Narrow-Channel, Fluidized Beds for Effective Particle Thermal Energy Transport and Storage

Greg Jackson
Mechanical Engineering, Colorado School of Mines

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Acknowledgements of Collaborators and Funding

Many at Mines currently contribute to particle-sCO₂ HX development:

**Current Contributors** – Research Assoc. Jesse Fosheim, Prof. Ivar Reimanis, Students: Winfred Arthur-Arhin, Azariah Thompson, Yahya Bokhary, Julia Billman

**Current Collaborators on particle-sCO₂ HX development**
- Sandia National Laboratories – Kevin Albrecht, Chris Owen, Andrea Ambrosini
- CARBO Ceramics – Brett Wilson

**Previous collaborations**
- REL – Zhiwen Ma, Janna Martinek, Judy Netter
- rayton Energy – Bill Caruso, Megan Kirschmeier

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Particle-Based TES for CSP-sCO$_2$ Brayton Power Cycle

Narrow-channel, counterflow, fluidized-bed particle-sCO$_2$ HX provides a promising pathway for primary HX for TES subsystems driving sCO$_2$ power cycles.
Narrow-channel fluidized beds with mild fluidization achieve high particle-wall association with flux limiting thermal resistance (relative to micro-channel flows).

Fluidization achieves optimal \( h_{T,w} \).

\[
ut = \frac{1}{A_w} \left( \frac{\Delta x_w}{h_{T,w}} + \frac{A_w}{\eta_{fin} A_{fin} h_{T,s\text{CO}_2}} \right)^{-1}
\]

Narrow-Channel Fluidized Beds:

\( h_{T,w} \geq 1000 \text{ W m}^{-2}\text{K}^{-1} \)

\( \approx 2000 \text{ W m}^{-2}\text{K}^{-1} \)
Single-channel Test Facility for Particle-Wall $h_{T,w}$ in Narrow-Channel Fluidized Beds
Single-channel $h_{T,w}$ Measurements and Correlations

To date, $h_{T,w}$ measurements at 6 locations in 0.25 m high bed for two channel depths (12 and 18 mm), mean particle diameters (260 and 360 μm CARBO HSP), and bed temperatures up to 500°C correlations based on Molerus (1992) approach with dependencies on Ar and $\hat{U}$ for convective are combined with radiative contribution to provide reliable predictions of local $h_{T,w}$ in the bed.

$$h_{T,w} = h_{T,w,pc} + h_{T,w,rad}$$

Molerus (1992)

$$\begin{align*}
\text{Nu}_pc(1 + \text{Pr}_f^{-1}) &= f(Ar_{lam})f(\hat{U}) \\
\text{Nu}_pc &= \frac{h_{T,w,pc} \lambda_g}{d_p} \\
\hat{U} &= (U_g - U_{mf}) \left( \frac{\rho_p c_p \lambda_g}{\rho_g \lambda_g} \right)^{1/3} \\
Ar_{lam} &= \sqrt{\frac{d_p^2 g (\rho_p - \rho_g)}{\mu_g}} \\
\text{Pr}_f &= 2c_{p,p} \mu_g / \lambda_g
\end{align*}$$

$T_p \approx 500°C$
$T_p \approx 400°C$
$T_p \approx 300°C$
$T_p \approx 200°C$
$T_p \approx 100°C$
Converting Experimental Results into Heat Exchanger Sizes and Responses

- $h_{T,w}$ correlations are integrated into vertically discretized 1-D model (MATLAB) of narrow-channel, counterflow fluidized-bed particle-sCO$_2$ HX to design demonstration HX geometry and assess performance at test conditions.

- The 1-D model employs a two-phase mass, momentum, and energy, fluidized bed sub-model coupled to a mass, momentum, and energy, plug-flow, microchannel sCO2 sub-model.
Model-based 40-kW$_{th}$ Particle-sCO$_2$ HX Design

### Counterflow Fluidized Bed Model Profiles

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Baseline</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\dot{m}_{p,in,bed}$, particle flow rate per bed</td>
<td>18.7 g/s</td>
</tr>
<tr>
<td>$T_{p,in}$, particle inlet temperature</td>
<td>620˚C</td>
</tr>
<tr>
<td>$d_p$, particle diameter</td>
<td>260 µm</td>
</tr>
<tr>
<td>$\dot{m}_{g,in,bed}$, fluidizing air flow rate per bed</td>
<td>0.281 g/s</td>
</tr>
<tr>
<td>$T_{g,in}$, fluidizing air inlet temperature</td>
<td>450˚C</td>
</tr>
<tr>
<td>$\dot{m}_{sCO2,in,bed}$, sCO$_2$ flow rate per bed</td>
<td>22.4 g/s</td>
</tr>
<tr>
<td>$T_{sCO2,in}$, sCO$_2$ inlet temperature</td>
<td>450˚C</td>
</tr>
<tr>
<td>$\Delta y_{bed,tot}$, bed height</td>
<td>0.4 m</td>
</tr>
<tr>
<td>$\Delta x_{bed}$, bed width</td>
<td>0.2 m</td>
</tr>
<tr>
<td>$\Delta z_{bed}$, bed depth</td>
<td>0.015 m</td>
</tr>
<tr>
<td># of beds</td>
<td>13</td>
</tr>
<tr>
<td>$n_{channel,bed}$, sCO$_2$ microchannels per bed</td>
<td>130</td>
</tr>
<tr>
<td>$d_{h,channel}$, sCO$_2$ channel hydraulic diameter</td>
<td>0.75 mm</td>
</tr>
</tbody>
</table>
Performance of Particle-sCO$_2$ HX Design Space to Evaluate Costs per kW

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\dot{m}_{p,\text{in,bed}}$</td>
<td>18.7 g s$^{-1}$</td>
</tr>
<tr>
<td>$\dot{m}_{g,\text{in,bed}}$</td>
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</tr>
<tr>
<td>$T_{g,\text{in}}$</td>
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<tr>
<td>$D_{h,\text{channel}}$</td>
<td>0.75 mm</td>
</tr>
</tbody>
</table>
K\textsubscript{th}W Particle-sCO\textsubscript{2} HX for Test at Sandia Natl. Labs

Collaboration with Sandia (Kevin Albrecht and Chris Bowen) has supported the design and fabrication of multi-channel SS diffusion bonded 12-parallel bed HX with microchannel-sCO\textsubscript{2} flow. Tests at Sandia this fall will explore particle heat transfer at $T_{p,in}$ up to 600°C at 40-kW\textsubscript{th} scale.
Counterflow Fluidized Beds Can Support Thermochemical Energy Storage (TCES) for CSP

Completed Mines-led CSP-ELEMENTS program with NREL collaboration explored fluidized bed design for redox active perovskites (doped CaMnO$_{3-\delta}$) to more than double energy storage density of particles.
Including Remarks and Path Forward

The correlation developed from single channel rig for narrow-channel fluidized beds to include new data obtained at 100–500°C with 260 and 360 µm particles in 12 & 18 mm deep beds for a range of gas-to-particle mass flow ratios.

Discretized models using $h_{T,w}$ correlation enabled assessment of geometric parameters and operating conditions to design a 40-kW$_{th}$ prototype HX fabricated by VPE for testing at Sandia National Labs this fall.

Average $h_{T,w} \approx 700$ W m$^{-2}$ K$^{-1}$, overall $U \approx 500$ W m$^{-2}$ K$^{-1}$, $\epsilon_{HX} \approx 0.80$, $q''_{w,avg} \approx 24$ kW m$^{-2}$ predicted with CARBOBEAD HSP40/70 at planned test conditions.

Heat transfer models can be utilized for scale-up and for exploring more complex system designs for other applications such as thermochemical energy storage.