Vortex chamber technology: Flow regimes and applications

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OUTLINE:

- **Introduction**
  - Limitations of conventional fluidized beds
- **VC-RFB**
  - Process Intensification through high-G operation
  - Flexibility in the operating conditions
- **Hydrodynamics**
  - Gas & solids flow pattern
  - Dense versus dilute flow
- **Applications**
  - Drying of granular materials and powders
  - (Fine) particle coating & granulation/agglomeration
  - Spray drying
  - Reactions
- **Conclusions & perspectives**

INTRODUCTION: Limitations of conventional fluidized beds: Bubbling

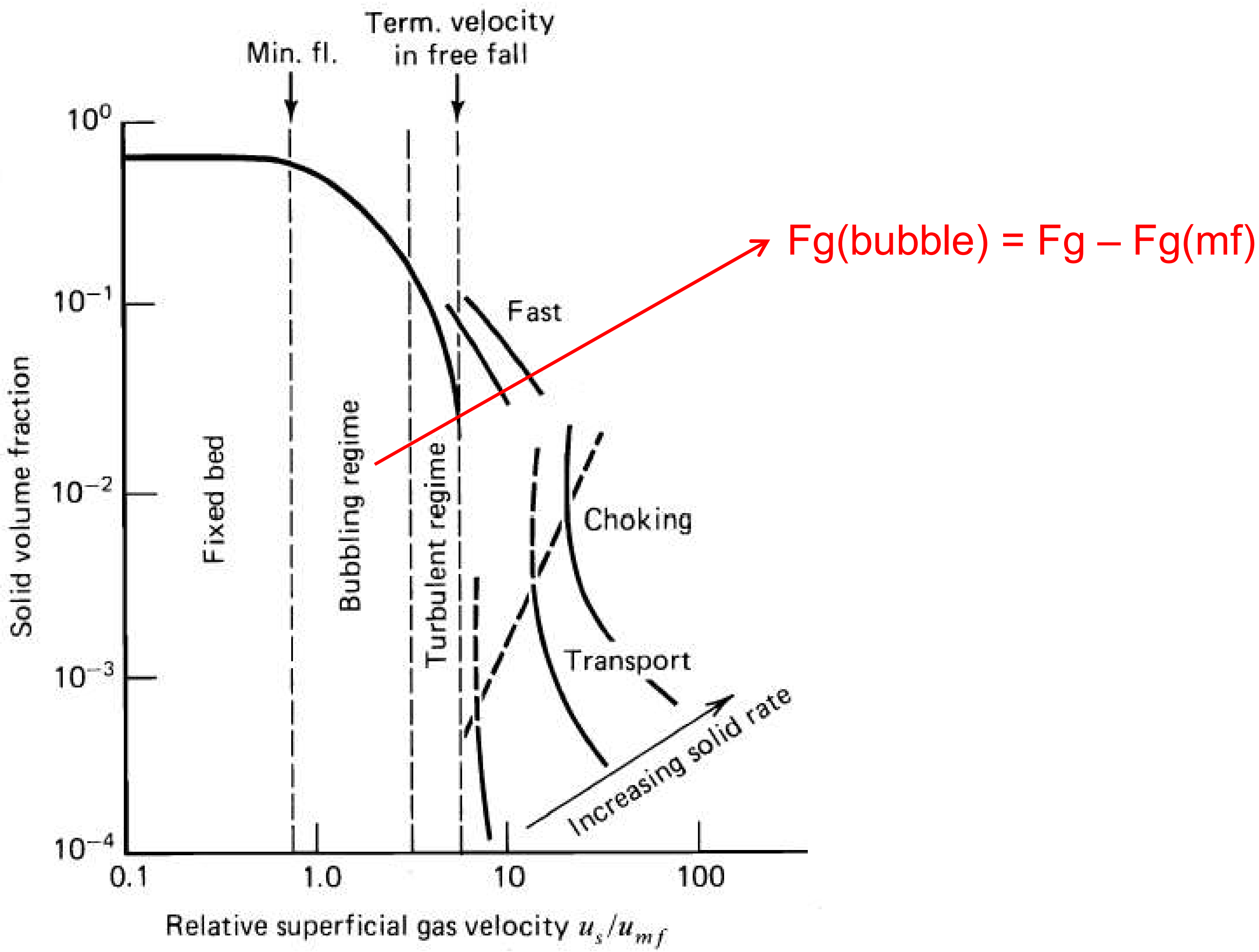


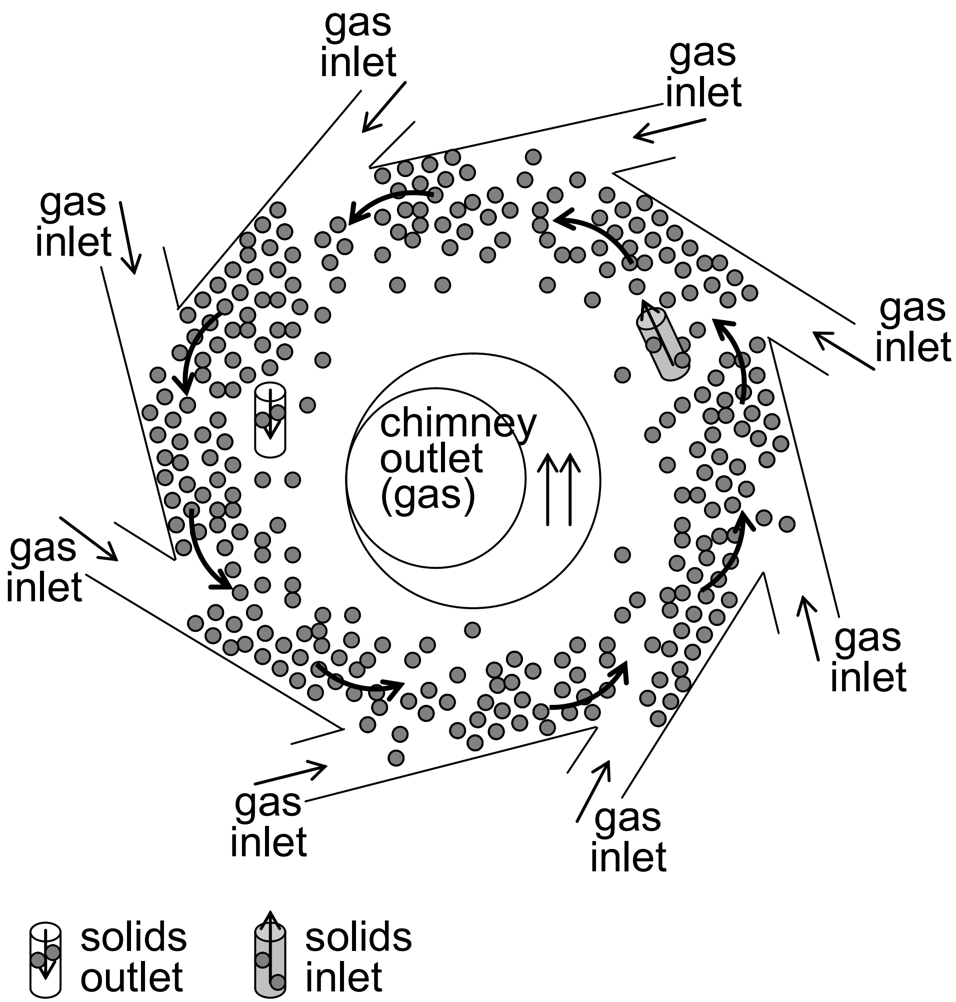
Figure 13.3-4

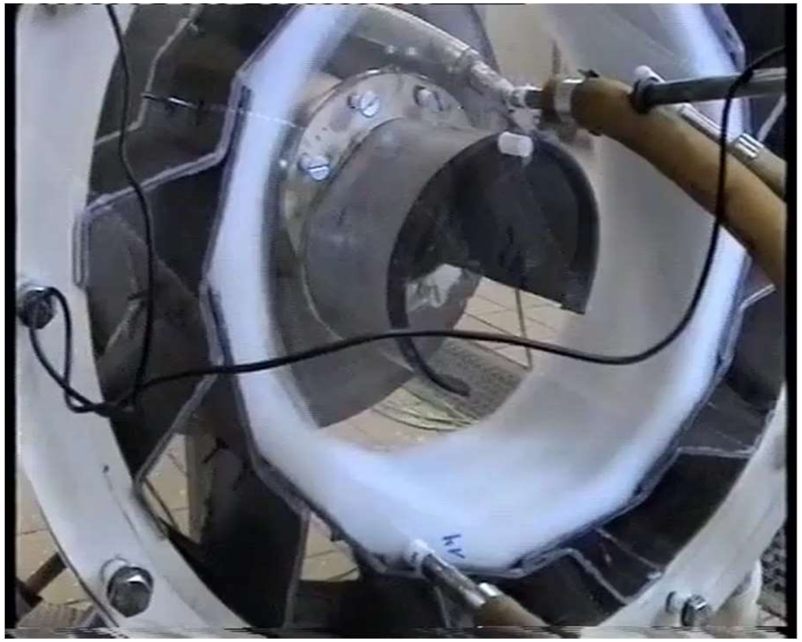
Fluidization regimes with coarse particles. After Squires et al. [1985].

(Froment et al., 2010)

VC-RFB: Process intensification through high-G operation

Combined high-G intensified gas-solids contact, gas-solids separation & segregation (applications: chemical looping combustion, particle coating, …)

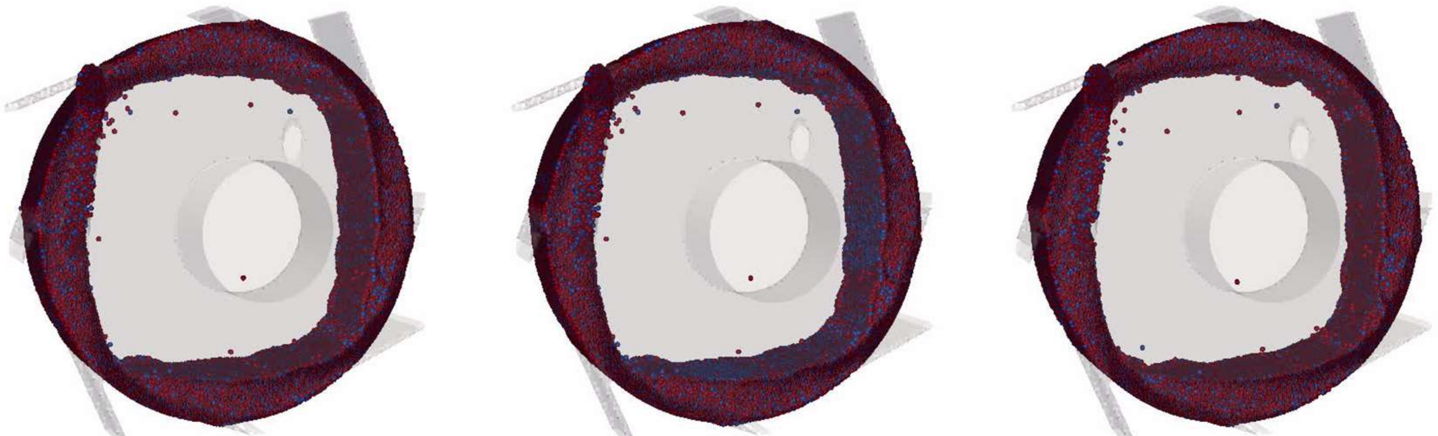




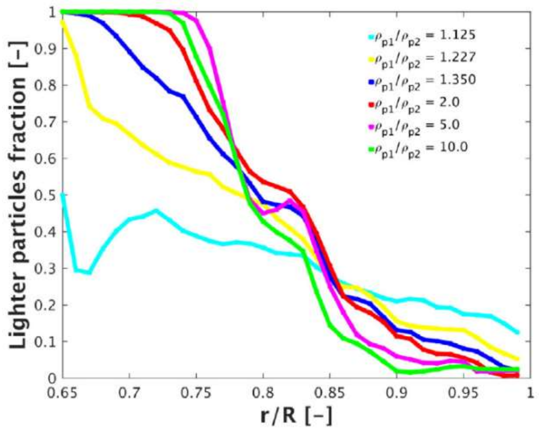
- No rotating equipment, but one degree of freedom lost
- Independent control gas and solids residence time
- Minimum gas flow rate requirement => Short gas-solids contact time

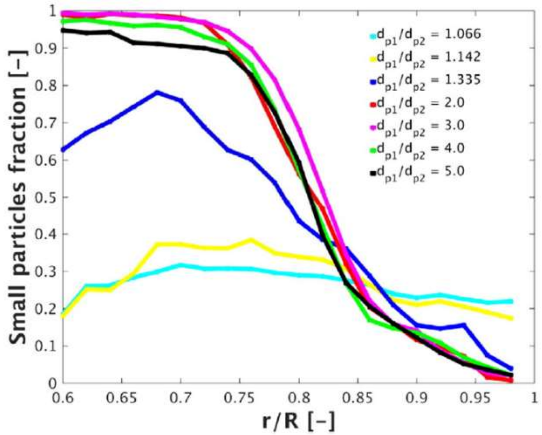
(De Wilde & de Broqueville, 2007)

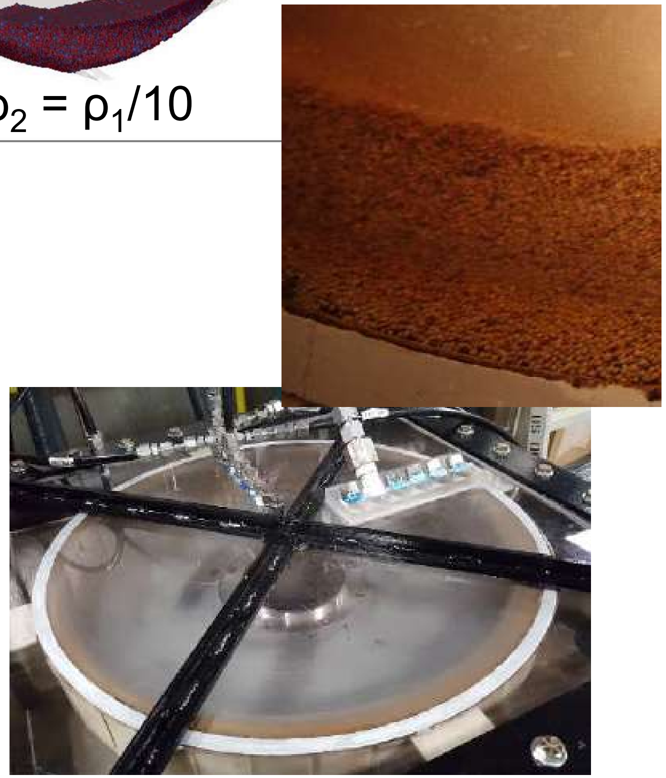
VC-RFB: Process intensification through high-G operation



$\rho_2 = \rho_1/2$ $\rho_2 = \rho_1/5$ $\rho_2 = \rho_1/10$





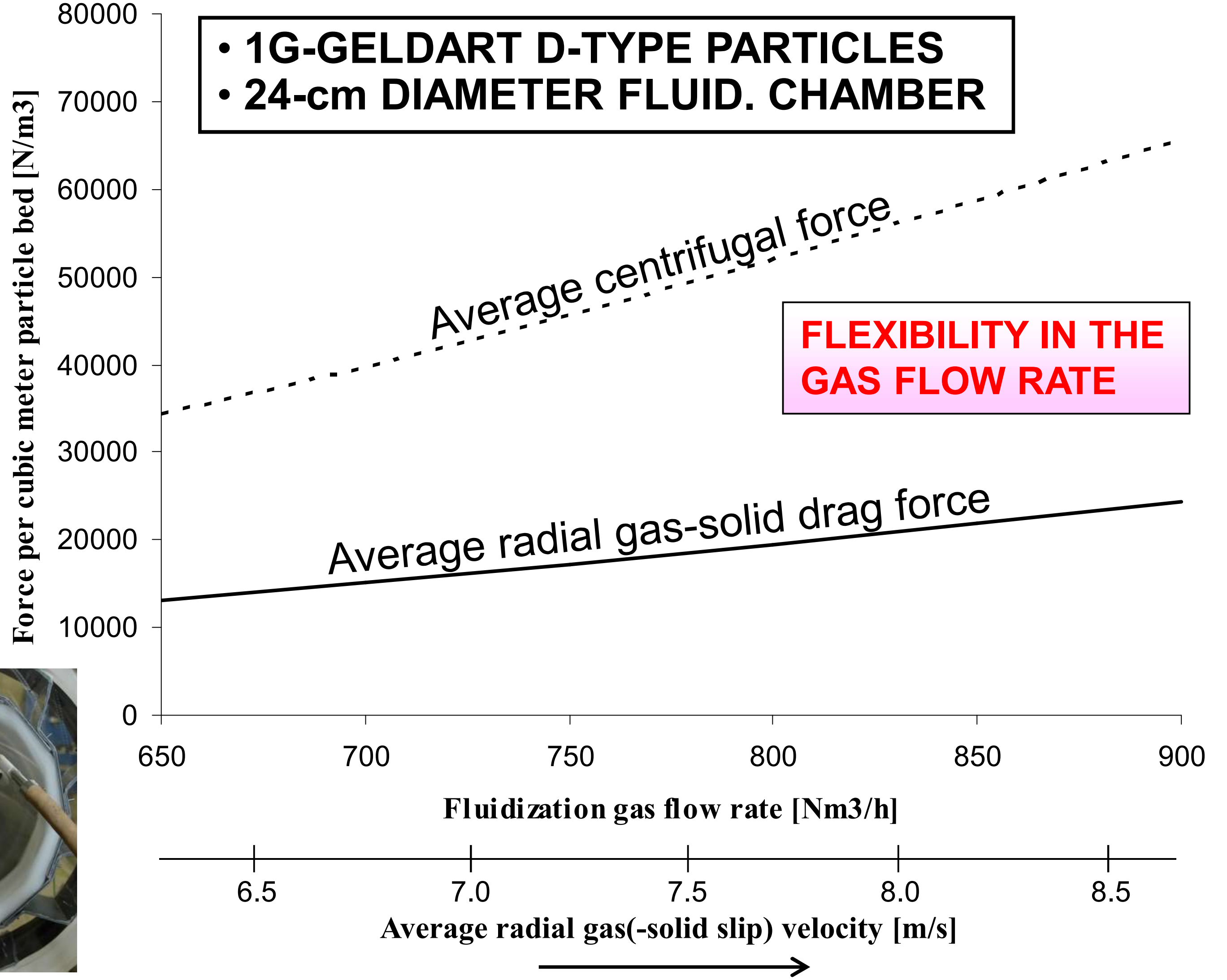


(Weber, Stehle, Breault & De Wilde, 2017)

(Verma, Li & De Wilde, 2017)

National Energy Technology Laboratory (NETL – US-DOE)

VC-RFB: Flexibility in the operating conditions

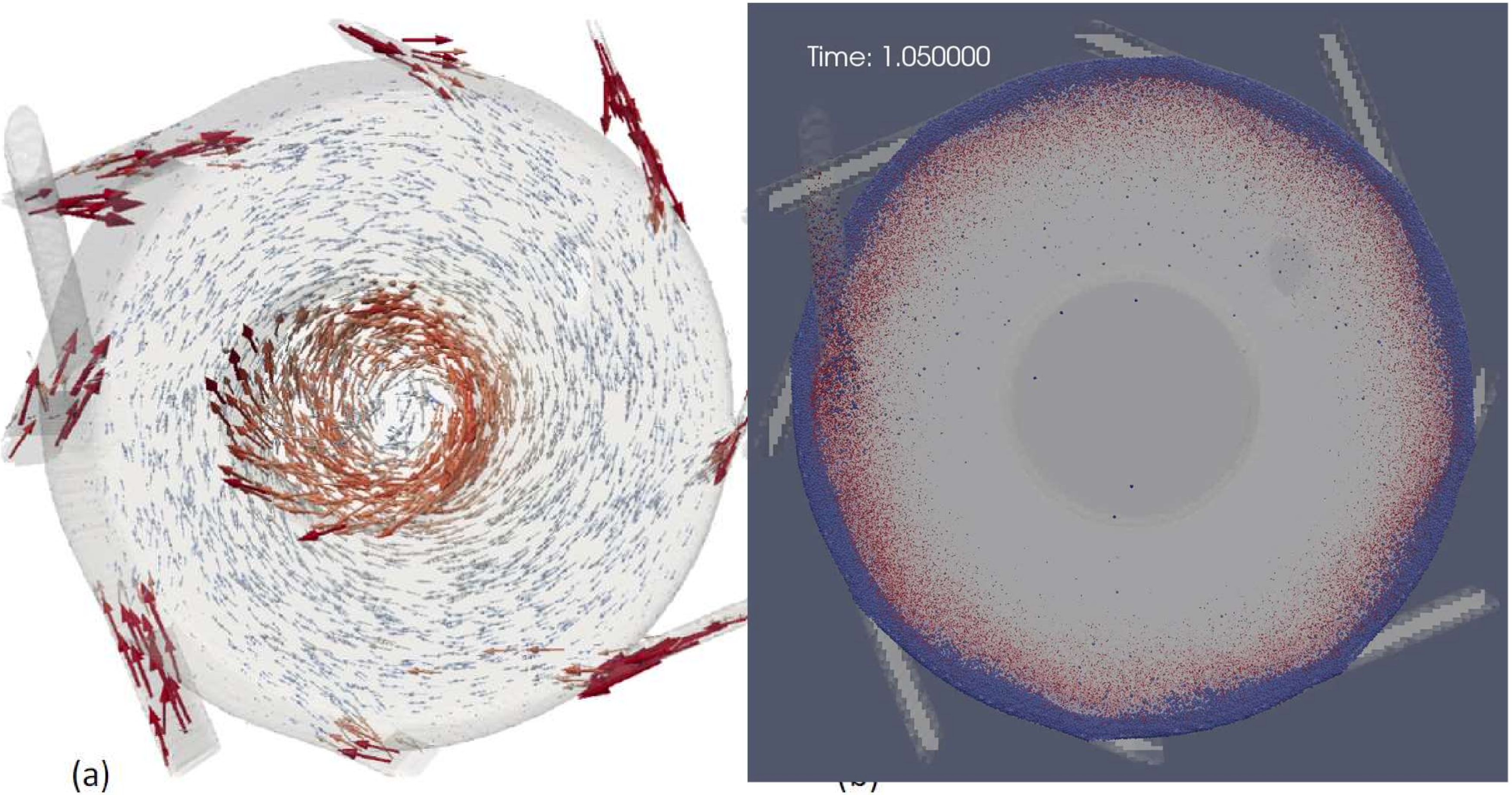


LIMITED RADIAL BED EXPANSION, EVEN RADIAL BED CONTRACTION

(De Wilde & de Broqueville, 2008)

VC-RFB: Flexibility in the operating conditions

Combined high-G intensified gas-solids contact, gas-solids separation & segregation (applications: chemical looping combustion, particle coating, …)

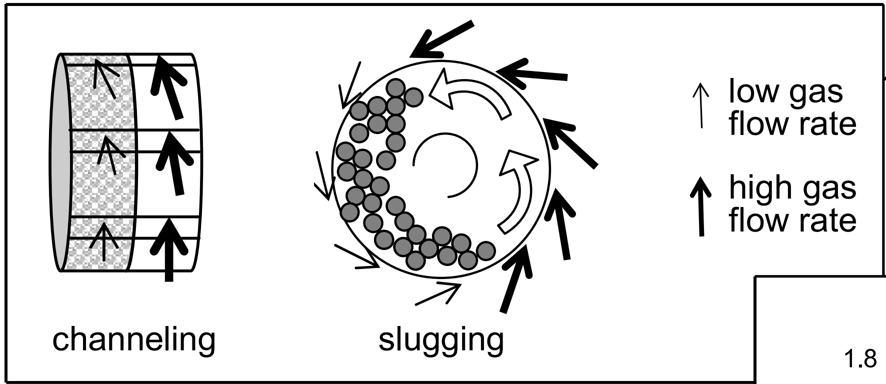


National Energy Technology Laboratory (NETL – US-DOE)

(De Wilde, Richards & Benyahia, 2016)

HYDRODYNAMICS: Gas & solids flow pattern

BED STABILITY AND LARGE-SCALE UNIFORMITY

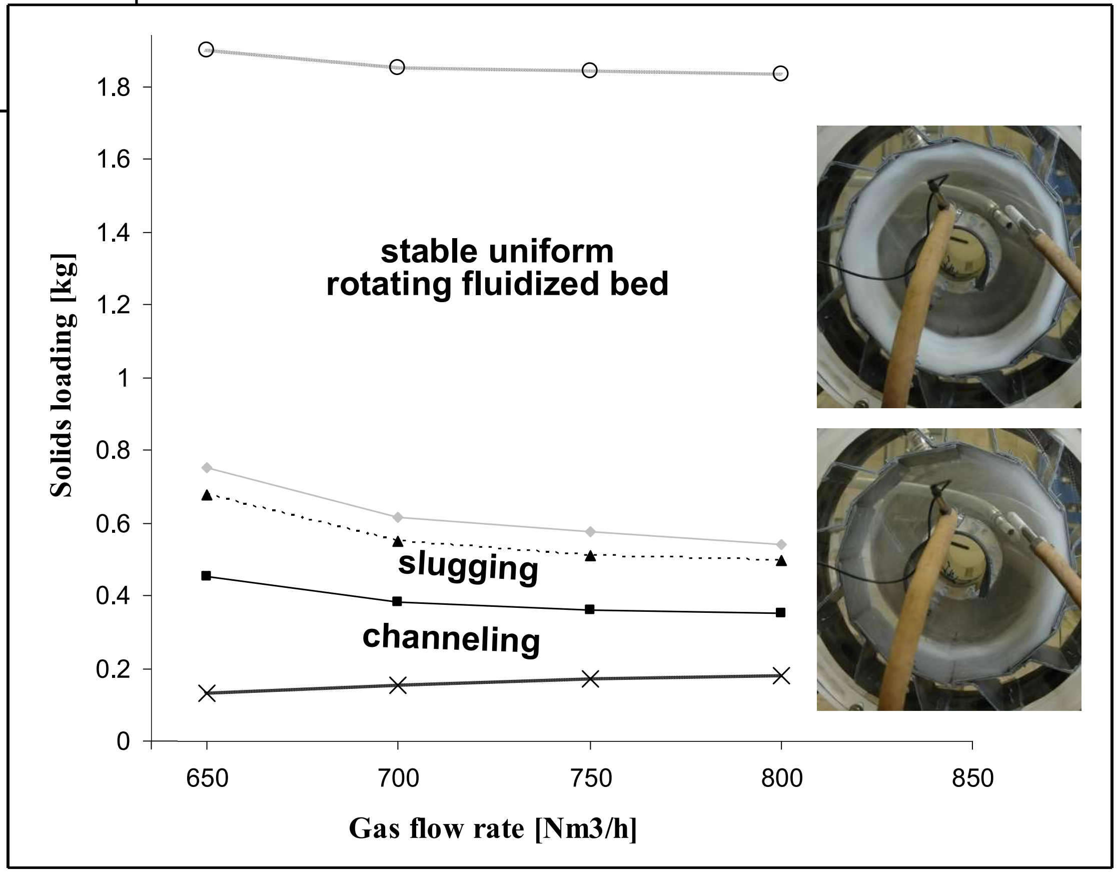


Process gas bypassing the particles
⇒ Poor gas-solid contact !

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

Stable bed

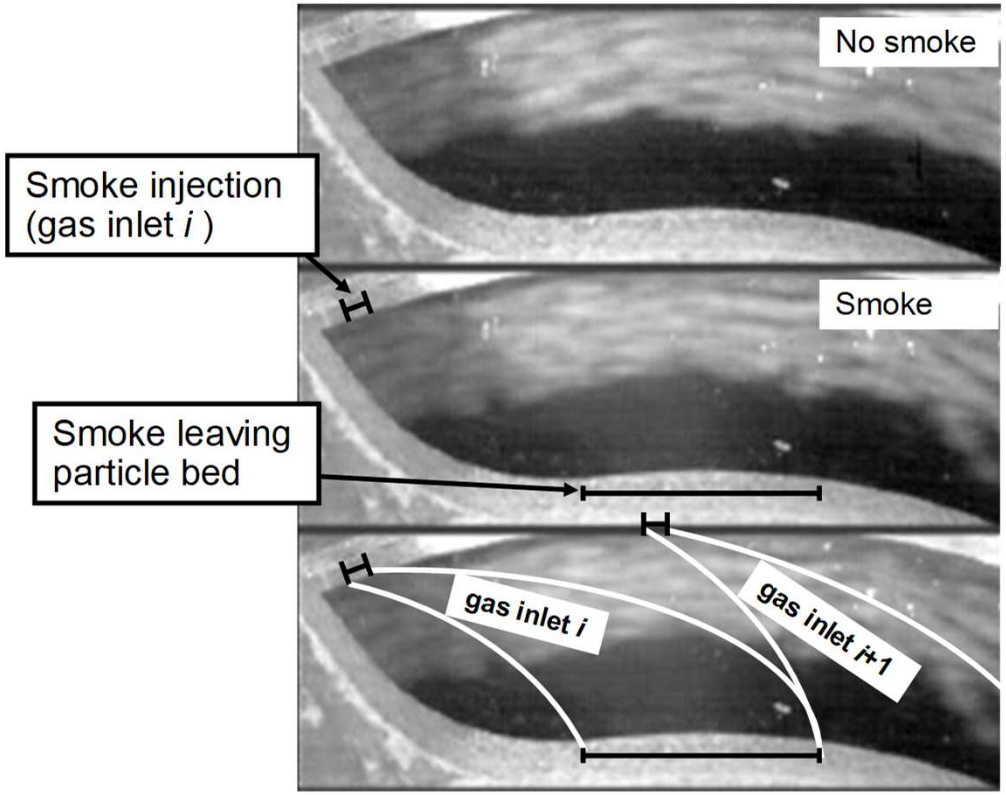
Slugging



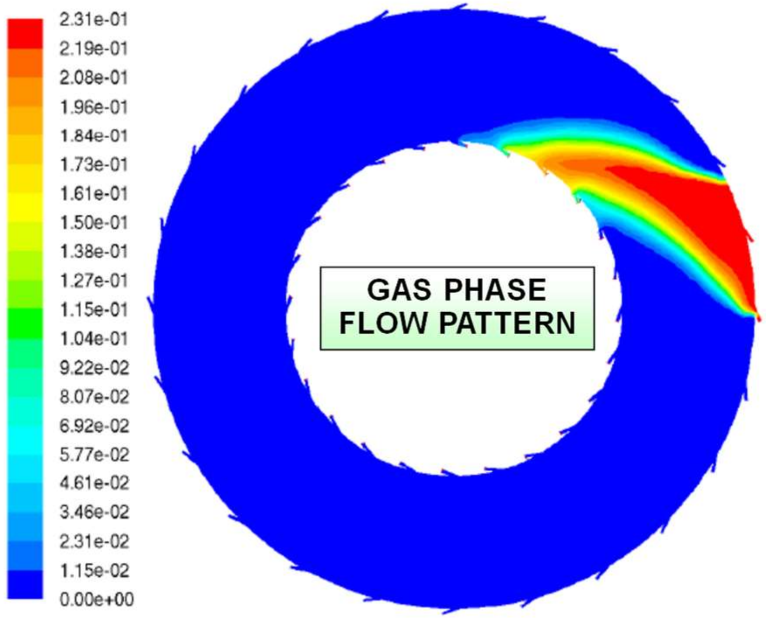
(De Wilde & de Broqueville, 2008)

HYDRODYNAMICS: Gas & solids flow pattern

Smoke tracer experiments

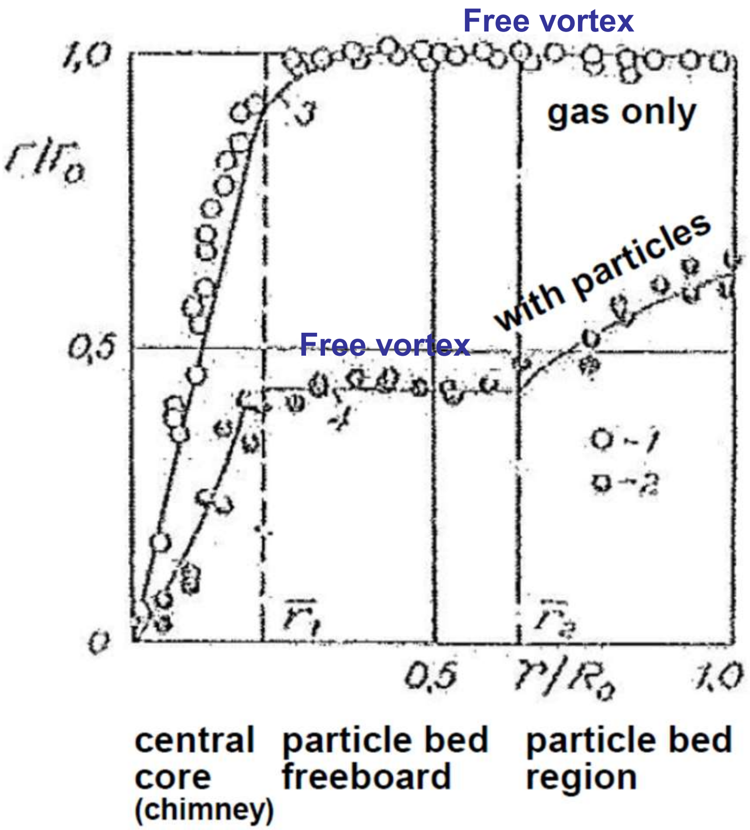


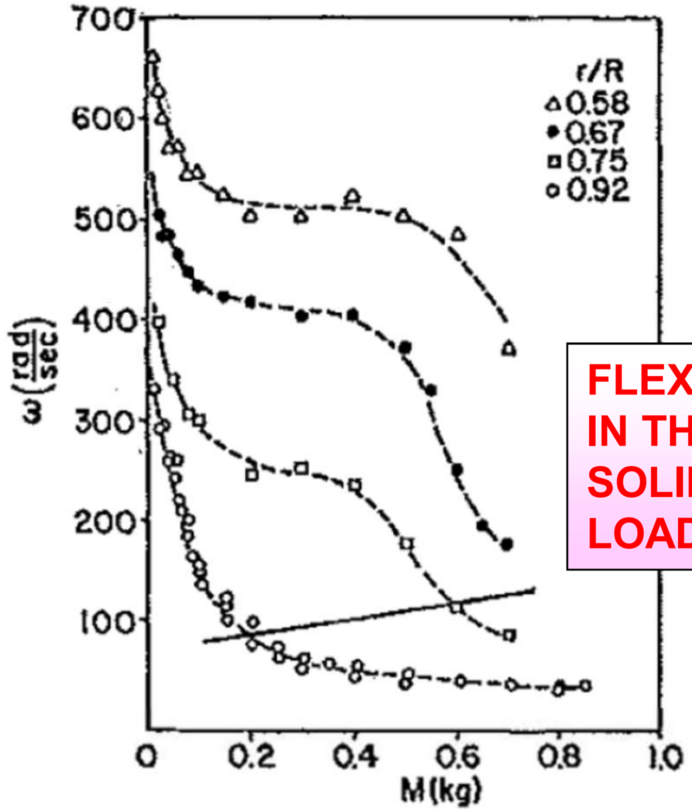
Computational Fluid Dynamics



- GASES INJECED VIA SUCCESSIVE GAS INLETS HARDLY MIXED
- GAS PHASE FLOW PATTERN CLOSE TO PLUG FLOW
- RTD GAS DETERMINED BY THE RADIAL VELOCITY COMPONENT

HYDRODYNAMICS: Dense versus dilute flow

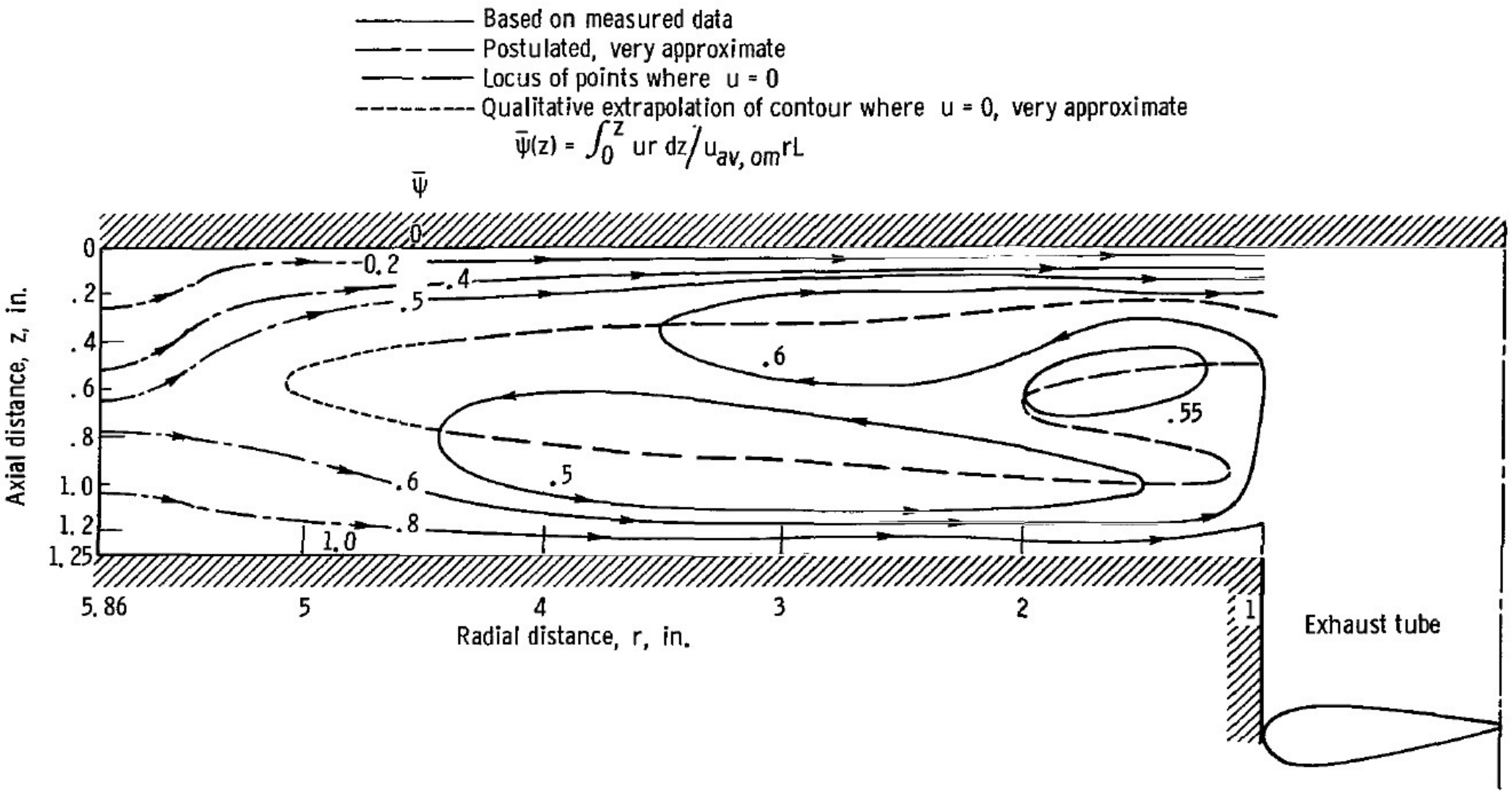




FLEXIBILITY IN THE SOLIDS LOADING

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.)

HYDRODYNAMICS: Dense versus dilute flow

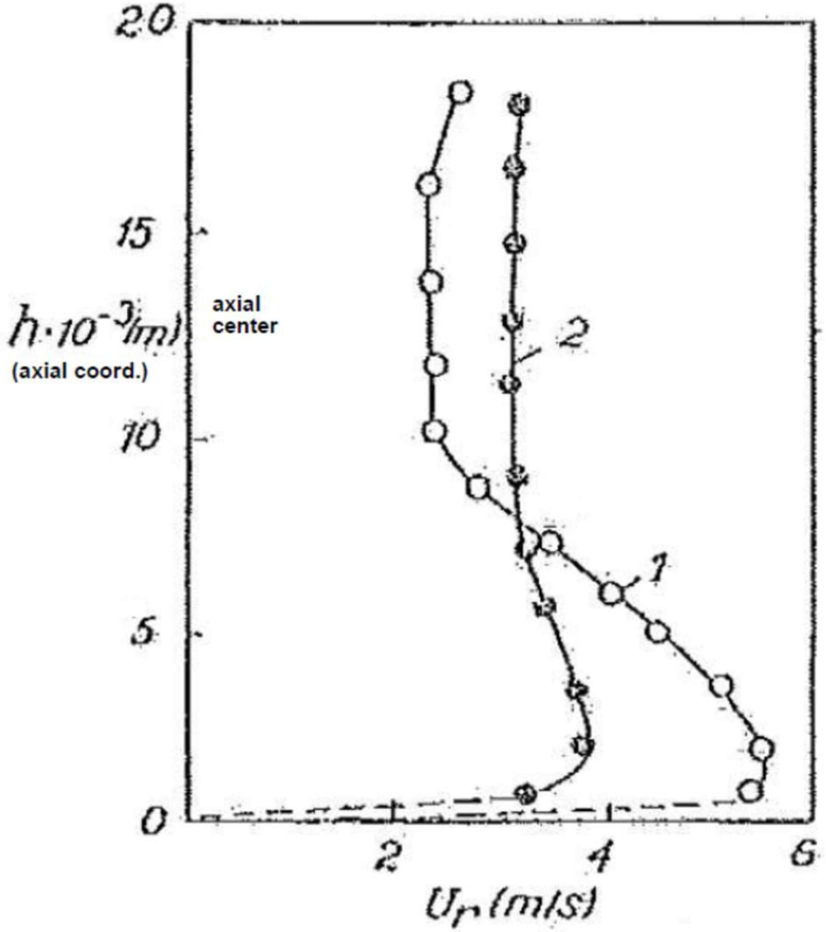


End wall boundary layer flow (stationary end walls) ⇔ Determined by amount of swirl:
For D(chimney) << D & L/D > 2:
- Low swirl: u(tang)/u(rad) < 1-2: radial inflow enough momentum to penetrate centrifugal field
- High swirl: u(tang)/u(rad) > 10: radial flow diverted axially & all flow leaves via end wall boundary layers

(NASA Lewis Research Center, TN D-3072, 1965)

HYDRODYNAMICS: Dense versus dilute flow

AXIAL BED UNIFORMITY



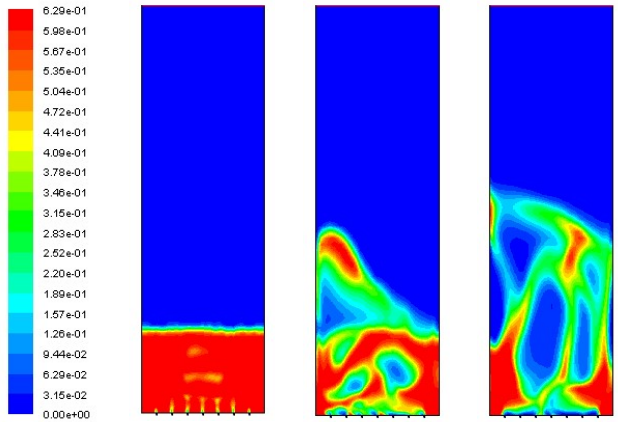
Problem of boundary layer flow

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.]

APPLICATIONS: Drying of granular materials and powders

PARTICLE BED UNIFORMITY

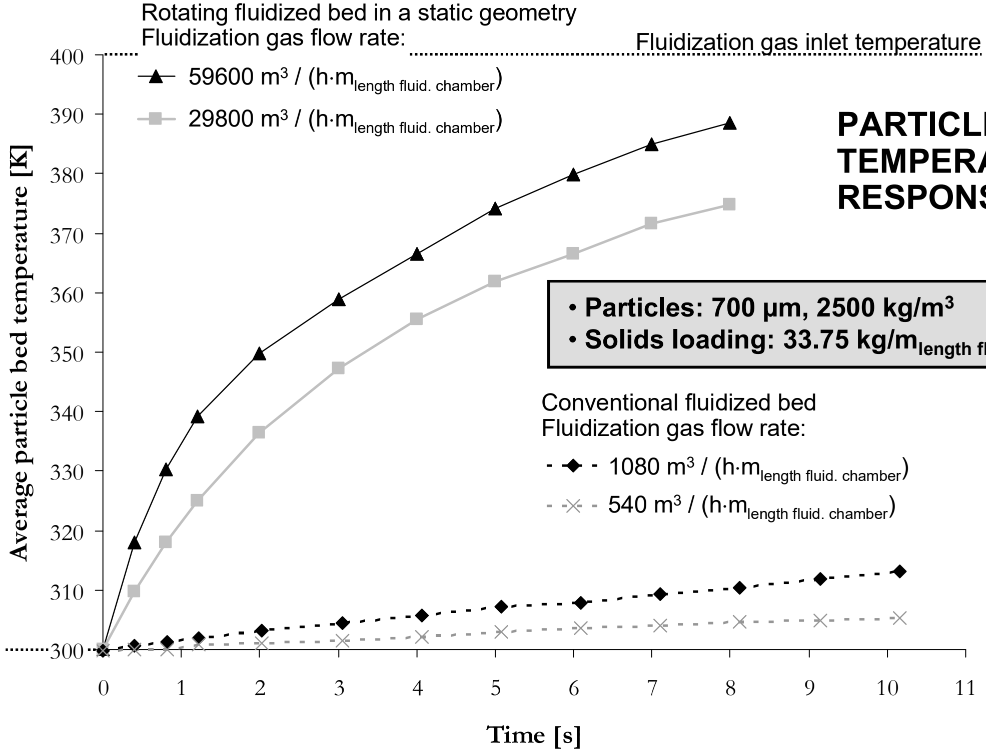
CONVENTIONAL FLUIDIZED BED



SOLIDS VOLUME FRACTION

195 m²/h 540 m²/h 1080 m²/h

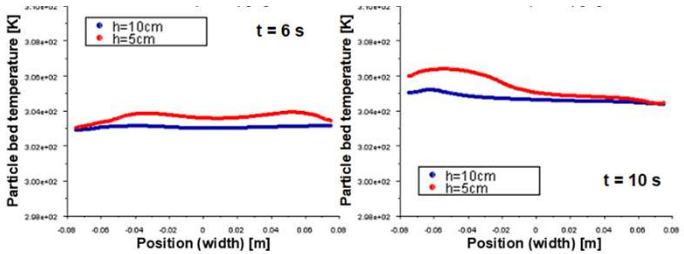
FLUIDIZATION GAS FLOW RATE



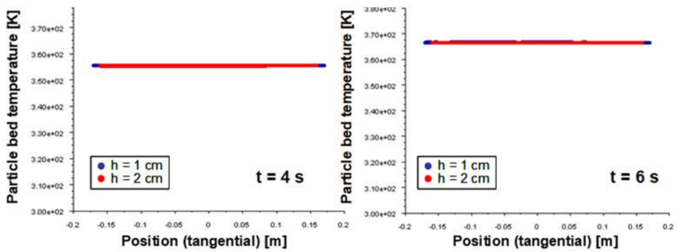
PARTICLE BED TEMPERATURE RESPONSE

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

PARTICLE BED TEMPERATURE UNIFORMITY

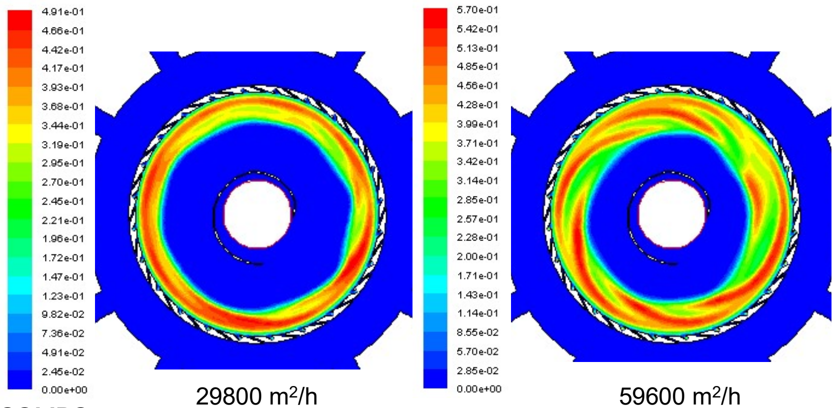


Conventional fluidized bed
Fluidization gas flow rate = 540 m³ / (h·m$_{\text{length fluid. chamber}}$)



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



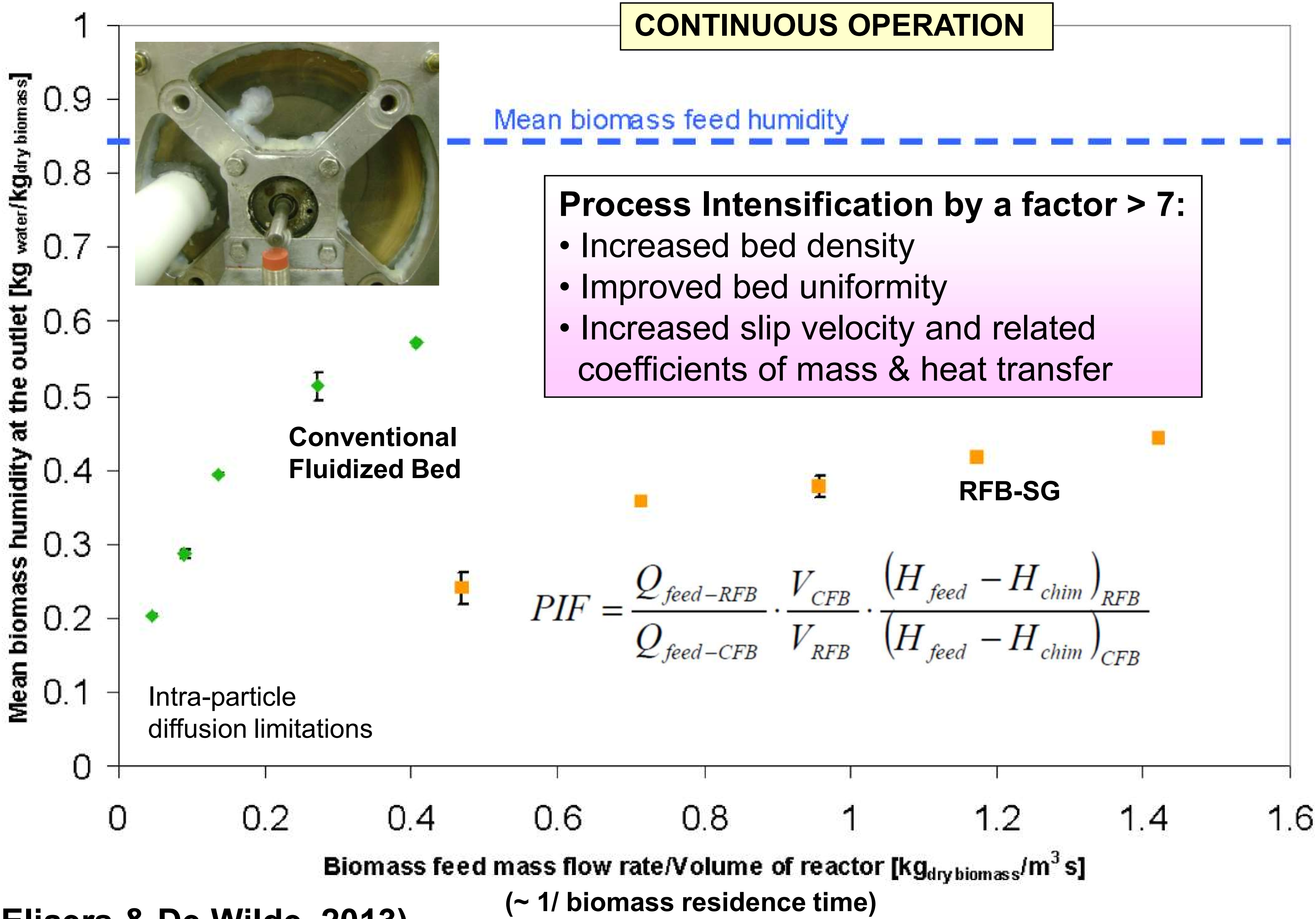
SOLIDS VOLUME FRACTION

29800 m²/h 59600 m²/h

FLUIDIZATION GAS FLOW RATE

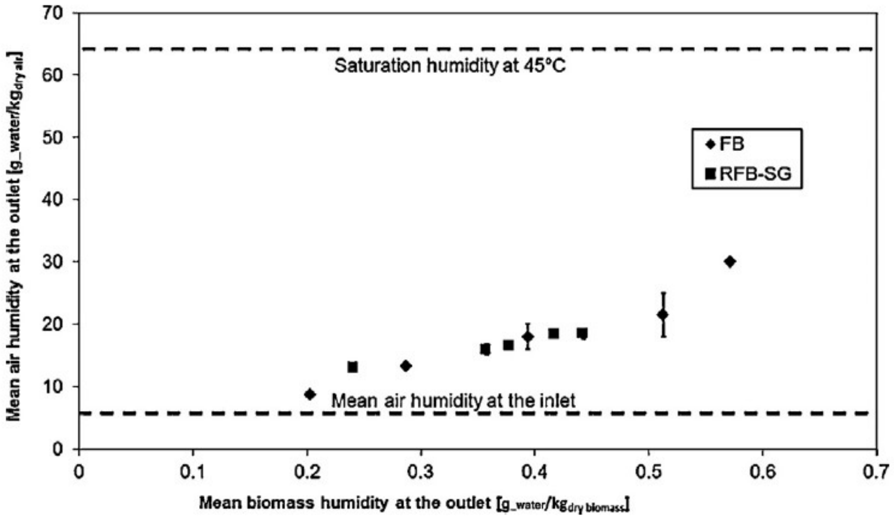
(de Broqueville & De Wilde, 2009)

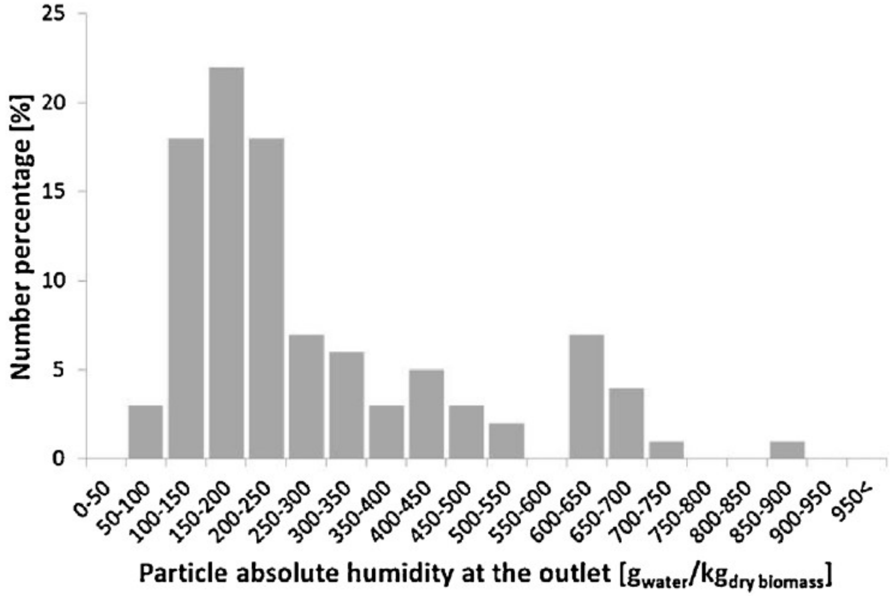
APPLICATIONS: Drying of granular materials and powders

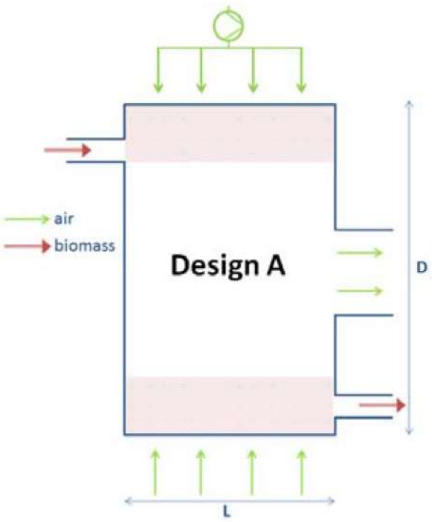


(Eliaers & De Wilde, 2013)

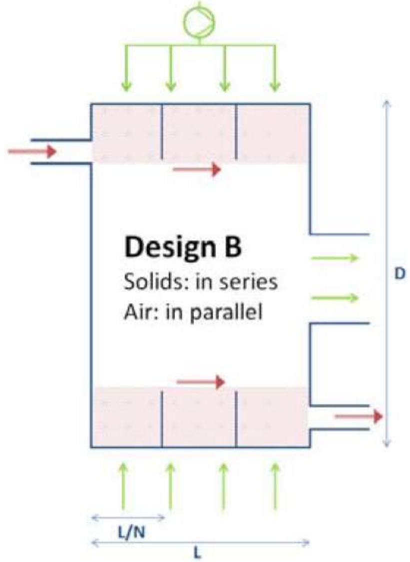
APPLICATIONS: Drying of granular materials and powders



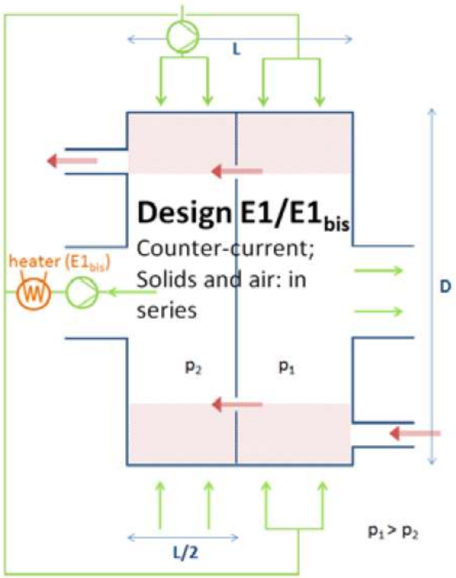




Standard chamber



Chamber compartmenting



Air re-utilization

(Eliaers et al., 2014)

APPLICATIONS: Fine particle coating

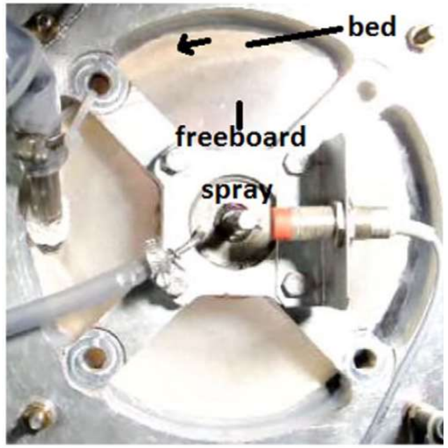
Fluidization & low-temperature wet coating of fine (cohesive) particles

<u>Efficiency *& novelty*:</u>

- Intensified interfacial transfer of mass, heat & momentum (reduced effect van der Waals forces)
- Use of relatively large droplets & eventually high liquid concentrations
- Fast coating (few seconds)
- Separation coated / non-coated particles & coating droplets

<u>Quality:</u>

- Limited / easily controlled agglomeration
- Uniform coating (no/few cracks & cavities)
- Non-burned, …



72 x 0.2 mm slots

APPLICATIONS: Fine particle coating

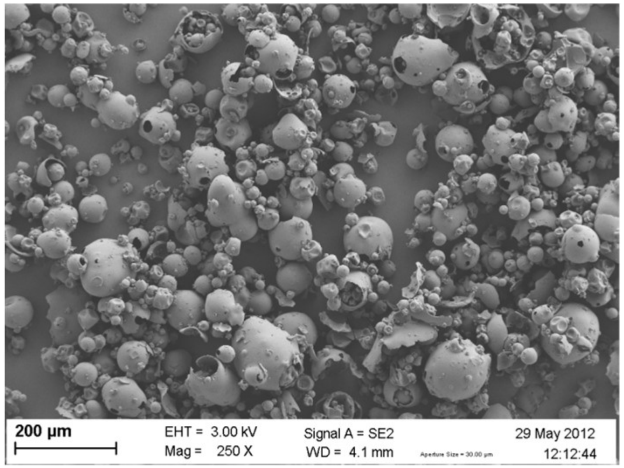
Other operating conditions: atomising air pressure of 1.5 bar, solids feeding rate of 2 g/s

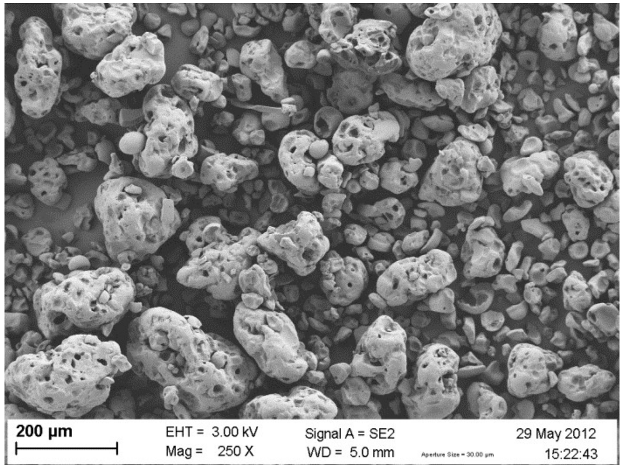
original powder

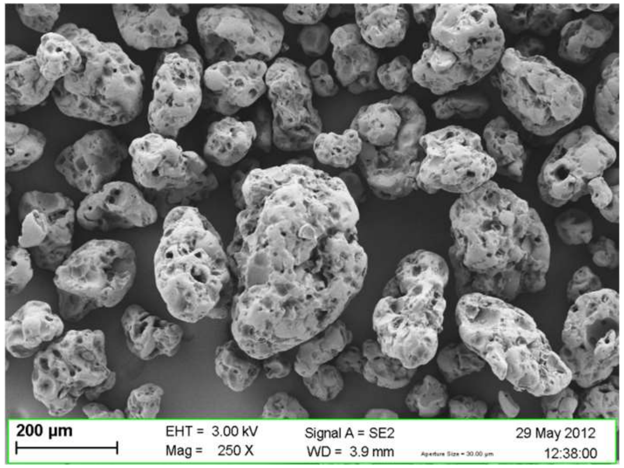
- Hiprotal whey protein alfa
- Mean size (70 µm), density (260 kg/m³)

coated powder
t_{inj} = 5 s
400 Nm³/h

coated powder
t_{inj} = 5 s
250 Nm³/h

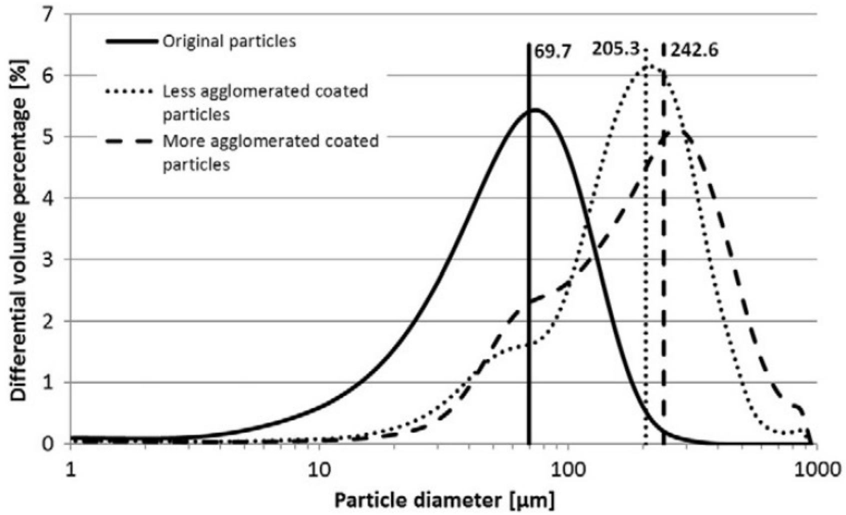






Visual inspection (SEM):

- Limited agglomeration (< 4 particles)
- Low level considering droplet size & low T
- Fast coating time (< 5 s)
- Agglomeration controlled by air flow rate

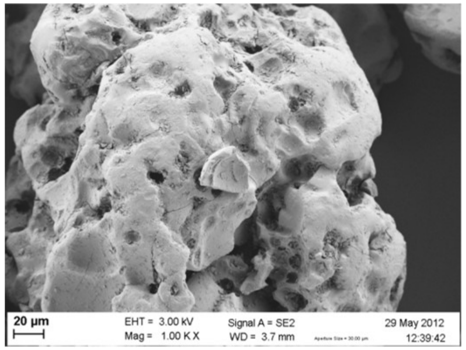


(Eliaers et al., 2014)

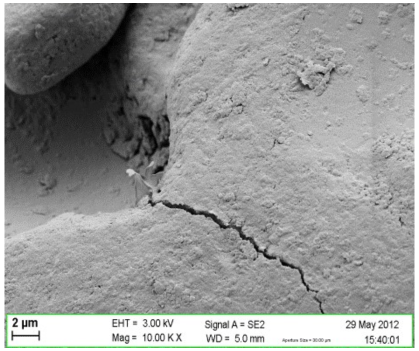
Particles morphology & coating quality: Active component release test

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
  → very few cracks & cavities
- 58 $g_{coating}$ /100 $g_{uncoated}$
  → on average 1.22 µm coating
  (assuming 70µm spherical uncoated particles)



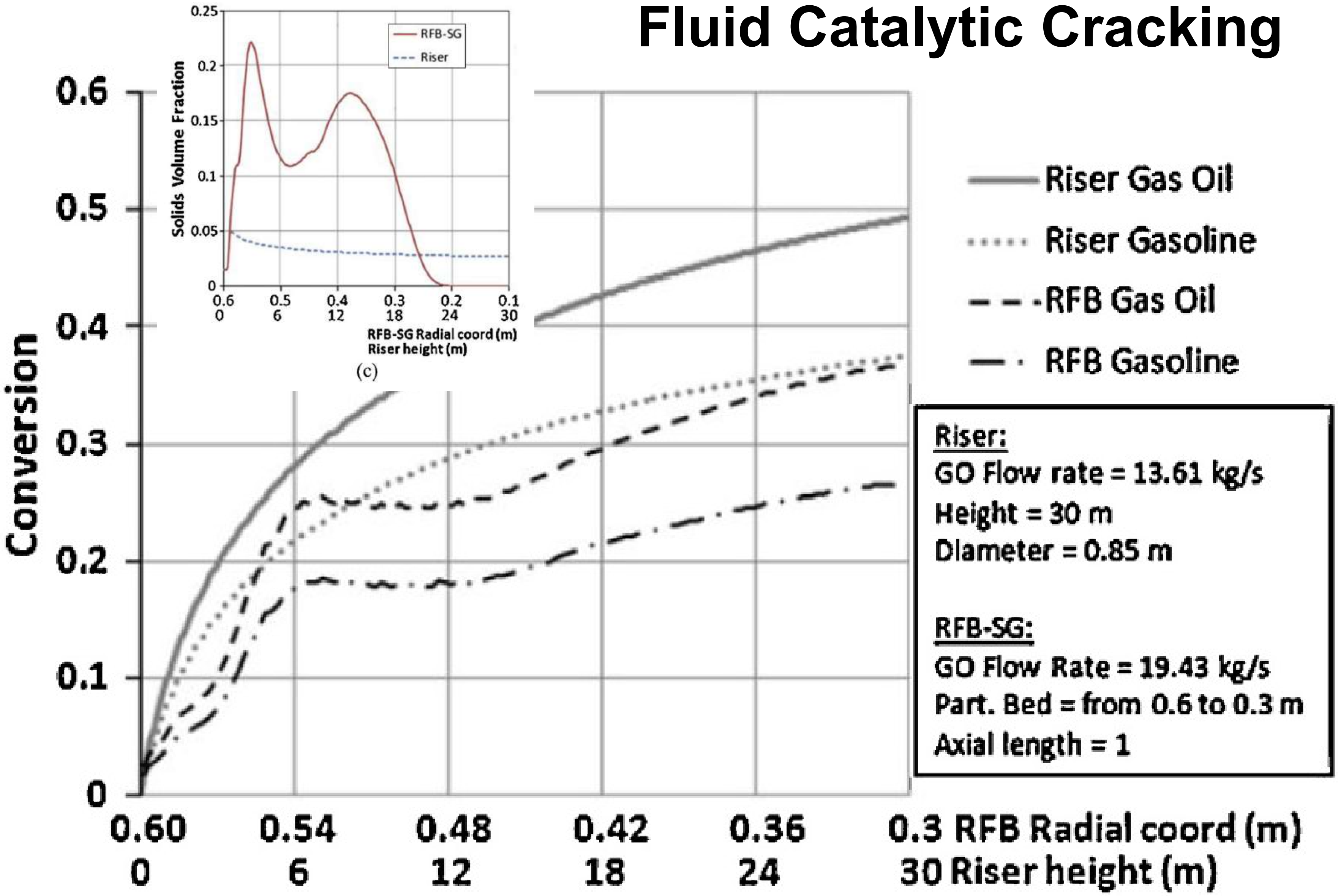
good quality coating



very few cracks

(Eliaers et al., 2014)

Fluid Catalytic Cracking



(a)

(Trujillo & De Wilde, 2010&2012)

SO_2 NOx Adsorption Process

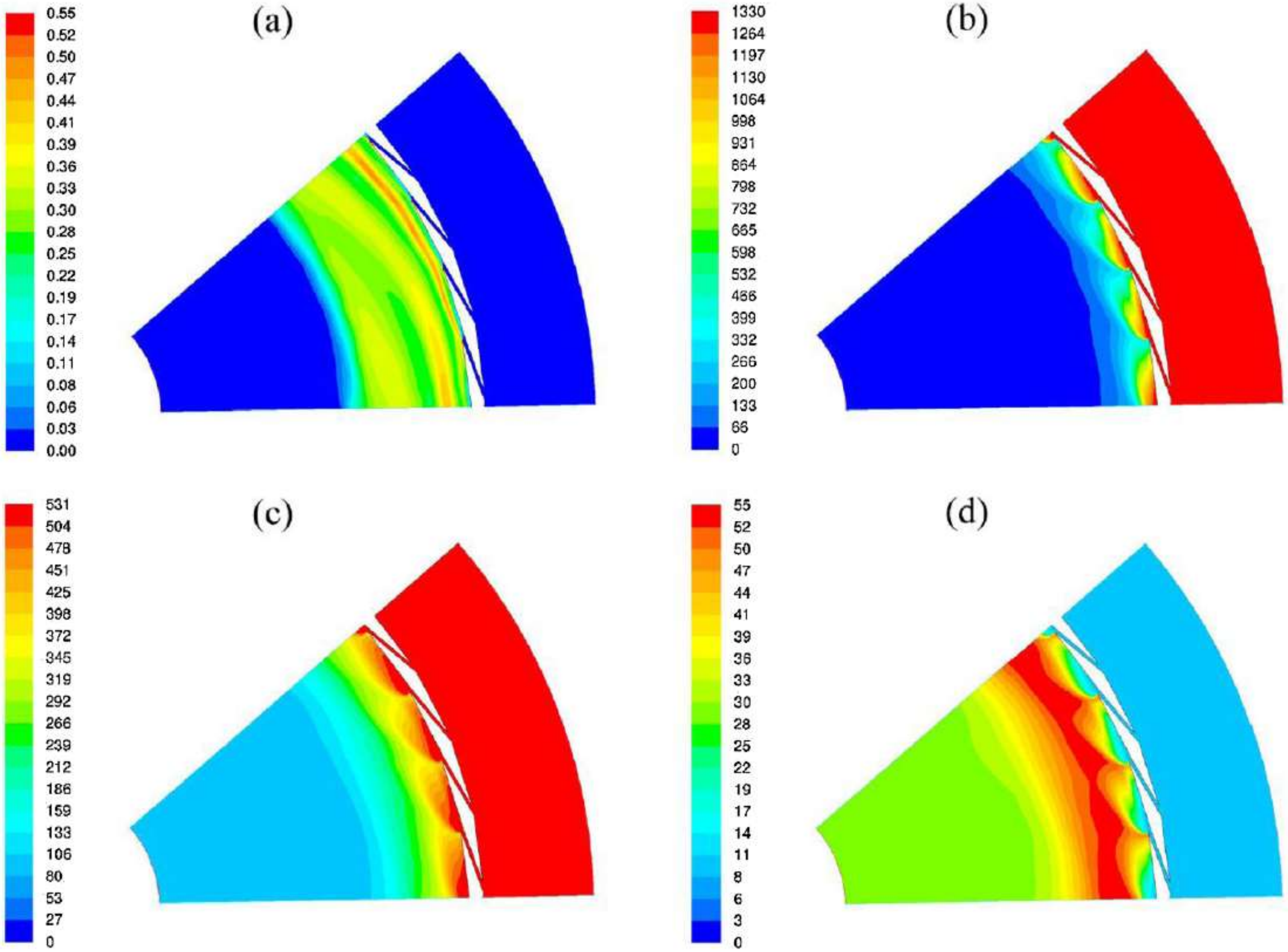


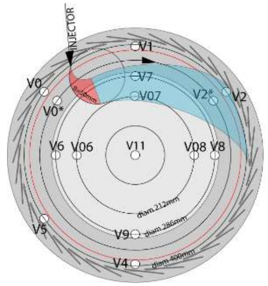
Fig. 32. 2D periodic domain CFD simulations of the simultaneous adsorption of SO_2 and NO_x on a γ-Al_2O_3 sorbent in a vortex chamber type reactor. Snapshot of the (a) solids volume fraction and the (b) SO_2, (c) NO and (d) NO_2 concentrations (ppm-v). Reactor volume and operating conditions: see Table 8(a) – 5.38 kg bed, single-pass case. (From Ref. [6]).

(Ashcraft et al., 2013)

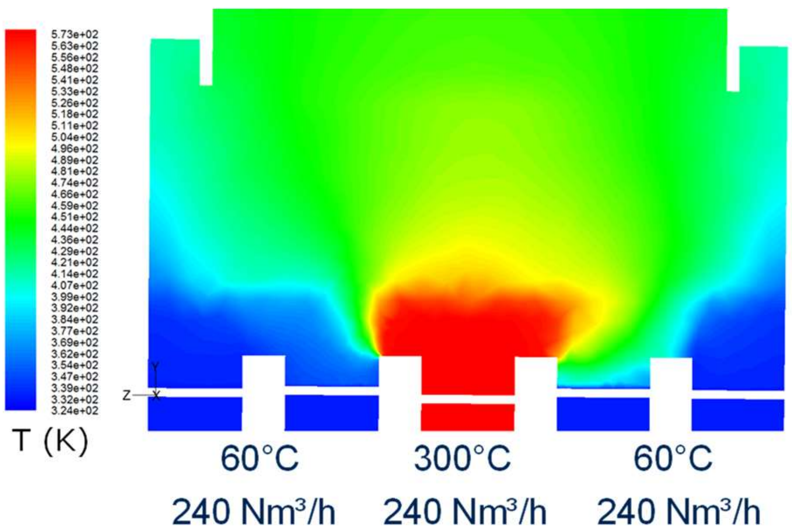
APPLICATIONS: Spray drying

- Dilute flow regime
- Strong vortex & secondary flows
- Droplet-air interaction complex
- Efficient drying:
    - Use hot air
    - Prevent product degradation

⇨ Multi-zone operation

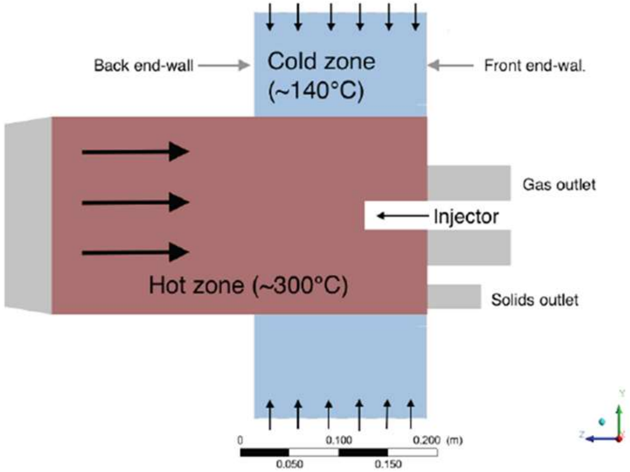


Axial multi-zone operation:

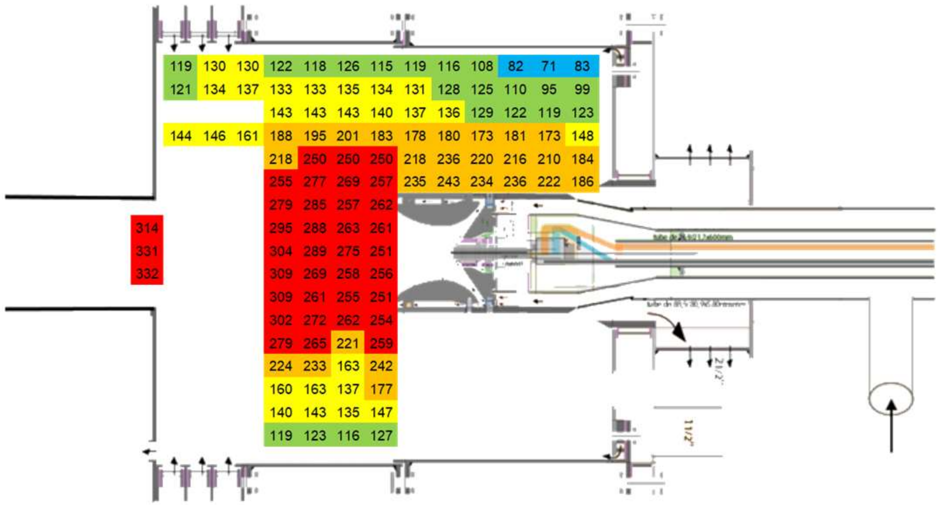


APPLICATIONS: Spray drying

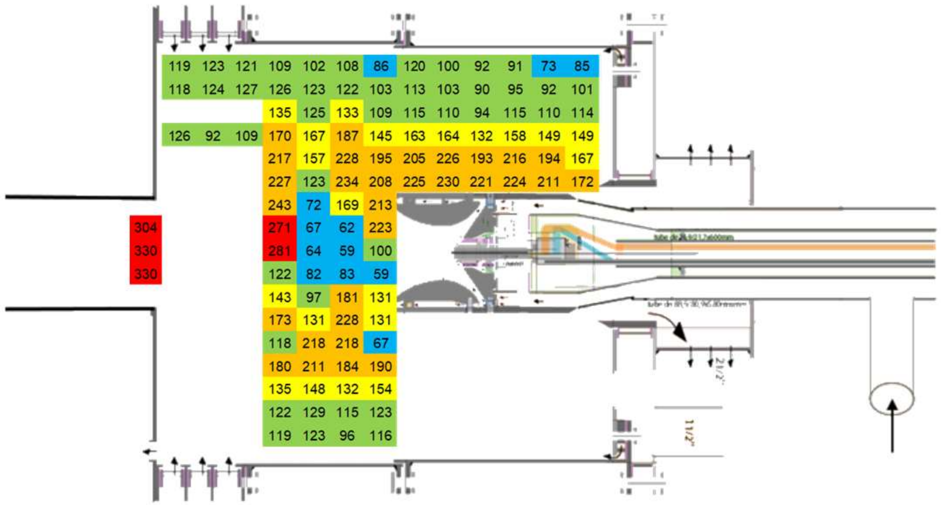
Axial multi-zone operation:



Without water injection

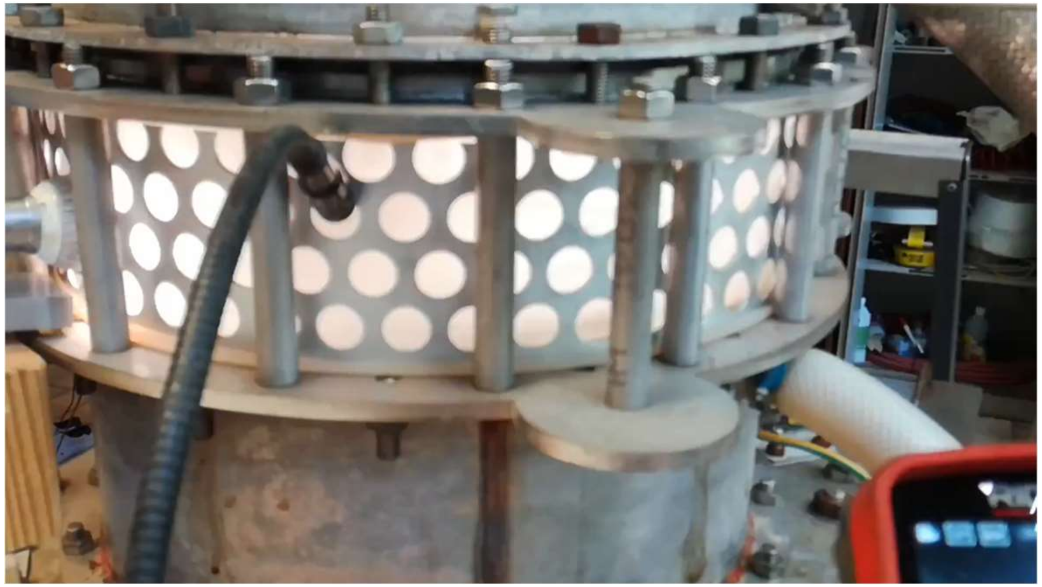


With water spraying



APPLICATIONS: Spray drying

Water injection => milk injection at t = +/- 40 s



Different solids outlets: Fine particles outlet

VORTEX CHAMBER

- UNIQUE HYDRODYNAMIC CHARACTERISTICS
- COMBINED HIGH-G INTENSIFIED GAS-SOLIDS CONTACT & SEPARATION & SOLIDS SEGREGATION
- MULTI-ZONE OPERATION

APPLICATIONS

- PARTICLE PRODUCTION & TREATMENT
- OTHER (POLYMERIZATION, COMBUSTION & GASIFICATION, HETEROGENEOUS CATALYTIC REACTIONS, …)

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- ORISE – Oak Ridge Associated Universities
- NETL – National Energy Technology Laboratory (US-DOE)
- Interreg France-Wallonie-Vlaanderen – Europese Unie

Interreg

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PSYCHE

Avec le soutien du Fonds européen de développement régional
Met steun van het Europees Fonds voor Regionale Ontwikkeling

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