Granular flow and thermal performance of Moving Bed Heat Exchangers: Comparison of the Euler-Euler model with experimental results

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Thermal Energy Storage (TES) for CSP-Plants

- Concentrating Solar Power (CSP) plants:
  - electricity from concentrated solar radiation

- Thermal energy storage:
  - Load following electricity production, dispatchability of CSP-system
  - based on flowable particulates: allows cost-effective large-scale solutions, simultaneous use as storage material and HTF
Heat exchanger for discharge of granular bulk
Moving Bed Heat Exchanger

- Particles directly heated in Particle Receiver of CRS
- Storage itself is simple: Hot/cold storage containers
- But:
  - Discharge and supply of Rankine cycle requires a particle heat exchanger to run a Rankine or Bryton cycle
  - Not commercially available
  - In principle various technology options thinkable
  - MBHE promising
  - Design basis uncertain, with little flexibility
Challenges & Motivation

**Overarching aim**
Sizing of component and its system integration
- Quality of heat transfer, i.e. temperature loss?
- Required heat transfer area?
- Max. size and # of modules?

**Problem**
- Determination of thermal performance mandatory for MBHE-design
- Thermal performance of MBHE directly depends on velocity distribution of the bulk
- Flow behaviour of granular bulks differs from (Newtonian) fluids → adequate determination of the flow field required

**Proceeding**
- **Euler-Euler** multiphase continuum approach to predict flow and heat transfer
- Parametric studies: tube shape, bundle arrangement
- Experimental validation of results

\[
h_{SO} = \frac{2}{\sqrt{\pi}} \cdot \sqrt{\frac{\rho \cdot c_p \cdot k}{\sqrt{t}}}
\]

Penetration theory proposed by Schlünder et al.
Model basis: Mass and momentum

- Euler-Euler multiphase continuum approach:
  - Considers both gaseous (air) and solid phase as interacting and penetrating continua

→ Navier Stokes conservation equations to be solved for each phase
- Regards kinematic, collisional and frictional effects of solid phase

\[
\frac{\partial}{\partial t} \left( \alpha_q \rho_q \right) + \nabla \cdot \left( \alpha_q \rho_q \bar{v}_q \right) = 0
\]

\[
\frac{\partial}{\partial t} \left( \alpha_f \rho_f \bar{v}_f \right) + \nabla \cdot \left( \alpha_f \rho_f \bar{v}_f \right) = -\alpha_f \rho_f \bar{v}_f \cdot \bar{\tau}_f + \alpha_f \rho_f \bar{g} + \alpha_f \rho_f \bar{p} \left( \bar{F}_f + \bar{F}_{lift,f} + \bar{F}_{vm,f} \right) + \sum_{p=1}^n \left( K_{fs} \left( \bar{v}_s - \bar{v}_f \right) + \dot{m}_f \bar{v}_s \right)
\]

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\]

Stress tensor:
\[
\bar{\tau}_s = \alpha_s \mu_s \left( \nabla \bar{v}_s + \nabla \bar{v}_s^T \right) + \alpha_s \left( \lambda_s - \frac{2}{3} \mu_s \right) \bar{v} \cdot \bar{v}_s \bar{\tau}
\]

Shear viscosity:
\[
\mu_s = \mu_{s,col} + \mu_{s,kin} + \mu_{s,fr}
\]

Frictional viscosity:
\[
\mu_{s,fr} = \frac{p_s \sin \phi}{2 \sqrt{I_{2D}}}
\]
Model basis: Energy

- Euler-Euler multiphase continuum approach:
  - Considers both gaseous (air) and solid phase as interacting and penetrating continua
  → Navier Stokes conservation equations to be solved for each phase
- Regards kinematic, collisional and frictional effects of solid phase

Energy:
\[
\frac{\partial}{\partial t} \left( \alpha_p \rho_p h_p \right) + \nabla \cdot \left( \alpha_p \rho_p \mathbf{u}_p h_p \right) = -\alpha_p \frac{\partial p}{\partial t} + \tau_q : \nabla \mathbf{u}_q - \nabla \cdot \mathbf{q}_q + S_q + Q_{pq}
\]

Heat transfer rate (interphase): \( Q_{pq} = h_{pq}(T_p - T_q) \)

HT-coefficient (interphase):
\[
h_{qp} = \frac{6k_q \alpha_p \alpha_q N \nu_p}{d_p^2}
\]

Nusselt number via correlation (e.g. by Gunn)

Heat flux @ boundaries:
\[
q = k_{SO} \left( \frac{\partial T}{\partial n} \right)_{wall}
\]
Modelling of the MBHE design:
Geometry study

- Five MBHE-designs including three different tube shapes (circular, rhombic, oval)
- Varying staggered tube arrangement (different horizontal tube pitches)
- Minimal tube pitch (bundles B, D, E) and inclination angle (bundles C and D) determined from analysis of rheological bulk properties
- Sintered Bauxite is considered as bulk material; inlet velocity 2 mm/s

<table>
<thead>
<tr>
<th>Material</th>
<th>Mean grain size [mm]</th>
<th>Molecular density [kg/m³]</th>
<th>Molecular specific heat capacity [J/kgK]</th>
<th>Porosity of randomly packed bed [-]</th>
<th>Inner friction angle [°]</th>
<th>Restitution coefficient [-]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sintered Bauxite</td>
<td>1.0</td>
<td>3900</td>
<td>1040</td>
<td>0.45</td>
<td>29.2</td>
<td>0.9</td>
</tr>
</tbody>
</table>
Results: Thermal performance

- High average heat transfer coefficients for narrow tube arrangements (B,D,E)
- No improvement of HTC by rhombic tubes
- Best heat transfer achieved for oval tubes

$\bar{h} = \frac{q_{\text{tube}}}{(T_\infty - T_{\text{tube}})}$

- thermal performance is mainly affected by flow distribution of the bulk, which in return is influenced by the tube shape and bundle arrangement
Results: Velocity distribution

- Higher velocity in narrow bundle designs due to cross section constriction
- Formation of zones of low velocity (stagnant zones and voids) at circular tubes → low local surface velocity → insulating effect on heat transfer
- Rhombic design prevents formation of stagnant zones, but exhibits lower average surface velocity than circular tubes → higher contact time
- No emphasized formation of stagnant zones or voids at the oval shaped tubes, high share of high velocity along the surface → low contact time → high HTC
Results: Volume fraction distribution

- High mean velocity for circular and oval tubes
- Solid volume fraction at circular tubes decreases close to the lower vertex
- Particles tend to detach from the lower half of the rhombic surface
- Integral solid packing at the oval tubes higher than for circular and rhombic tubes
- High void fraction leads a decreased integral heat transfer coefficient (heat transfer wall/air is lower than for wall/bulk)
Final HX design for optimized performance

Two different HX designs:
a. „Reference“ design, based on common 60°-triangle arrangement
b. „Adapted“ design, taking into account design parameters determined from analysis of rheological measurements → critical opening width = minimum distance between adjacent tube walls

- Adapted design advantages:
  - High heat transfer rates due to high particle velocities at the tube wall
  - High HT-area to volume ratio → compact design
Example case: assumptions
Operating conditions & HX geometries

**MBHE modules**
- Cross-flow
- Gravity-driven bulk flow
- Staggered tube arrangement
- Tube diameter of 26.9 mm
- Adapted bundle: horizontal split ratio 1.37, based on analysis of rheological bulk properties

**Bulk material**
- Sintered bauxite and quartz sand
- Ø 0.5; 0.8 mm
- inner friction angle: 29°; 33°
- Restitution coefficient: 0.9

**Operating conditions**
- Bulk velocity @inlet: 1 – 5 mm/s
- Porosity @inlet: 0.48; 0.44
Experiments
Test Rig

- Test bench allows integration of different MBHXs
- Investigation of granular flow field inside HX
- Investigation of thermal performance of HX

- Caloric heat determined applying temperatures of the granular core flow
- Outer heat transfer coefficient \( \alpha \) computed in terms of overall heat transfer coefficient (NTU-method for crossflow HX)

Quick facts

<table>
<thead>
<tr>
<th>Bulk loop</th>
<th>Oil loop</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flow</td>
<td>0 - 1.0 m³/h</td>
</tr>
<tr>
<td>Heating power</td>
<td>35 kW</td>
</tr>
<tr>
<td>Inlet temperature</td>
<td>max. 600°C</td>
</tr>
</tbody>
</table>
Experiments
Flow Measurements - Setup & method

PIV-Setup
2D-projection plane
MBHE model
Light source
Highspeed-CCD

Area of Interest

Superficial bulk velocity
\( v_{\text{in}} = 0.3 - 3.0 \text{ mm/s} \)

- Continuous mass flow inside the adapted tube bundle → no arching → appraised critical tube pitch suitable (same goes for the reference bundle)
- Equally distributed flow
Experiments
Flow Measurements - Results

- Significant divergence (exp/sim)
- Exp: Much slower acceleration from upper vertex, max. velocity @ lower half
- Mean velocity up to 60% higher than in CFD

- Better consistence (exp/sim)
- Max velocity @ mid position
- Exp.: slight acceleration at lower half

→ Where do these effects come from?
Experiments
Flow Measurements - Results

- Overall particle velocity is potentially higher for adapted design with narrow arrangement.

- Tube bundle design significantly affects flow distribution near the tube wall → contact time and heat transfer.

- Specific dimension of stagnant zones cannot accurately be reflected by Euler-Euler model due to model inherent simplifications in continuum approach.

- **Stagnant zones** constrict free cross section between upper, adjacent tubes in reference bundle → increased local velocity, spec. @ lower half.

- Effect is minimized due to varied tube configuration in adapted bundle.
Experiments
Thermal Characterization – Results

- Heat transfer regressively increases with mass flux
- Higher heat transfer coefficients for adapted tube bundle (up to 240 W/m²K)
- Slightly better performance for operation with sintered bauxite
Experiments
Thermal Characterization – Results

- Heat transfer regressively increases with mass flux
- Higher heat transfer coefficients for adapted tube bundle (up to 240 W/m²K)
- Slightly better performance for operation with sintered bauxite
- Increase of heat transfer coefficient lower than expected from CFD-results:
- Higher htc expected at higher mass fluxes according to penetration theory (approx. 300 W/m²K @ 10 kg/m²s, tc = 5 s)
Experiments
Thermal Characterization – Results

- Insulating effect of stagnant zone limits heat transfer at high mass fluxes
- Effect less pronounced at lower mass fluxes since contact time is high either way
Summary & conclusions

- Narrow tube arrangement potentially increases thermal performance of MBHX
- Experimental flow visualisation analysis shows good agreement with the computed results
- Tube bundle configuration has significant influence on granular velocity distribution at tube walls, especially on stagnant zone formation
- Drawbacks in accuracy of flow due to model-inherent simplifications in granular rheology
- Despite insufficiency to accurately reflect discrete stagnant zones, the Euler-model is considered a solid basis for further MBHE parametric and design studies, specifically for moderate mass fluxes

Outlook:
- Identification and implementation of improved models for granular viscosity
- Validation and further design studies (Simulations and Experiments)
Thank you!

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