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Selected topics on...

MIXING AND SEGREGATION IN FLUIDIZED BED THERMOCHEMICAL CONVERSION OF BIOMASS

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Istituto di Ricerche sulla Combustione
Consiglio Nazionale delle Ricerche

Napoli (Italy)

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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

- Wood pellets
- Straw pellets
- Sewage sludge
- Refuse-derived fuel
- Tyre-derived fuel
- Robinia-pseudoacacia
- Pine nut shell
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!

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.

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
THE MISSION

harnessing the thermochemical process...

...to drive it along the desired chemical pathway
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).
Combustion/attrition pattern
Biomass (Robinia Pseudoacacia)
Enhanced segregation of gas-emitting particles

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

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

the “endogenous” VM bubble

the 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)
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)
algorithm, as explained in relation to Figs. 5 and 6. In addition, the release of volatiles in the hot experiments may influence the dispersion and such effects are obviously not included in the cold tests. Yet, under industrial conditions, velocities and thereby bubble movements are rather vigorous (convection dominates) and it is fair to assume that effects from volatile release is much less than what has been experimentally determined by [35] under low velocities.

After validating the fluid-dynamical downscaling of the fuel mixing, an evaluation of the two methods used and of the influence of wall effects is shown as three sets of data in Fig. 11. Concerning the comparison between the experimental methods, the same test conditions (bed height 0.3 m and high pressure drop distributor) were applied for both cold flow models and the two experimental methods. The robustness of both methods is seen in Fig. 11, which shows that both methods yield similar result values at a given test condition. The two methods yield the same trends in three out of four cases; wood chips at 0.21 m/s do not follow the expected trend when using the direct method, which may suggest that the indirect method is more robust. Note that data points in Fig. 11 are one order of magnitude lower than those in Fig. 10. This is due to that data from Fig. 11 is sampled at much lower gas velocities and lower bed height.

The presence of wall effects is clear from data in Fig. 11, for which the same set of four different conditions are applied to the two different fluidized bed units presented above using wood chips and pellets, i.e. fuel particles of different density. The lateral dispersion coefficients obtained in cold flow model B are consistently lower than the values for cold flow model A.

As noted above some uncertainty exists in the analysis using the direct method and the error is estimated to ±20%. Multivariate data analysis is used to determine common trends for the three different fuels, in this analysis the operational conditions (velocity, bed height and gas distributor characteristics) are also included together with the lateral dispersion coefficient for bed material [37,38].

Fig. 12a is a loading plot of the parameters used in the multivariate data analysis showing the common relationships among the data, three components from the multivariate data analysis are used and together they explain 94% of the variation in the data. Fig. 12b exemplifies some of those trends by plotting the lateral dispersion coefficients for pellets and char.

Tables A.1–A.3 in Appendix A show all lateral dispersion coefficient values obtained.

Table 2

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Niklasson et al. [11]</th>
<th>According to scaling laws</th>
<th>Actually used in the present work</th>
</tr>
</thead>
<tbody>
<tr>
<td>Particle size, bed material</td>
<td>l m</td>
<td>700</td>
<td>140</td>
<td>140</td>
</tr>
<tr>
<td>Particle density, bed material</td>
<td>kg/m^3</td>
<td>2600</td>
<td>10,600</td>
<td>8900</td>
</tr>
<tr>
<td>Particle density, fuel</td>
<td>kg/m^3</td>
<td>700</td>
<td>2200</td>
<td>2200</td>
</tr>
<tr>
<td>Gas velocity m/s</td>
<td>2.3</td>
<td>1.03</td>
<td>1.03</td>
<td></td>
</tr>
<tr>
<td>Bed height m</td>
<td>0.5</td>
<td>0.1</td>
<td>0.1</td>
<td></td>
</tr>
</tbody>
</table>

Fig. 10. Lateral dispersion coefficient values found in literature, the size of the equipment used and the obtained lateral dispersion coefficients spans several orders of magnitude. The values obtained in the present work for soaked wood chips should be compared with the value determined by Niklasson et al. [11].

Fig. 11. Lateral dispersion coefficient for two fuel types at two different velocities in the two geometries, indicating the presence of wall effects. Wall effects are shown by the dispersion coefficient for cold flow model A is higher than those for the cold flow model B.

Fig. 12. (a) Loading plot from the multivariate data analysis, showing the common features in the data. (b) Lateral dispersion coefficient for pellets and char plotted against bed height for the two gas distributors.

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

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: $D_{LS} = \frac{t_{LS}}{t_D}$

Criteria for uniform VM distribution:

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

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

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)
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

Basic “turbulent” gas flow structures and mixing patterns
Assessment of gas flow structures and mixing patterns
Flow and concentration mapping by Planar Laser Light-Induced Fluorescence

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

\[ l_K = O(1\text{mm}) \]

Establishing quantitative gas mixing criteria

chemical time-scale: \[ t_{CH} \]

micromixing time scale: \[ t_\mu = \frac{l_K^2}{2 \cdot D} \] \( D \) = diffusion coefficient; \( l_K \) = Kolmogorov length scale

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

macromixing time scale: \[ t_M = \frac{(2R)^2}{2 \cdot D} \] \( R \) = radial length scale; \( D \) = dispersion coefficient; \( Pe_R = \frac{2R \cdot U}{D} \approx 200 \); \( t_M = 200 \frac{R}{U} \)

macromixing Damköhler number: \[ Da_M = \frac{t_M}{t_{CH}} \]
The controlling kinetic regime:

combustion of $\text{H}_2$, CO, $\text{CH}_4$

Measures to counteract segregation of solids

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;
- ...

“Gulf Stream” (Merry and Davidson, 1973)
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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