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Mixing and segregation in fluidized bed thermochemical conversion of biomass

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Selected topics on...

MIXING AND SEGREGATION IN FLUIDIZED BED THERMOCHEMICAL CONVERSION OF BIOMASS

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Napoli (Italy)

Fluidization XV
May 22-27, 2016 - Fairmont Le Chateau Montebello
Quebec, Canada

SCOPE

- Thermal processing of biomass/waste
- Combined heat/power generation.
- Production of liquids/gases and char to be used either as commodity fuels or as chemical feedstocks
- Exploitation of solid residues: char, ash "mining".

Candidate biomass/waste

Robinia-pseudoacacia

Pine nut shell

Refuse-derived fuel

Tyre-derived fuel


Wood pellets

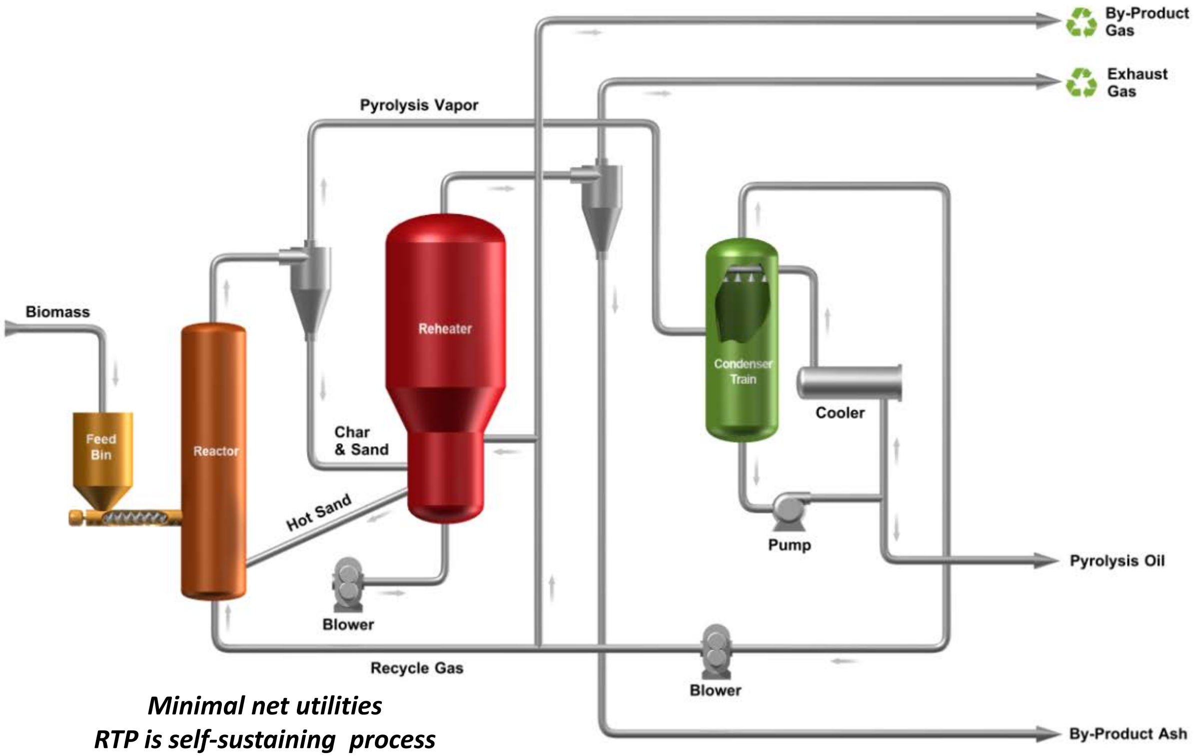

Straw pellets


Sewage sludge

THERMOCHEMICAL PROCESSES: PYROLYSIS

- Thermal decomposition of solids in absence of gasification agents,
- Mostly aimed at maximizing yields in liquids.
- Allothermal: heat indirectly provided by combustion of gas or char

Thank you, Maurice !



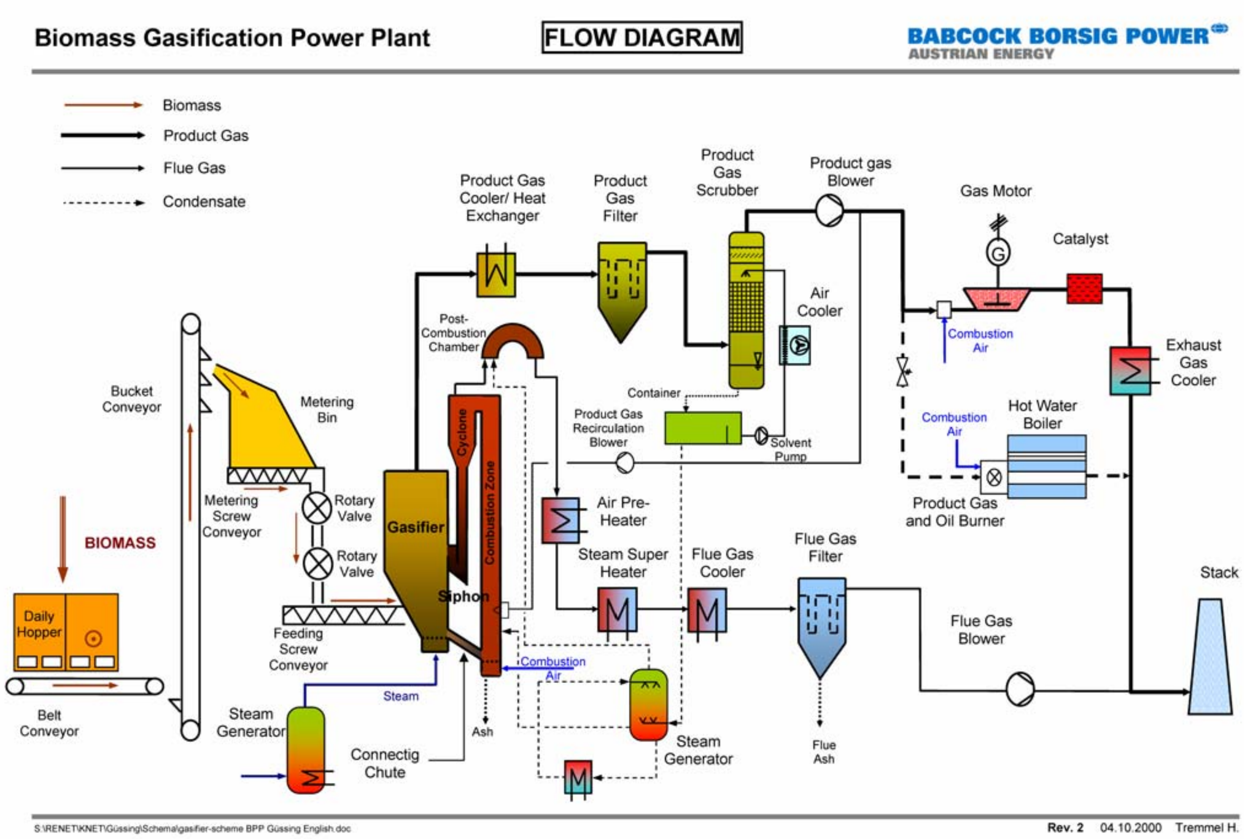
Minimal net utilities
RTP is self-sustaining process

ENSYN

Riser reactor in a circulation loop: indirect heating by combustion of residual char

THERMOCHEMICAL PROCESSES: GASIFICATION

- Thermal decomposition of solids by partial oxidation with oxygen and/or reforming with steam.
- Aimed at producing gas, either as a fuel or as a chemical feedstock (syngas).
- Autothermal or allothermal: heat provided by combustion of gas or char.



Riser reactor in a circulation loop: indirect heating by combustion of residual char.

after H. Hofbauer, R. Rauch, K. Bosch, C. Aichernig & R. Koch (2007) “Biomass CHP-Plant Güssing: A Success Story” Vienna University of Technology, Repotec GmbH, Biomasse Kraftwerk Güssing GmbH

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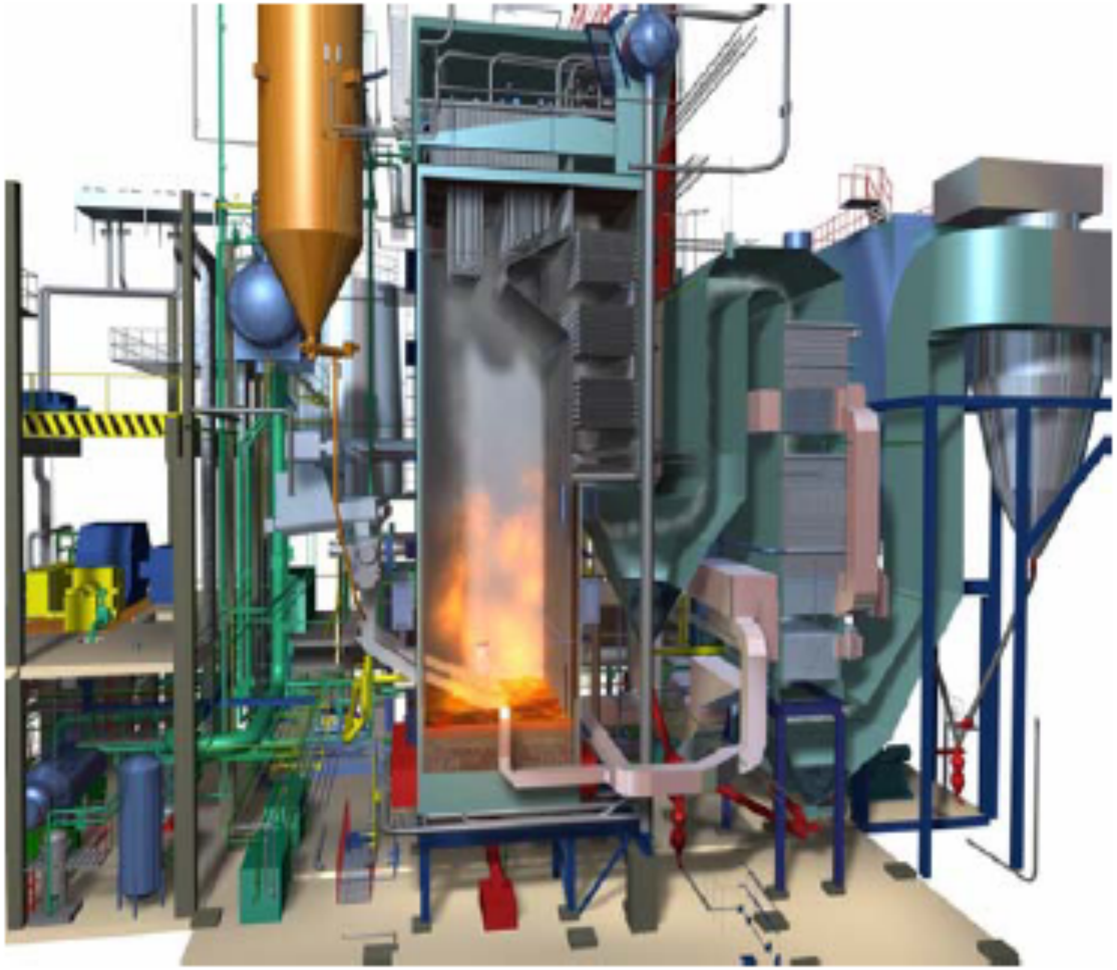
THERMOCHEMICAL PROCESSES: COMBUSTION

- Full direct oxidation of solids in air/enriched air.
- Combined heat and power generation, volume reduction.
- Exothermal: excess heat used to raise steam (eventually electricity through steam cycles) and/or thermal energy



Bubbling fluidized bed combustor

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Why fluidized beds ….?

- Controlling chemical pathways requires:
  - thorough thermal control,
  - good gas-solid contacting patterns,
  - effective gas-phase micromixing.
- If properly designed and operated, fluidized bed reactors may provide an optimal environment for thermal processing of biomass and waste, with superior control of the thermal history and of the course of chemical reactions over competing technologies (fixed beds, grate reactors, rotary kilns).

But……………

- Favourable features of FB reactors may be jeopardized by phase segregation:
  - segregation of solids (axial, lateral);
  - segregation of gas phases.
- The negative effects of phase segregation are emphasized in biomass processing due to the importance of gas-phase processes, as compared with heterogeneous gas-solid processes.

Axial segregation of solids: mechanisms

- the “basic” segregation mechanism is driven by size/density difference (flotsam/jetsam): finer/lighter solids tend to be layered on top of the bed;
- segregation is much emphasized by attrition (generation of fine “elutriable” particles from coarse non-elutriable ones);
- segregation is much emphasized for gas-emitting particles (e.g. during drying and devolatilization).

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Combustion/attrition pattern

Biomass (Robinia Pseudoacacia)

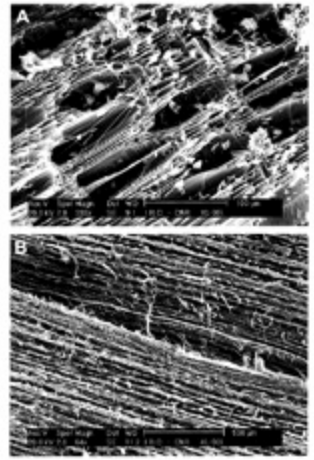
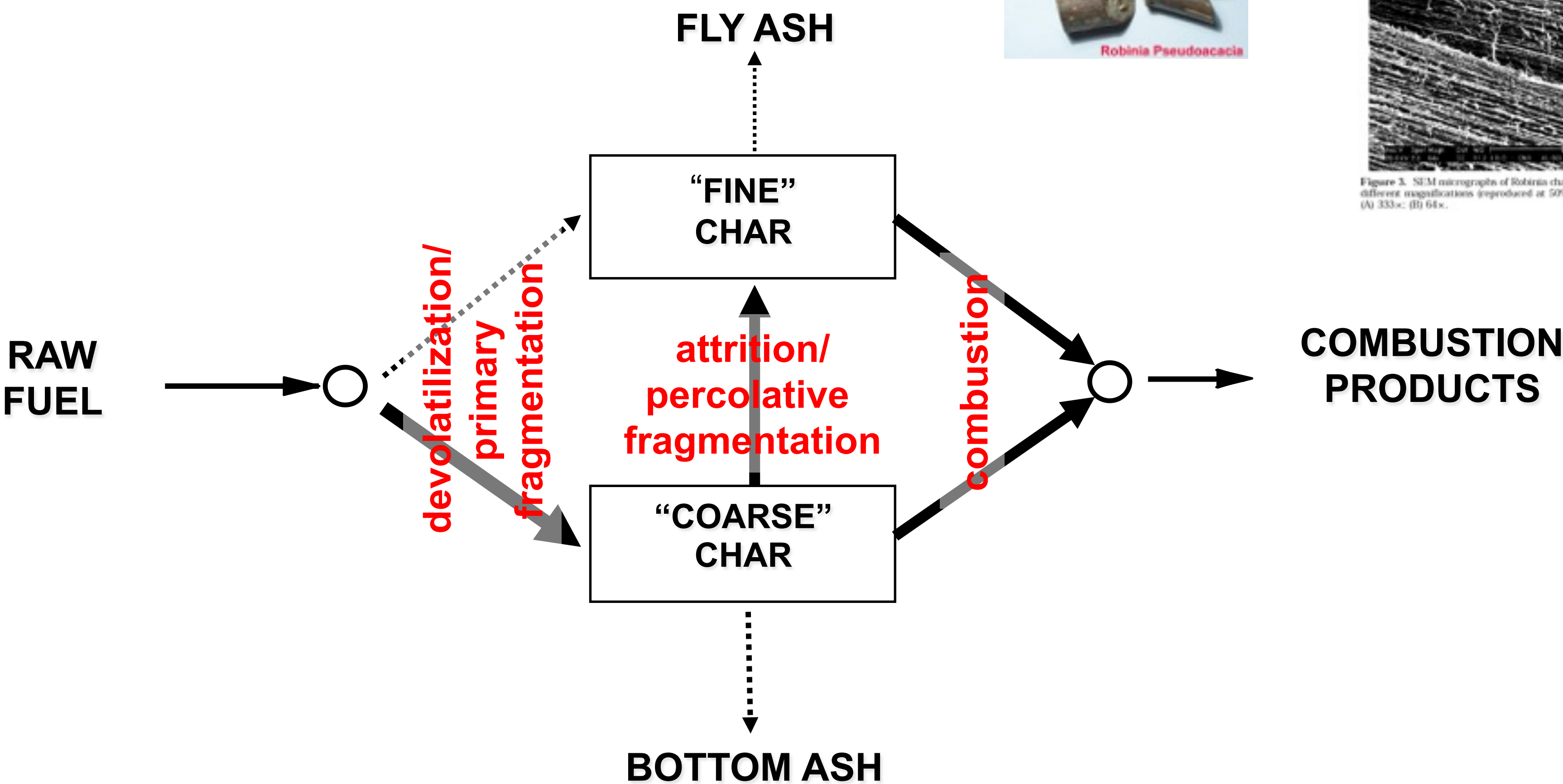
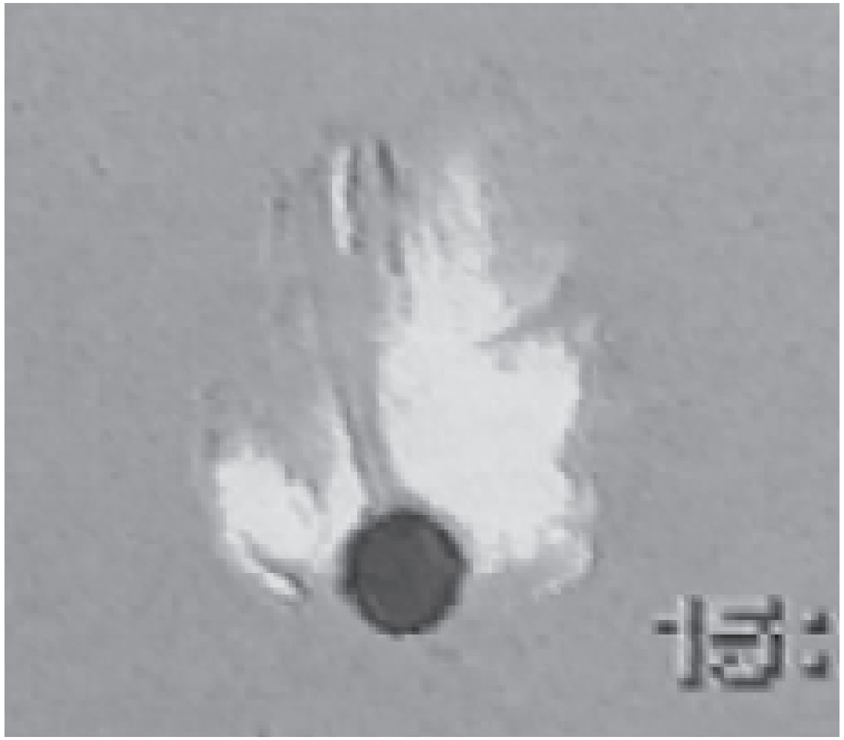
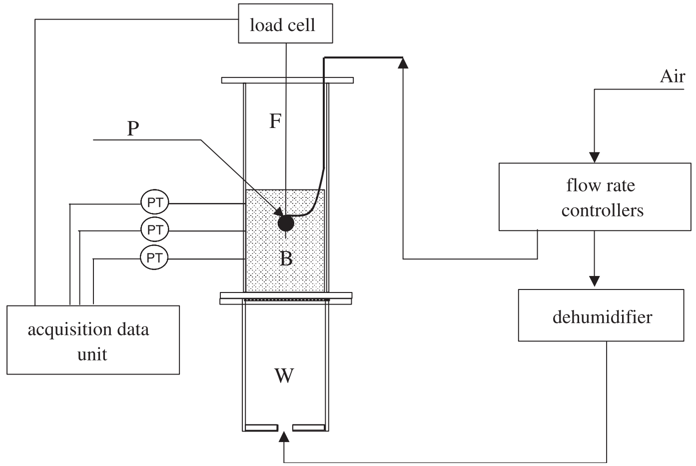


Figure 3. SEM micrographs of Robinia char particles at two different magnifications (reproduced at 50% of the original): (A) 333×; (B) 64×.



Enhanced segregation of gas-emitting particles





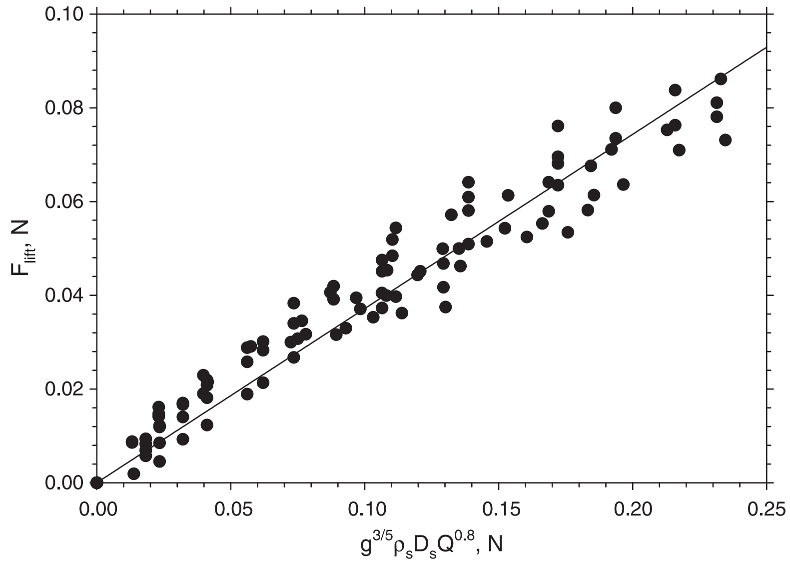


Fig. 8. Time-averaged lift force as a function of the dimensional parameter $g^{3/5}\rho_E D_s Q^{0.8}$. All the data points are reported, together with the best-fit line.

after Solimene, Marzocchella, Salatino, Powder Technology 133 (2003) 79–90

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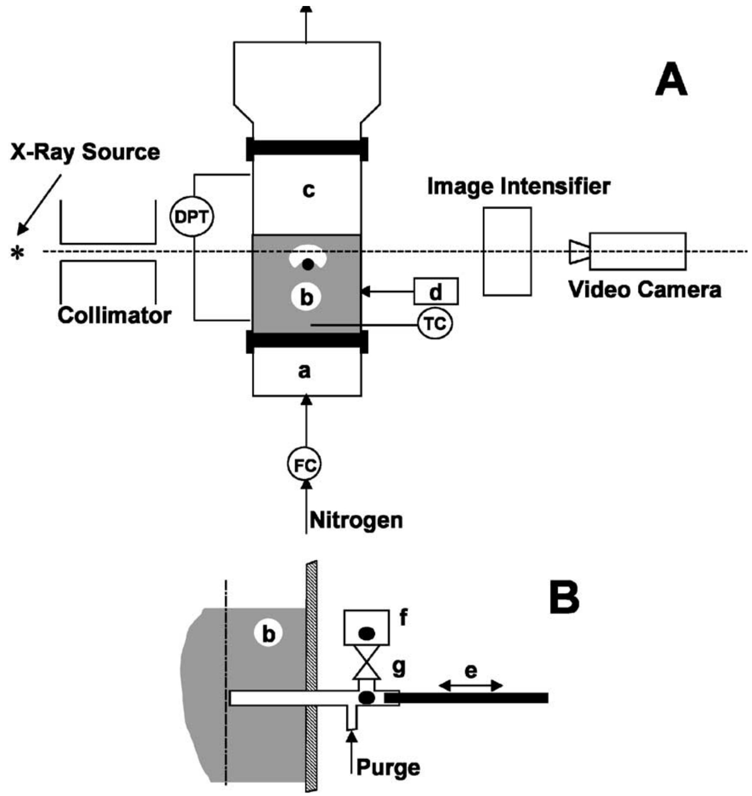
Enhanced axial segregation of a gas-emitting biomass particle

detected in an X-ray equipped hot FB facility



after Bruni, Solimene, Marzocchella, Salatino, Yates, Lettieri and Fiorentino
Powder Technology 128 (2002) 11–21

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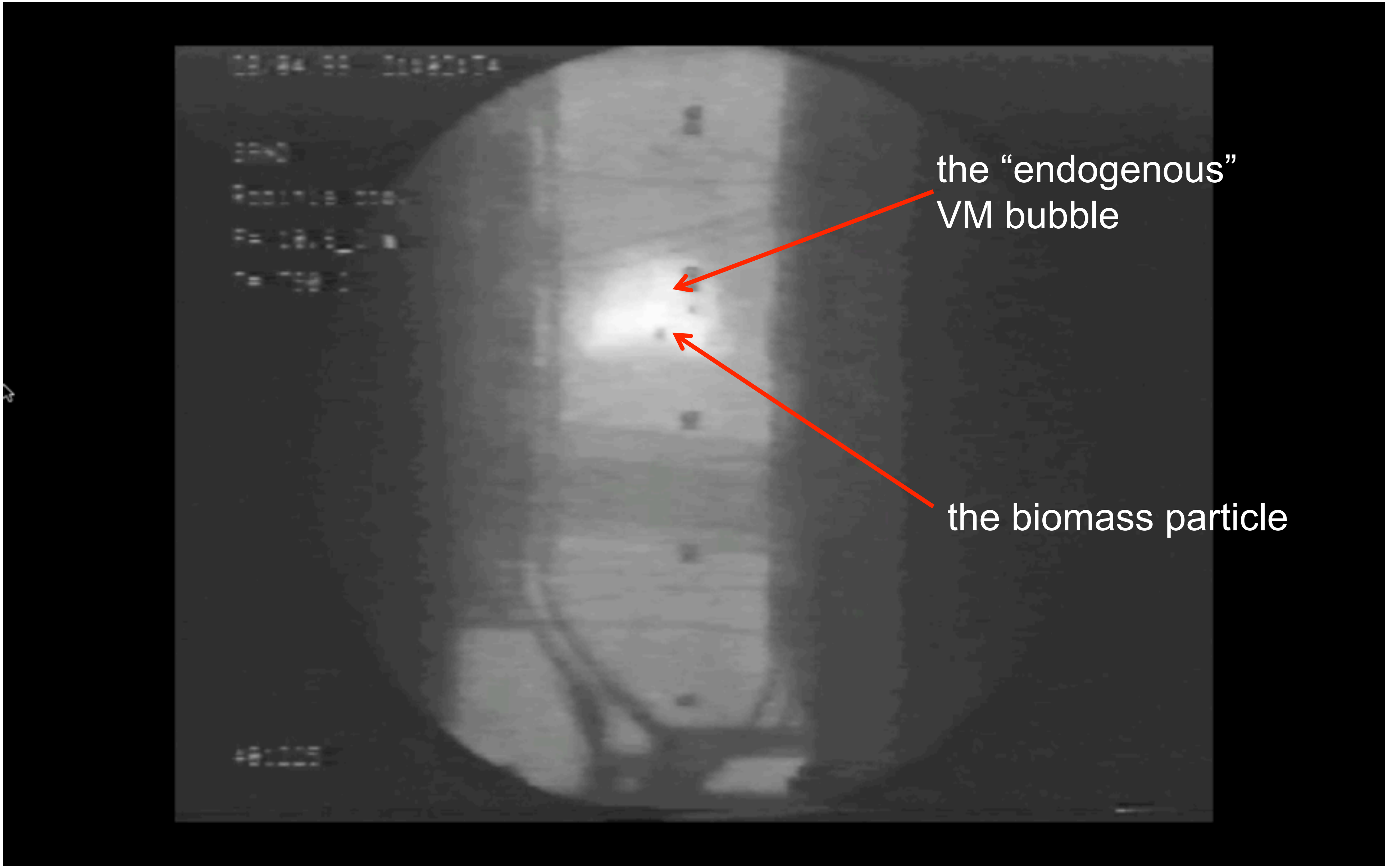


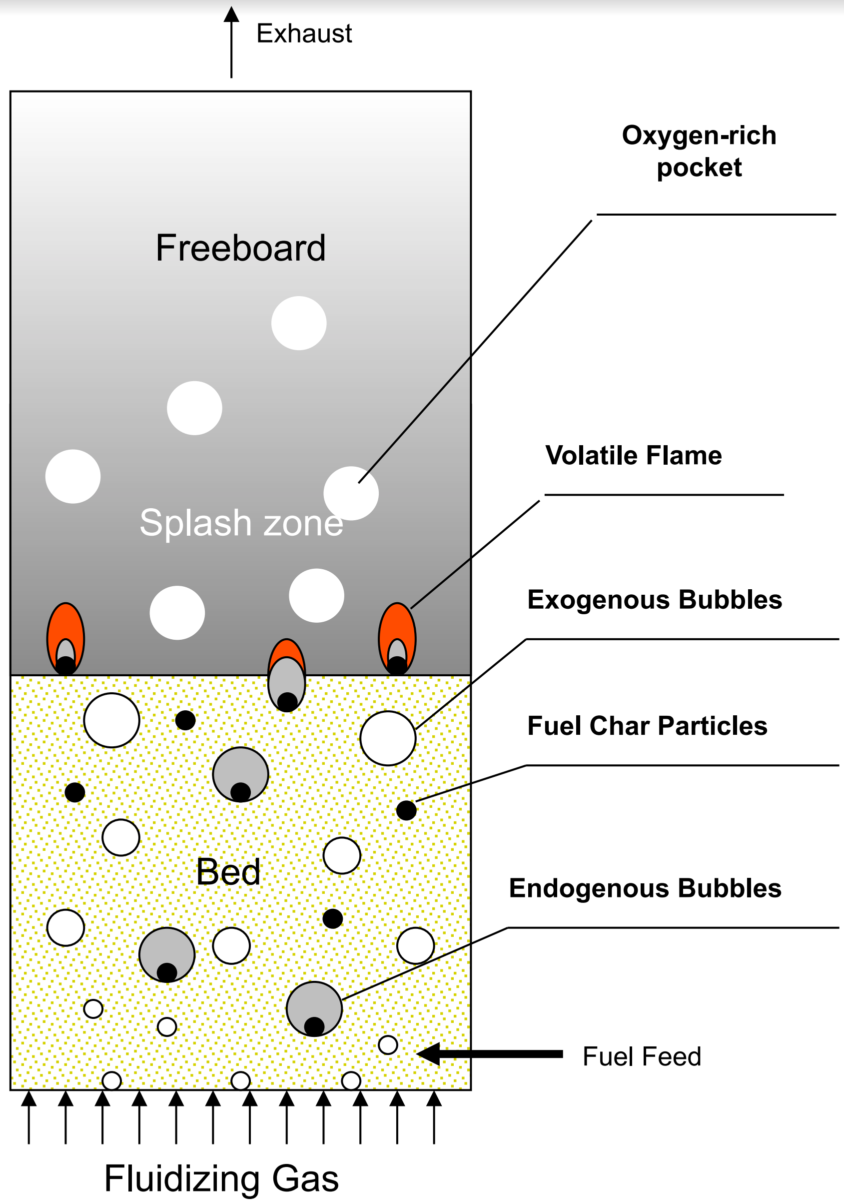
Self-segregation of a gas-emitting biomass particle

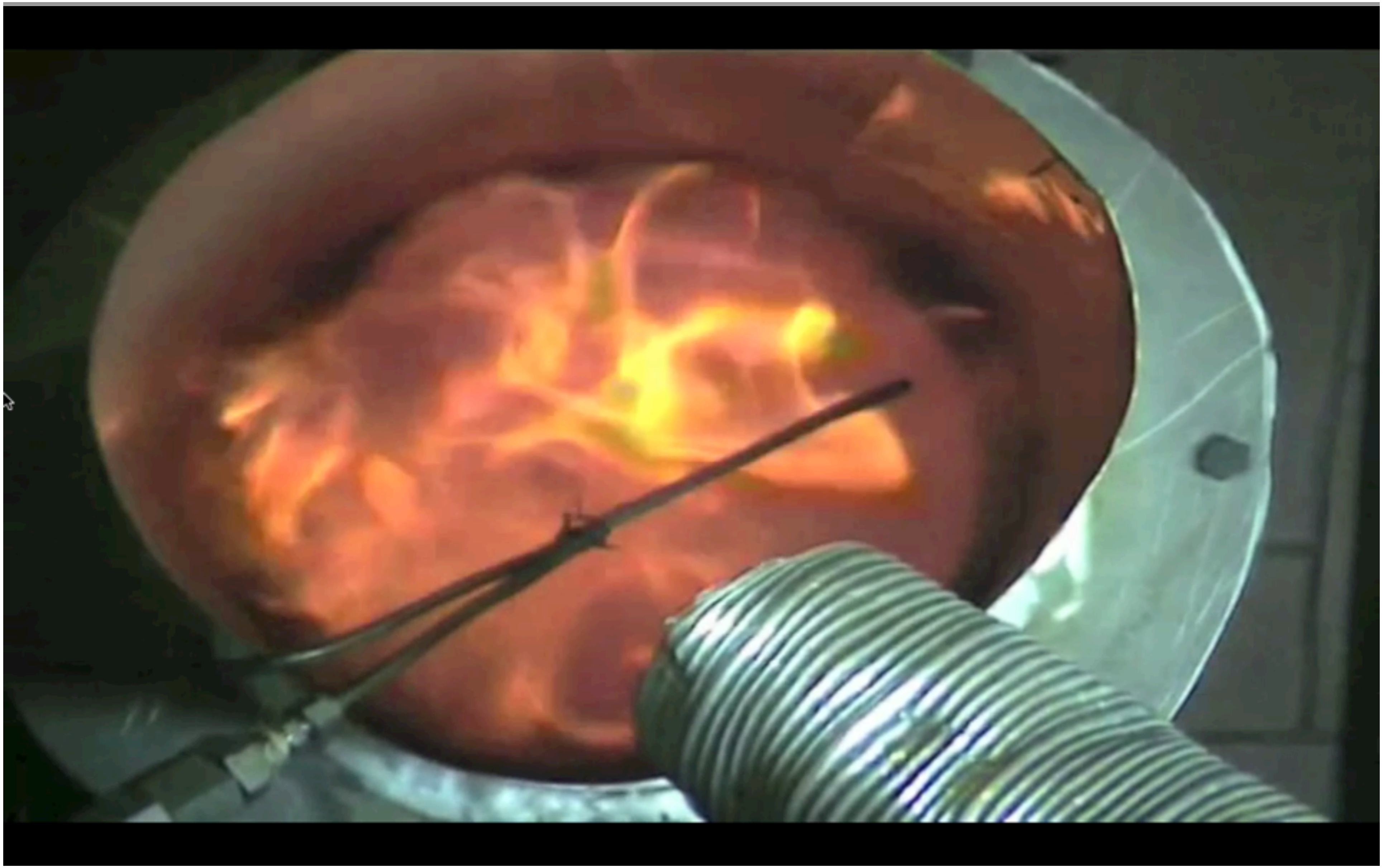
Enhanced VM segregation from gas-emitting particles: key phenomenological patterns

- Biomass particles act as pointwise sources of gas, forming "endogenous" VM bubbles
- As far as the endogenous VM bubble envelopes the fuel particle, bubble-emulsion phase mass transfer (e.g. by gas throughflow) is largely hampered.
- "Normal" gas exchange between the bubble and the emulsion phase is restored once the endogenous bubble lags the fuel particle behind.
- The prevailing segregation pattern of biomass particles brings about extensive VM segregation even in the case of submerged (underbed) fuel feeding.

Axial segregation of solids: consequences

- "stratified" conversion: volatile matter mostly released above the bed and bypassing bed solids:
  - loss of beneficial effects of bed solids as thermal flywheel,
  - prevalence of "flaming" over "flameless" combustion
  - loss of potential catalytic effects of bed solids (e.g. tar cracking).
- burn-out of fine particles in the freeboard/upper riser, higher conversion temperature





Stratified combustion (courtesy of R. Chirone, R. Solimene, M. Urciuolo)

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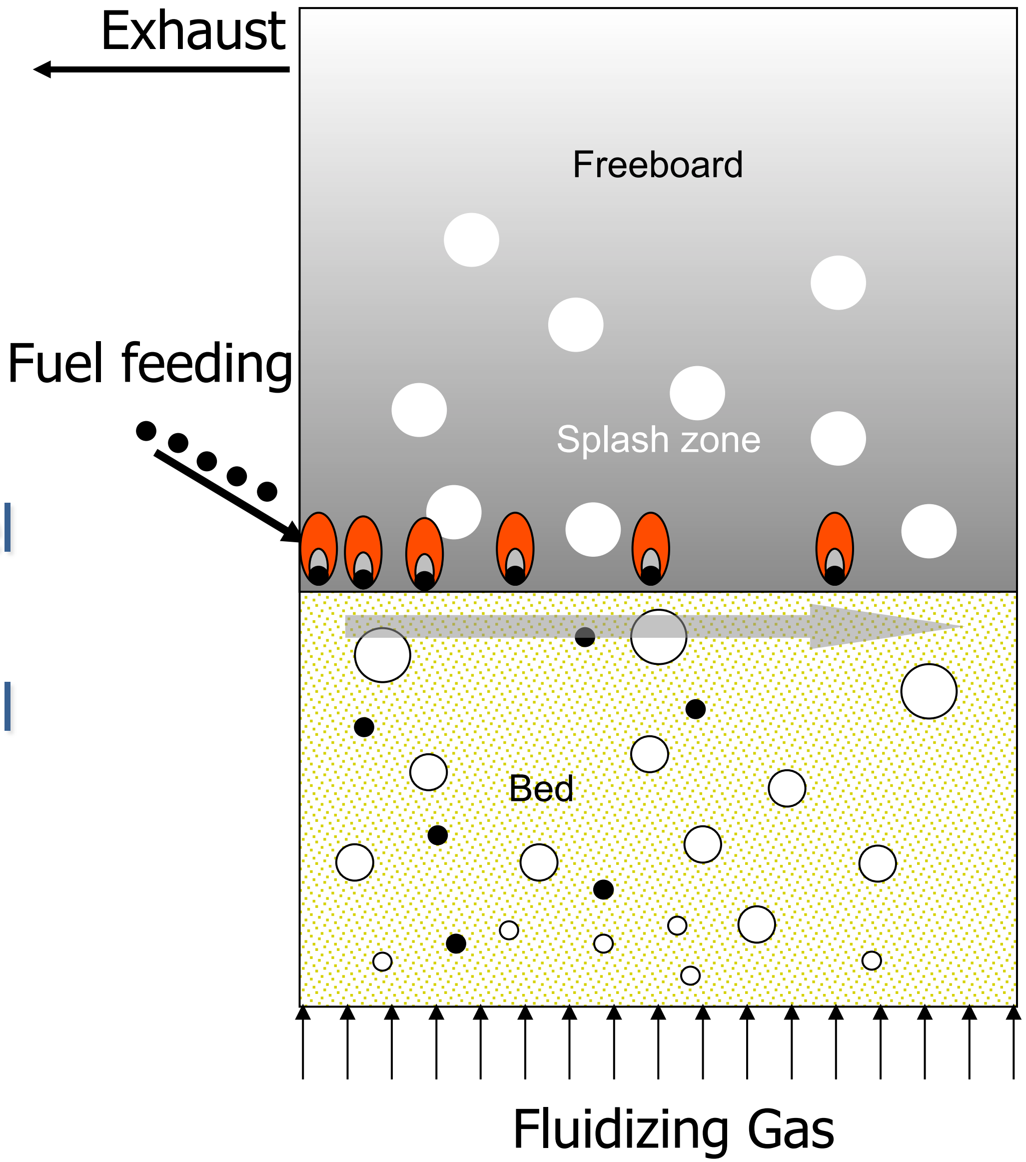
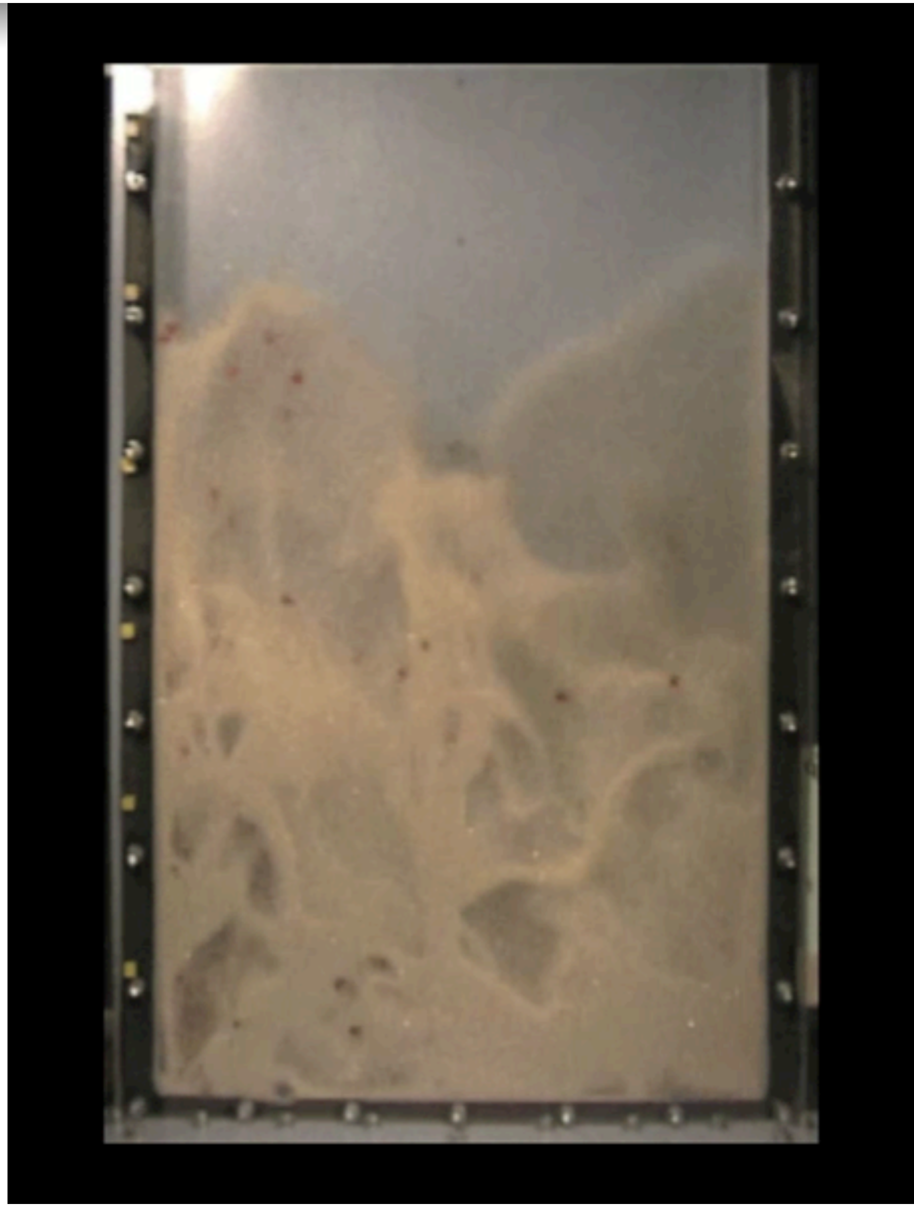
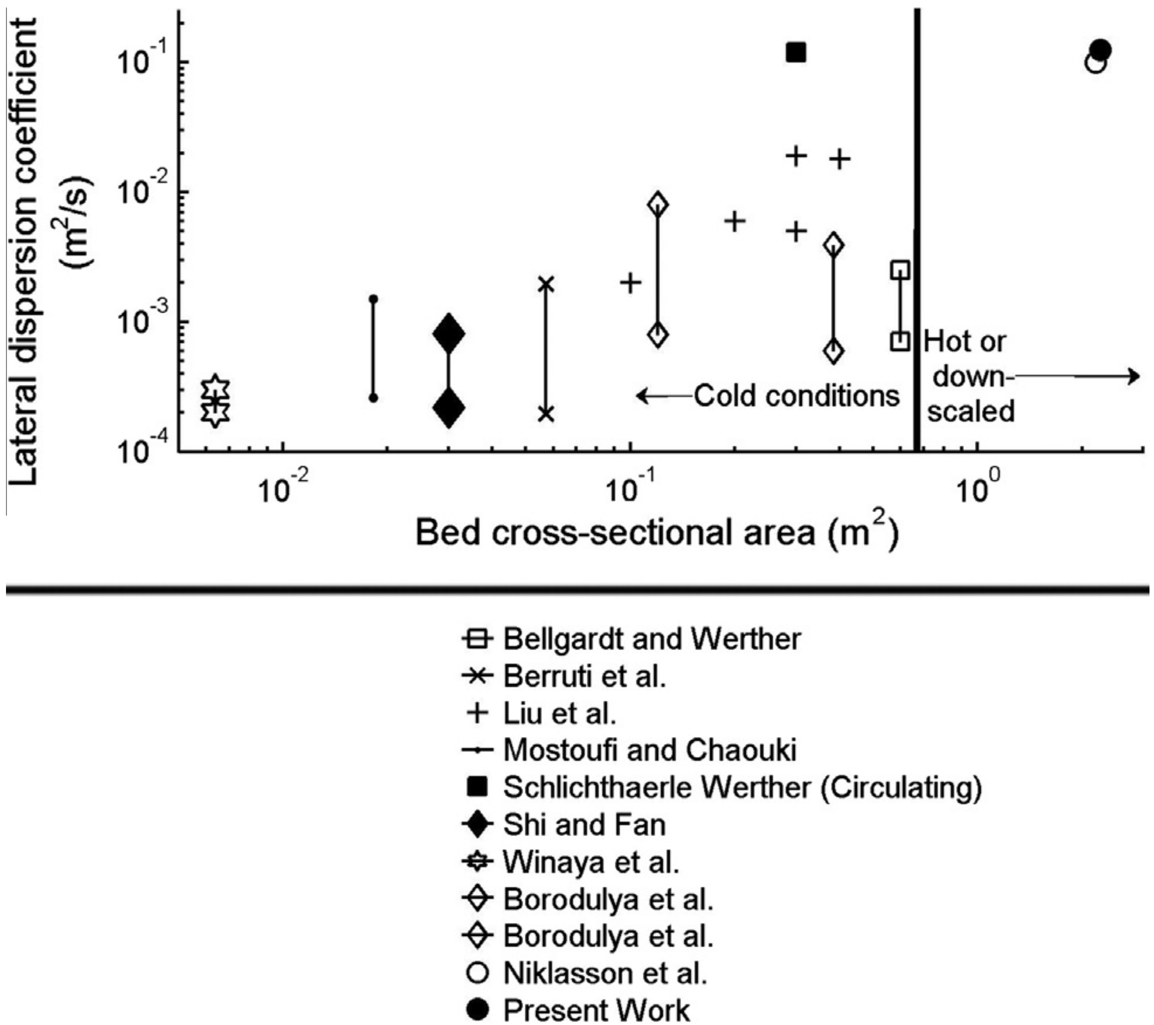
Lateral segregation of solids: mechanisms

- localized feeding of fuel particles,
- inefficient lateral spreading of particles.





Lateral mixing of dissimilar solids (courtesy of prof. F. Johnsson, CTH SE)

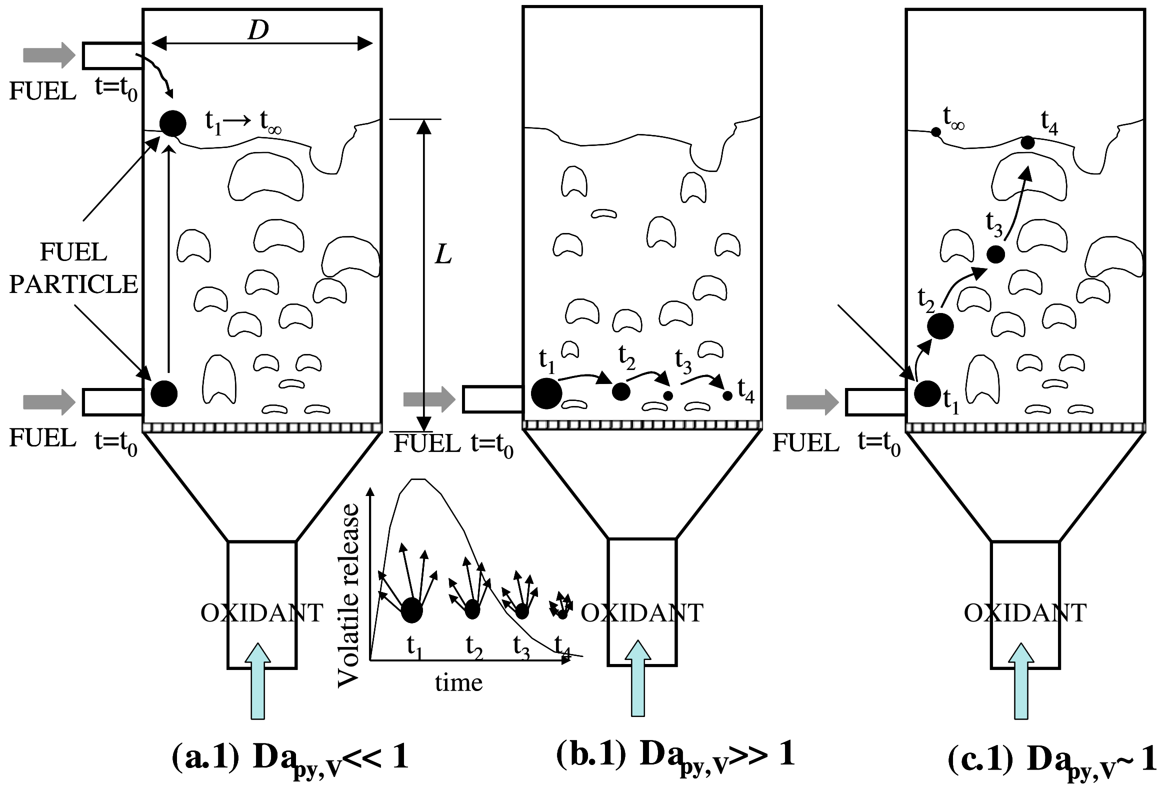


after Sette, Pallarès and Johnsson, Applied Energy 136 (2014) 671–681

Lateral segregation of solids: consequences

- Uneven release of volatile matter and localized formation of “plumes”
- Poor contact between volatile matter and the mainstream oxidizer

Establishing quantitative criteria for uniform VM release



after Gómez-Barea A, Leckner B. Progr Energy Combust Sci 2010;36(4):444–509.

Segregation and volatile matter release:

axial segregation time: t_{AS}

lateral spreading time: t_{LS}

devolatilization time: t_D

axial Damköhler number: $D_{AS} = \frac{t_{AS}}{t_D}$

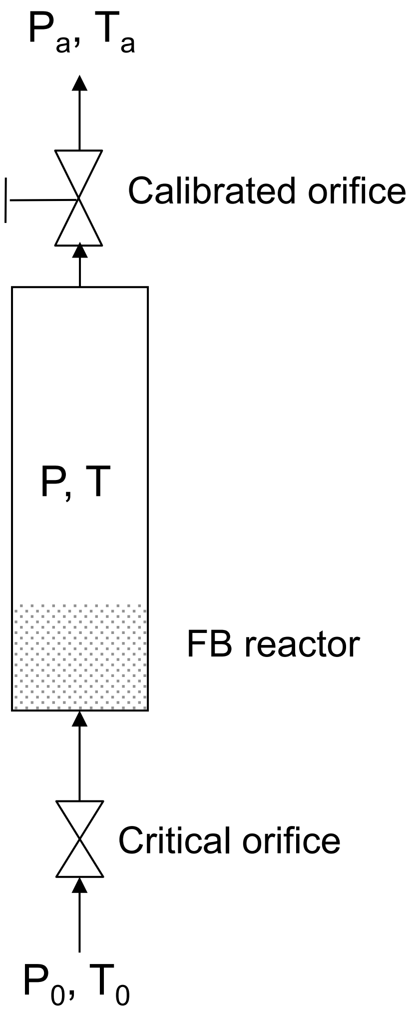
lateral Damköhler number: $D_{LS} = \frac{t_{LS}}{t_D}$

<u>Criteria for uniform VM distribution:</u>

uniform in-bed VM release: $D_{AS} \gg 1$ unlikely!

even VM lateral distribution: $D_{LS} \ll 1$

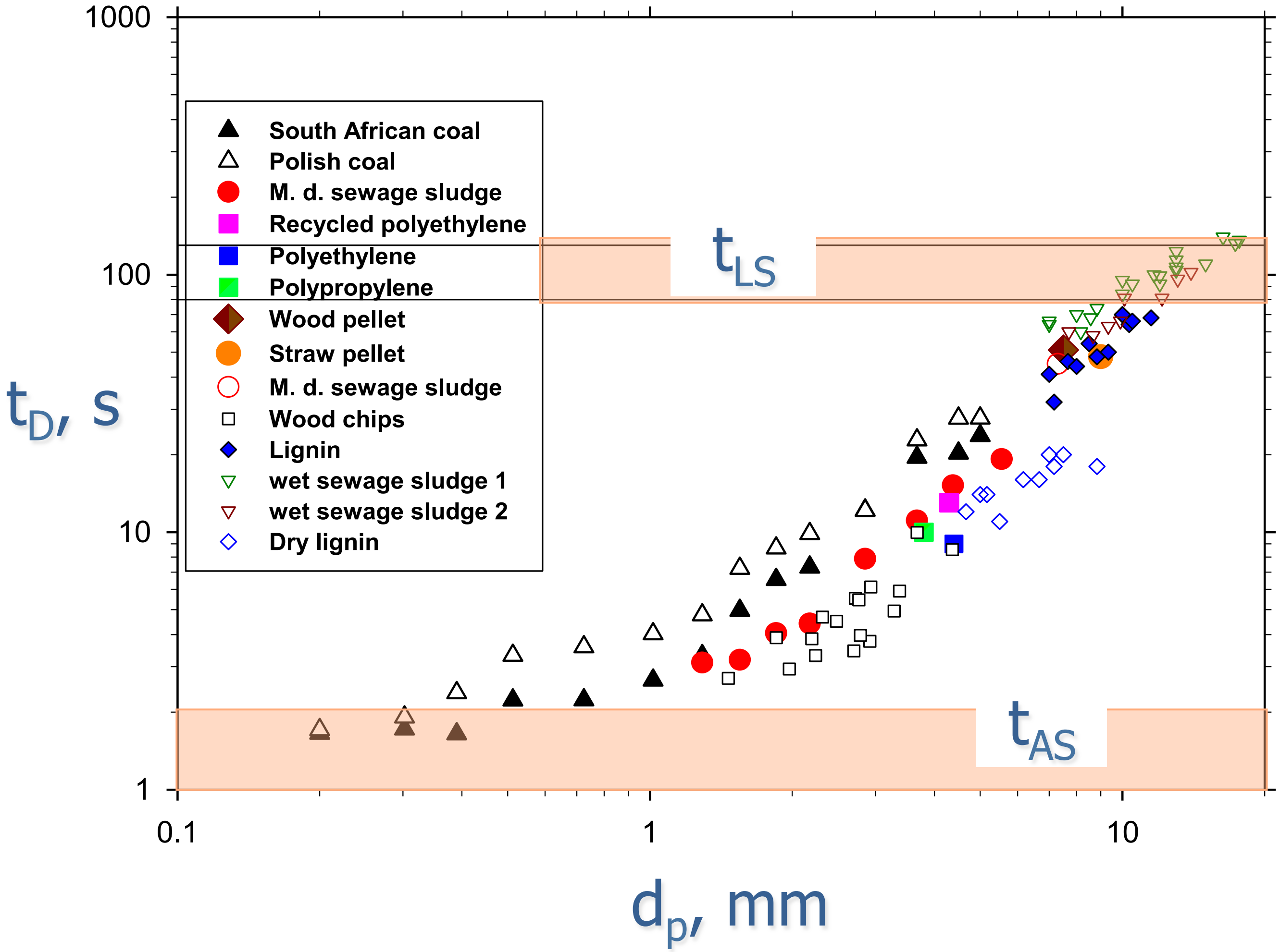
A novel technique for the characterization of fast devolatilization at FB conditions



$$V_R \frac{dP_R}{dt} + KP_R\left(P_R - P_{atm}\right) = KP_0\left(P_0 - P_{atm}\right) + RT_R \frac{\dot{m}_v(t)}{M_{vol}}$$

after Solimene et al, AIChE Journal 58 (2012) 632-645

Fuel devolatilization vs solids mixing time-scales



re-compilation of data after Solimene et al, AIChE Journal 58 (2012) 632-645

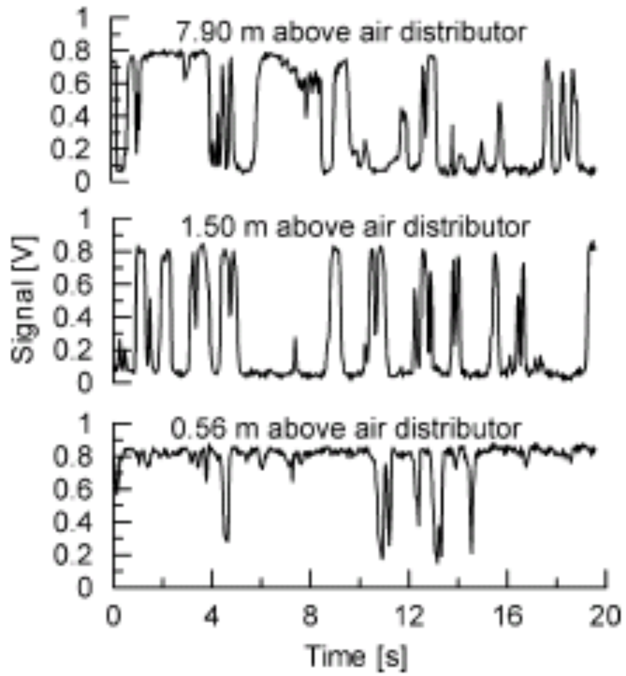
Gas phase segregation: mechanisms

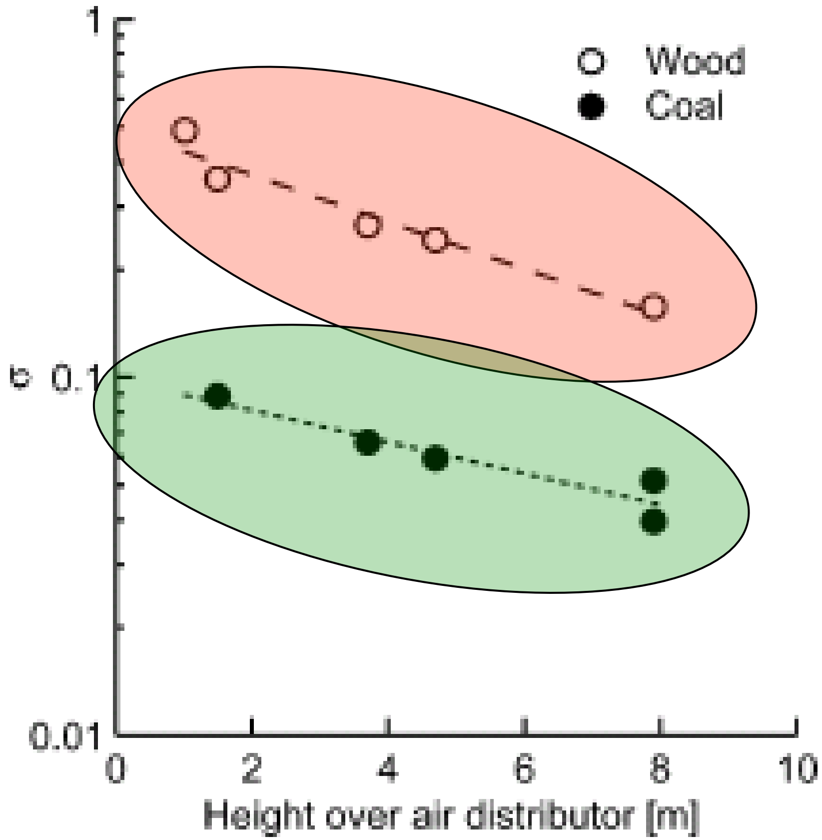
- Unlike dedicated gas converters, gas mixing in fluidized beds is controlled by "turbulence" induced by bubble bursting and hydrodynamics of the splash zone.
- Bubble-induced turbulence is far less energetic and has a much coarser structure than typical jet-induced turbulent structures.

Gas phase segregation: consequences

- Segregation and poor mixing are reflected by relatively large fluctuations in gas phase composition (e.g. oxidizing/reducing).
- Combination of “stratified” release of volatile matter and poor gas phase mixing may give rise to flaming behaviour, which negatively impacts the reactor performance.

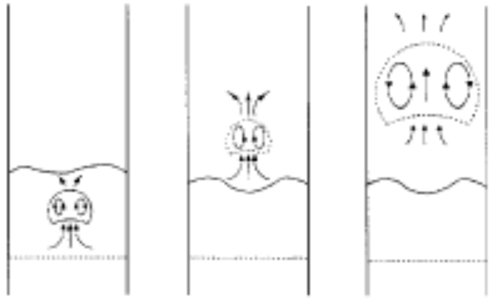
Analysis of the fluctuations of oxygen concentration in the riser of a CFBC (Chalmers 12MWth)



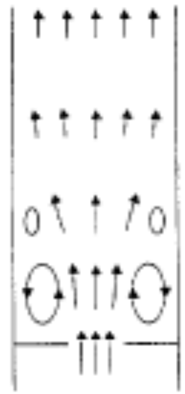


Basic "turbulent" gas flow structures and mixing patterns

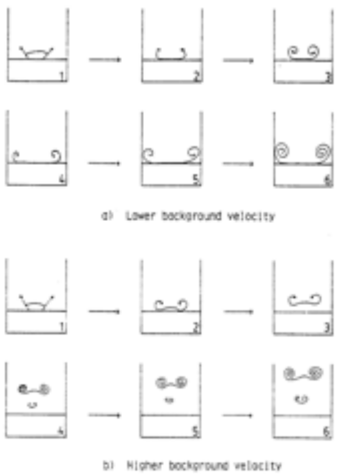
Pemberton and Davidson (1984):
the "ghost" bubbles



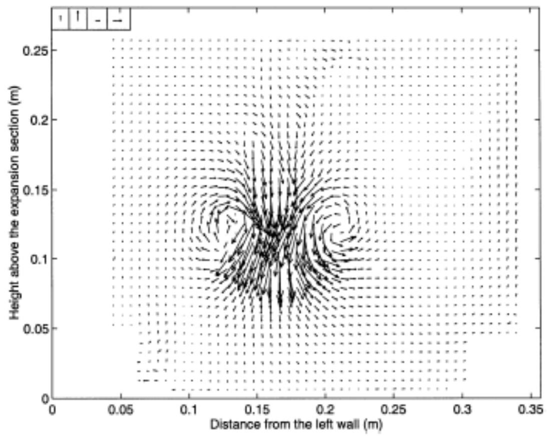
Horio et al. (1980):
the intermittent jets



Caram et al. (1984)



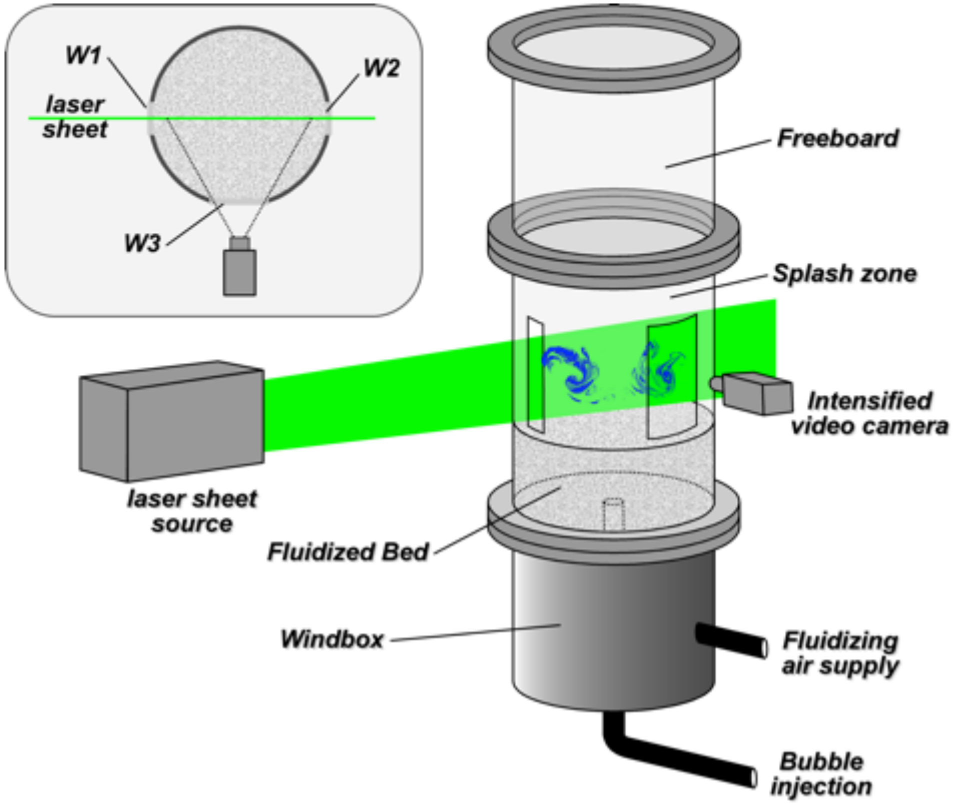
Yorquez-Ramirez
and Duursma (2000)



the toroidal vortex ring

Assessment of gas flow structures and mixing patterns

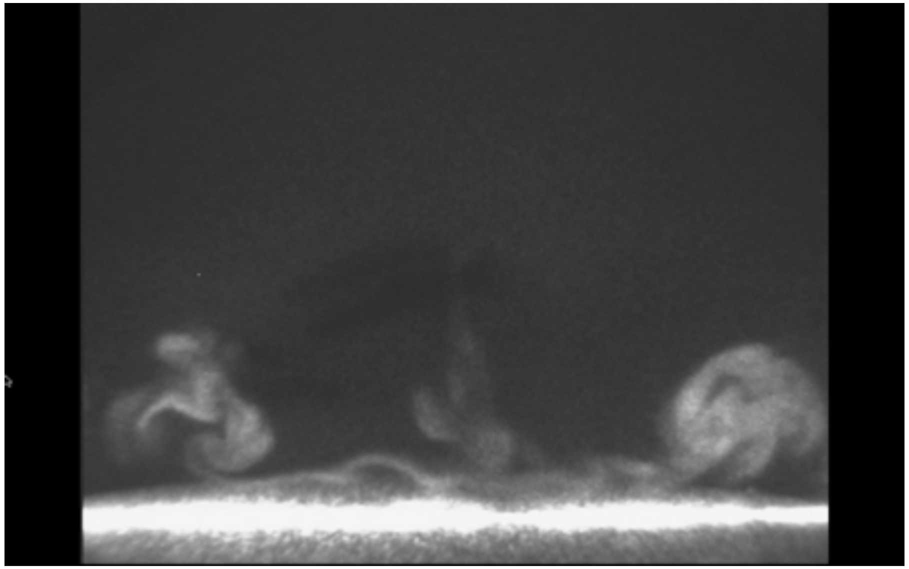
Flow and concentration mapping by Planar Laser Light-Induced Fluorescence



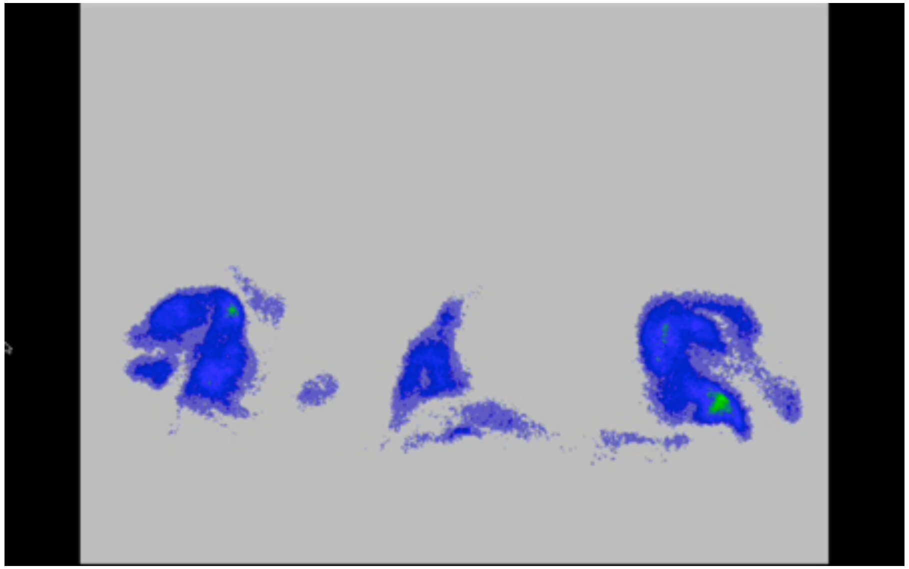
after Solimene et al., Chem. Eng. Sci. 62 (2007) 94-108

Planar Laser Light-Induced Fluorescence
(tracer: acetone)

Raw image



LIF map



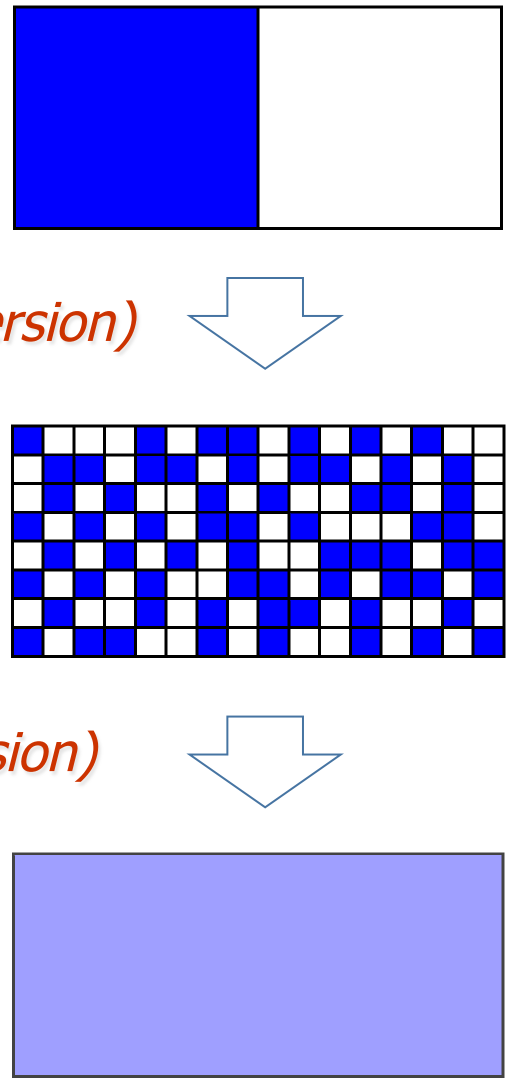
Fully segregated phases

Macromixing (dispersion)

"Macromixed" fluid

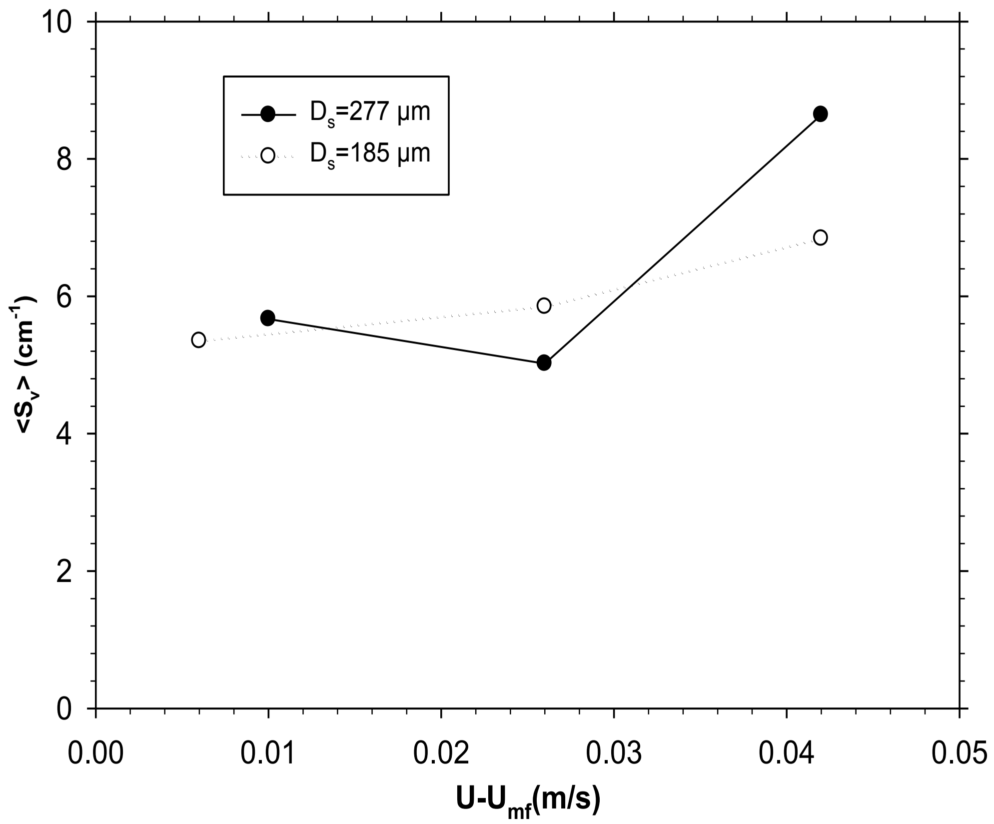
Micromixing (diffusion)

"Micromixed" fluid



The micromixing (Kolmogorov) length scale

l_K=O(1mm)



after Tebianian, Solimene and Salatino, Ind. Eng. Chem. Res. 2014, 53, 9296–9302

Establishing quantitative gas mixing criteria

chemical time-scale: t_{CH}

micromixing time scale: $t_{\mu} = \frac{l_K^2}{2 \cdot \mathcal{D}}$

$\mathcal{D}$ = diffusion coefficient; l_K= Kolmogorov length scale

micromixing Damköhler number: $Da_{\mu} = \frac{t_{\mu}}{t_{CH}}$

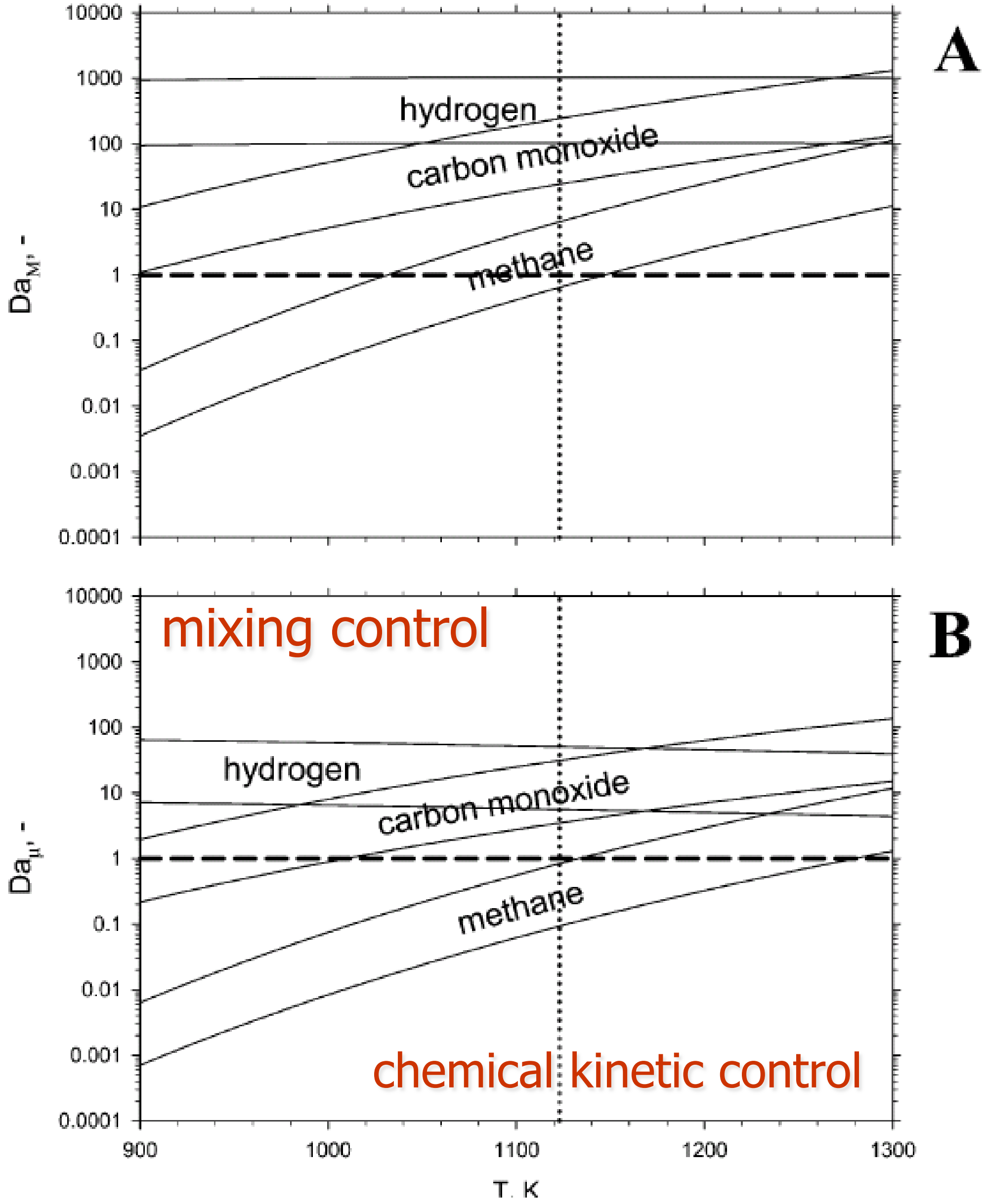
macromixing time scale: $t_{\mathbf{M}} = \frac{(2R)^2}{2 \cdot D}$

R = radial length scale; D = dispersion coefficient; $Pe_R = \frac{2R \cdot U}{D} \approx 200$; $t_M = 200 \frac{R}{U}$

macromixing Damköhler number: $Da_{\mathbf{M}} = \frac{t_{\mathbf{M}}}{t_{CH}}$

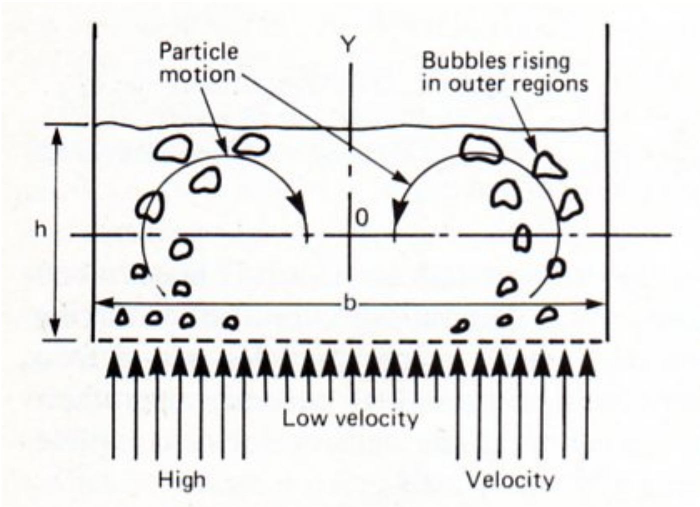
The controlling kinetic regime:

combustion of H_2, CO, CH_4



after Solimene et al, Ind. Eng. Chem. Res. 2014, 53, 9296−9302

Measures to counteract segregation of solids



"Gulf Stream" (Merry and Davidson, 1973)

Axial and lateral segregation of fuel particles (and non-uniform VM release) during devolatilization in fluidized bed reactors may be effectively contrasted by:

- promoting circulation of fluidized solids (Gulf Stream), e.g. by controlled uneven distribution of fluidizing gas flow across the distributor;
- increasing feed particle size: coarse feeding, pelletization of fine particles;
- increasing particle moisture content;
- …

Measures to counteract gas phase segregation

- Gas phase segregation in combustion may be contrasted by secondary (and possibly tertiary) “over fire” air injection, possibly associated with local restrictions of the reactor cross-sectional area to emphasize turbulence.
- Penetration lengths of secondary air jets are negatively impacted by increased solids concentration: design must be optimized to achieve a good trade-off between “earliness” of over fire feeding and effectiveness of jet penetration.
- Schemes based on sequential biomass pyrolysis followed by gas combustion are being considered, as an alternative to direct combustion. One advantage of these schemes is that gas mixing can be better controlled.

CONCLUSIONS

- Fluidized bed reactors may provide good environments to drive thermochemical processing of biomass/waste along the desired chemical pathways, provided that segregation (of solids, of gas phases) is overcome by proper design and operation.
- Fluidized bed reactors are versatile and robust solutions to many biomass-to-energy and biomass-to-chemicals processes. Flexibility must be exploited by tailoring solutions to the specific needs.

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+ MSc and PhD students and post-doctoral fellows……

Thank you…..