Cold flow investigations of a Circulating Fluidized Bed Chemical Looping Combustion system as a basis for up-scaling to an industrial application

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Chemical Looping Combustion (CLC):
A divided combustion process with intrinsic CO\(_2\) separation. An oxy-fuel process without the need of an oxygen plant (potential lower costs and higher net power efficiency)
The BIGCLC project
A subproject within the larger BIGCO2/BIGCCS project framework

Reactor system:
1. **Cold Flow Model (CFM)** construction, commissioning and testing for validation of the 150kW\textsubscript{th} atmospheric rig design
2. **150kW\textsubscript{th} atmospheric rig** construction, commissioning and test campaigns
3. Pressurized conditions

Bischi et al.,
“Design study of a 150kW\textsubscript{th} Double Loop Circulating Fluidized Bed reactor system for Chemical Looping Combustion with focus on industrial applicability and pressurization”

Oxygen carrier materials:
1. Screening and preliminary investigation
2. Selection and TGA testing (Mn-ore + Ca & Ti)
3. Fabrication by industrial methods
4. Testing in a small continuous FB process

Fossdal et al.,
“Study of inexpensive oxygen carriers for chemical looping combustion”
Double Loop Circulating Fluidized Bed (DLCFB)

Design criteria

- High gas–solids contact
- High solids exchange
- Flexibility of configuration
- Compactness
- Choose industrial solutions wherever possible
- Continuous operation
Double Loop Circulating Fluidized Bed (DLCFB)

Design parameters

<table>
<thead>
<tr>
<th>Design parameter</th>
<th>AR 150kW_\text{th}</th>
<th>FR 150kW_\text{th}</th>
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</thead>
<tbody>
<tr>
<td>( u_0 ) [m/s]</td>
<td>~4</td>
<td>~4</td>
</tr>
<tr>
<td>( D ) [m]</td>
<td>0.25</td>
<td>0.15</td>
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<tr>
<td>( L ) [m]</td>
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<tr>
<td>( \rho_p ) [kg/m(^3)]</td>
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<td>( \rho_f ) [kg/m(^3)]</td>
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<tr>
<td>( d_{50} ) [(\mu)m]</td>
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<tr>
<td>( \mu ) [Ns/m(^2)]</td>
<td>4.84E-05</td>
<td>4.29E-05</td>
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<tr>
<td>( T ) [°C]</td>
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<td>1000</td>
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<tr>
<td>( P ) [Pa]</td>
<td>100000</td>
<td>100000</td>
</tr>
</tbody>
</table>

- Geldart Group A particles
- Fast fluidization flow regime (CFB regime)
Scaling criteria for fluidized bed hydrodynamics

**Glicksman scaling laws**
- Simulating the hydrodynamics of a high temperature FB reactor with a smaller cold flow model
- Based on non-dimensional particles and fluid equations of motion
- A set of scaling parameters to be matched between actual reactor and model
  - May impose different Geldart Group of particles and different flow regime
Scaling criteria for fluidized bed hydrodynamics

Knowlton scale-up

1. Select operating regime
2. Construct a pilot plant (typical diameter 150 – 300 mm for group A particles)
   - Continuous operation for significant time
   - Industrial concerns can be addressed
   - Reduced wall effects
3. Construct a large cold-flow model (generally larger than the pilot)
4. Construct a demonstration plant
5. Construct a commercial plant
   → Flow regime and particle Geldart Group should be kept the same
Cold Flow Model (CFM) scaling strategy

**Industrial Demo ~30MW**

- **Simplified Glicksman Criteria:**
  \[ \frac{u_0^2}{g \cdot D}, \frac{\rho_p}{\rho_g}, \frac{L}{D}, \frac{u_0}{u_{mf}}, \frac{G_z}{\rho_p u_0}, \varphi, \text{PSD}. \]

- **Geldart A particles**

- **Fluidization regime:**
  Ar & Re_p

- **Process parameters:**
  T, P, gas composition

- **Same Particles:**
  Density, PSD, \( \varphi \)

- **Fluidization regime:**
  Ar & Re_p

- **Geometrical identity**

- **Geldart A particles**

- **Fluidization regime:**
  Ar & Re_p

**Cold Flow Model**

**Hot Rig**

150 kW
Cold Flow Model (CFM) scaling strategy

Industrial Demo ~30MW

Cold Flow Model

Hot Rig 150 kW

Lim, Zhu and Grace (1995)
Experimental set-up

**Cold Flow Model, full scale:**

Air Reactor (AR):
- **5m** h, **0.23m** id
- Nominal air flow: ~**5500 Nl/min** (2.4 m/s at 20°C)

Fuel Reactor (FR):
- **5m** h, **0.14m** id
- Nominal air flow: ~**2400 Nl/min** (2.6 m/s at 20°C)

Air Reactor Loop-seal:
- Nominal air flow: ~**165 Nl/min**

Fuel Reactor Loop-seal:
- Nominal air flow: ~**95 Nl/min**

**Fe-Si Powder:**

Geldart group A
- Starting d$_{50}$: **34 micrometers**
- Density: **7000 kg/m$^3$**
- Total Solids Inventory (TSI): ~ **120kg**
Frequency controlled fan and filter box mounted on scale
Experimental campaign overview

Design condition performance
• Operational performance and stability
• Validate design solutions

“Off-design” tests
• FR increased flux/concentration
• Part-load (50%)
• Simulate reforming conditions
Design conditions

AR: 5500 Nl/min (2.4 m/s)
Primary Secondary 1 Secondary 2
55% 22.5% 22.5%

FR: 2400 Nl/min (2.6 m/s)
Primary Secondary 1 Secondary 2
50% 42% 8%

Lift: 700 Nl/min (1.5 m/s)
Primary Secondary
~70% ~30%
Design conditions

Pressure loop

AR
Active mass ~25kg
AR Solids flow (flux)
~ 2kg/s (48kg/m²s)
FR
Active mass ~16kg
FR Solids flow (flux)
~ 0.8kg/s (46kg/m²s)

Solids concentration

AR
FR

Solids concentration [m³ sol/m³ tot]
Design conditions

Pressure balance between loop-seals & return points
Design conditions

Fuel Reactor (FR) sensitivity

- Superficial gas velocity: 2.4 m/s
  ~0.62 kg/s (~38.1 kg/m²s)

- Superficial gas velocity: 2.6 m/s
  ~0.74 kg/s (~45.7 kg/m²s)

- Superficial gas velocity: 2.8 m/s
  ~0.79 kg/s (~48.7 kg/m²s)
Conclusions & Outlook

1. **Achievement of stable operation at design conditions of the DLCFB cold flow model:**
   - Solids flow above 2 kg/s → Solids flux (AR) 48 kg/m²s

2. **Stable operation achieved at some defined off-design conditions:**
   - Increased FR solids concentration/entrainment
   - Part load conditions
   - Simulated reforming conditions

3. **Integrate lessons learnt in the final design of the 150 kWₜh hot rig**
   - Return leg height
   - Increase in FR solids concentration/entrainment

4. **Scaling strategy incorporating elements from both Glicksman and Knowlton;** the 150 kWₜh hot rig (i.e. the next step of the BIGCLC project) and the existing large CFM will together give valuable guidelines and process and design validation for further up-scaling
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