Residence Time Distribution of Fine to Coarse Particles in Rotary Kilns

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Rotary Kilns

**cylindrical shell**
- inclined (or not)
- continuous flow of solid charge
- counter-current of gas
- directly or externally heated
- equipped with:
  - lifters (or not)
  - dam at the kiln outlet end (or not)

(simple)

**many applications**
- reduction of oxide ore, pyrolysis of hazardous waste, calcining of petroleum coke, conversion of uranium fluoride into uranium dioxide for the manufacture of nuclear fuel, sugar drying, etc.

**BUT lack of simple tools for industry**
Our Rotary Kilns

Paris
- Length = 1.95 m
- Diameter = 0.101 m
- Rot. speed: 0.5 - 12 rpm
- Slope: 0 - 5°
- Flow rate: 0.5 - 3 kg h\(^{-1}\)
- Dam: 0 - 33.5 mm
- Lifters: NL - SL - RL

Albi
- Length = 4.2 m
- Diameter = 0.21 m
- Rot. speed: 0.5 - 21 rpm
- Slope: 0 - 7°
- Flow rate: 0.5 - 10 kg h\(^{-1}\)
- No Dam
- Lifters: NL - G - 3SL - 6SL
Our Rotary Kilns

Paris
- Length = 1.95 m
- Diameter = 0.101 m
- Rot. speed: 0.5 - 12 rpm
- Slope: 0 - 5°
- Flow rate: 0.5 - 3 kg h⁻¹
- Dam: 0 - 33.5 mm

Alb
- Length = 4.2 m
- Diameter = 0.21 m
- Rot. speed: 0.5 - 21 rpm
- Slope: 0 - 7°
- Flow rate: 0.5 - 10 kg h⁻¹
- No Dam
- Lifters: NL - SL - RL

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# Materials

<table>
<thead>
<tr>
<th></th>
<th>Fine Sand</th>
<th>Medium Sand</th>
<th>Broken Rice</th>
<th>Beech Chips</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Bulk Density [kg m(^{-3})]</strong></td>
<td>1053</td>
<td>1422</td>
<td>889</td>
<td>260</td>
</tr>
<tr>
<td><strong>Tapped Density [kg m(^{-3})]</strong></td>
<td>1170</td>
<td>1543</td>
<td>934</td>
<td>284</td>
</tr>
<tr>
<td><strong>Hausner Ratio [-]</strong></td>
<td>1.111</td>
<td>1.085</td>
<td>1.051</td>
<td>1.092</td>
</tr>
<tr>
<td><strong>Size [mm]</strong></td>
<td>0.1</td>
<td>0.55</td>
<td>3.8 x 1.9</td>
<td>10 x 4.5 x 2</td>
</tr>
<tr>
<td><strong>Angle of Repose [°]</strong></td>
<td>33</td>
<td>39</td>
<td>36</td>
<td>42</td>
</tr>
<tr>
<td><strong>Tracer</strong></td>
<td>Calibrated NaCl</td>
<td>Calibrated NaCl</td>
<td>Dyed Broken Rice</td>
<td>Dyed Beech Chips</td>
</tr>
</tbody>
</table>

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**Free flowing materials**

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2014 AIChE

Bongo et al., Powder Tech., 2016
Materials: fine sand

0.1 mm
Materials: medium sand
Materials: broken rice
Materials: beech chips

10 x 4.5 x 2 mm
Methods

- reach steady-state conditions
- introduce 12 g of tracer in inlet flow (impulse input)
- collect samples at the end of kiln every 30 s & weight them
- obtain tracer signal:
  - separate dyed particles and weight
  - or
  - dissolve sample in 20 mL water and measure conductivity
PARIS: Medium sand & broken rice
Results:

a) Influence of kiln rotational speed - SL - Sand

b) Influence of kiln slope - SL - Sand

c) Influence of flow rate - SL - Sand

d) Influence of kiln exit dam height - SL - Sand
Results: mean residence time (MRT)

a) Variation of MRT with kiln rotational speed

b) Variation of MRT with kiln slope

c) Variation of MRT with mass flow rate

d) Variation of MRT with kiln exit dam height
Model #1

\[
\bar{t} = k \left( \frac{\rho_{\text{bulk}} LD^2}{\dot{M}} \right)^\alpha \left( \frac{N^2 D}{g} \right)^\beta \left( \frac{D_{\text{open}}}{D} \right)^\gamma (\theta)^\delta \left( \frac{\dot{M}}{\rho_{\text{bulk}} NLD^2} \right)^\varepsilon \left( \frac{4S_{\text{lift}}}{\pi D^2} \right)^\varepsilon \left( \frac{\rho_{\text{bulk}}}{\rho_{\text{tapped}}} \right)^\zeta \left( \frac{L}{D} \right)
\]


### Experimental Data

<table>
<thead>
<tr>
<th>Exp. data</th>
<th>k</th>
<th>( \alpha )</th>
<th>( \beta )</th>
<th>( \gamma )</th>
<th>( \delta )</th>
<th>( \varepsilon )</th>
<th>( \varepsilon )</th>
<th>( \zeta )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sand</td>
<td>0.1363</td>
<td>0.0508</td>
<td>-0.4008</td>
<td>0.8749</td>
<td>-0.9814</td>
<td>0.8115</td>
<td>-4.5285</td>
<td>0.7723</td>
</tr>
<tr>
<td>Rice</td>
<td>0.0792</td>
<td>-0.0218</td>
<td>-0.3387</td>
<td>0.8749</td>
<td>-1.2277</td>
<td>0.8184</td>
<td>-8.0175</td>
<td>0.7723</td>
</tr>
<tr>
<td>Sand &amp; rice</td>
<td>0.2611</td>
<td>0.0842</td>
<td>-0.3649</td>
<td>0.8749</td>
<td>-1.1243</td>
<td>0.8350</td>
<td>-5.5283</td>
<td>0.7723</td>
</tr>
</tbody>
</table>

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Model #1 with medium sand & rice
ALBI: Beech chips
Results

a) Influence of kiln rotational speed - 3 SL - Beech chips

b) Influence of kiln slope - 3 SL - Beech chips

c) Influence of flow rate - 3 SL - Beech chips
Results

a) Variation of MRT with kiln rotational speed

```
\text{Kiln rotational speed [rpm]}
```

b) Variation of MRT with kiln slope

```
\text{Kiln slope [°]}
```

c) Variation of MRT with mass flow rate

```
\text{Mass flow rate [kg.h^{-1}]} 
```
Model #1 with beech chips
Model #2

Dimensional Analysis of Food Processes, Delaplace et al., Ed. Elsevier, 2015

\[ \bar{t} = k \sqrt{gL} \left( \frac{N^2 D_i}{g} \right)^{\alpha} \left( \frac{D_{ex}}{D_i} \right)^{\beta} \left( \frac{\theta}{\bar{S}} \right)^{\gamma} \left( \frac{M}{\rho_{bulk} D_i^3 \sqrt{gL}} \right)^{\delta} \left( \frac{4S_{lift}}{\pi D_i^2} \right)^{\varepsilon} \left( \frac{\rho_{bulk}}{\rho_{tapped}} \right)^{\xi} \]

- Froude number
- angle of repose
- dam slope
- kiln slope
- Hausner ratio

Model parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Confid. interval</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>(t)</td>
<td>0.0026</td>
<td>-0.0023 to 0.0074</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(k)</td>
<td>0.4422</td>
<td>-0.5367 to -0.3478</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(\alpha)</td>
<td>0.3597</td>
<td>-0.4715 to -0.2478</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(\beta)</td>
<td>0.9276</td>
<td>0.7730 to 1.0822</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(\gamma)</td>
<td>-0.1130</td>
<td>-0.1574 to -0.0686</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(\delta)</td>
<td>-8.8835</td>
<td>-11.459 to -6.3081</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(\varepsilon)</td>
<td>-2.4641</td>
<td>-5.3569 to 0.4286</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Bongo et al., Powder Tech., 2016
Model #2 with medium sand, rice & beech

Sand

Experimental $\bar{t}$ [min] vs. Calculated $t$ [min]

Broken Rice

Experimental $\bar{t}$ [min] vs. Calculated $t$ [min]

Beech chips

Experimental $\bar{t}$ [min] vs. Calculated $t$ [min]

Experimental $D$ [m$^2$.s$^{-1}$] vs. Calculated $D$ [m$^2$.s$^{-1}$]

- 4 RL
- 4 SL
- 4 NL
- 6 SL
- 3 SL
- G

- 4 RL
- 4 SL
- 4 NL
- 6 SL
- 3 SL
- G

- 4 RL
- 4 SL
- 4 NL
- 6 SL
- 3 SL
- G

- 4 RL
- 4 SL
- 4 NL
- 6 SL
- 3 SL
- G
PARIS: Fine sand
Preliminary results

- Fine Sand - 4 rpm
- Fine Sand - 6 rpm
- Fine Sand - 10 rpm
- Medium Sand - 4 rpm
- Medium Sand - 6 rpm
- Medium Sand - 10 rpm
- Rice - 6 rpm
- Rice - 10 rpm

Hausner ratio:
- Fine Sand: 1.111, 33°, 0.1 mm
- Medium Sand: 1.085, 39°, 0.55 mm
- Rice: 1.051, 36°, ~4x2 mm

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Towards Model #3

angle of repose & Hausner ratio alone can’t explain the value of MRT

add particles diameter?
Summary & Future work

Materials

- fine to coarse particles: 0.1 – 0.55 – 3.8x1.9 – 10x4.5x2
- free flowing particles

Kilns

- Ø 10 mm – 2 m – Dams – Lifters
- Ø 20 mm – 4 m – No dam – Different lifters

Model

\[ t = k \sqrt{gL} \left( \frac{N^2 D_i}{g} \right)^{\alpha} \left( \frac{D_{ex}}{D_i} \right)^{\beta} \left( \frac{\theta}{S} \right)^{\gamma} \left( \frac{\dot{M}}{\rho_{bulk} D_i^2 \sqrt{gL}} \right)^{\delta} \left( \frac{4S_{lift}}{\pi D_i^2} \right)^{\epsilon} \left( \frac{\rho_{bulk}}{\rho_{tapped}} \right)^{\xi} \left( \frac{L}{D_i} \right)^{\eta} \]

add particle diameter?
Acknowledgments

190 experiments performed