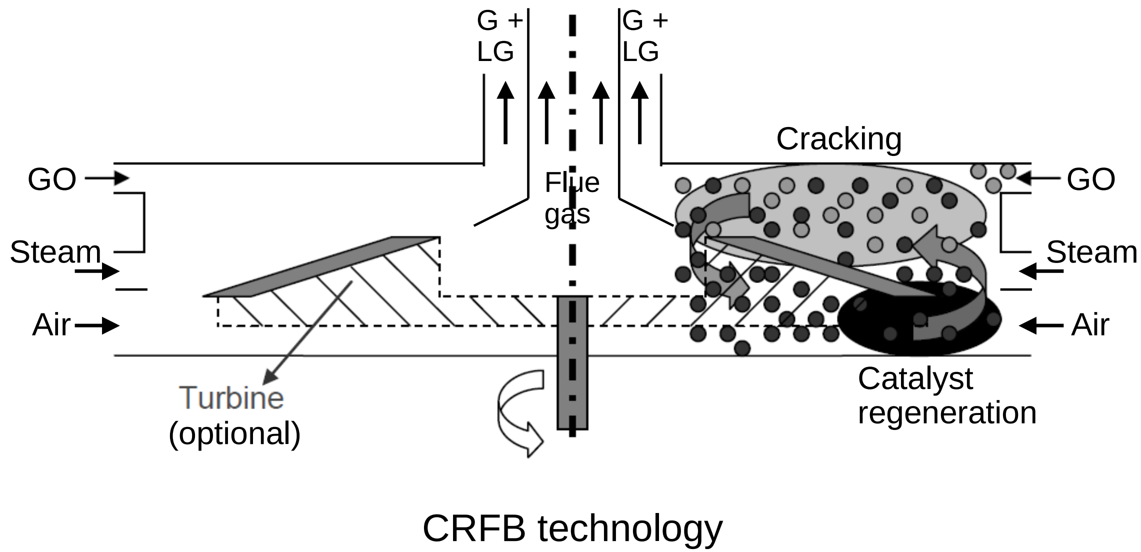
POTENTIAL APPLICATIONS OF RFB-SGs: CFD study of FCC

- 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 HETEROGENEOUS CATALYTIC PROCESSES (MTO)
- CFD STUDY:
  - DESIGN ASPECTS: IMPORATNCE 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

Full PI potential: Multi-zone operation





Tangential

Longitudinal

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

OUTLINE

- **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**

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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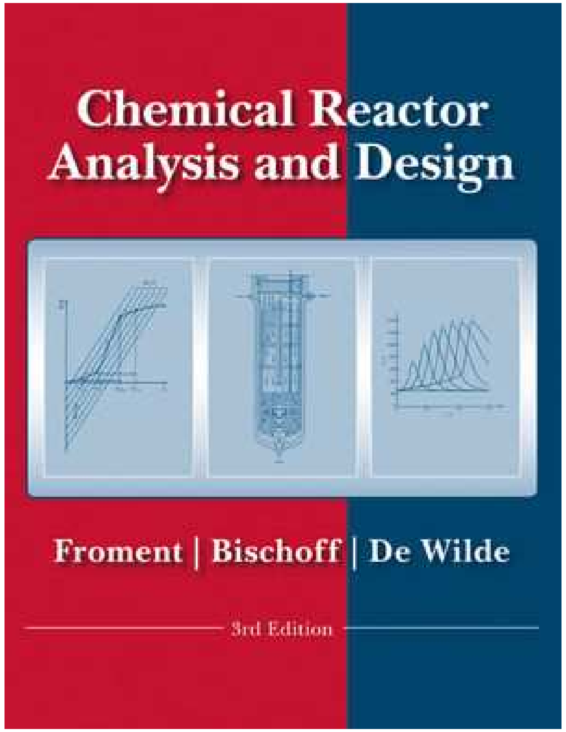

Wiley, September 2010

Thank you for your interest

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