Modeling and optimization of a multi-tubular solar receiver for solar-driven high temperature electrolysis

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Motivation and Introduction

- Solar driven high-temperature co-/electrolysis

![Diagram of solar driven high-temperature co-/electrolysis process.](image)
Motivation and Introduction

Flow boiling with complex physics:
• Nucleating of bubbles
• Bubbles growth and coalescence
• Segregation of vapor and liquid phase
• Evaporation of liquid in mist flow and partial films

Heat transfer in receiver cavity:
• Non-uniform distribution of heat flux
• Non-uniform temperature distribution

Model development (1D model for single tube)

1D model for two-phase flow in horizontal tube:

Assumptions (in control volume):
1. The velocity of liquid and gas are constant but not necessarily equal.
2. Thermodynamic equilibrium between phases (temperature and pressure are equal).
3. Empirical correlations are used to relate the frictional pressure drop and the void fraction to the independent variables of the flow.
4. CO$_2$ and H$_2$O are considered well mixed.


Model development (1D model for single tube)

Conservation equations

Mass conservation: \[ \dot{m}_i = \dot{m}_o \]

Momentum equation: \[ (p_i - p_o)A = \dot{m}_{g,o}v_{g,o} - \dot{m}_{g,i}v_{g,i} + \dot{m}_{l,o}v_{l,o} - \dot{m}_{l,i}v_{l,i} + \tau_w P \Delta z + mg \sin(\theta) \]

Energy equation: \[ \dot{q}_w P \Delta z = \dot{m}(e_{1,o} - e_{1,i}) + \dot{m}_{g,o}(e_{g,o} - e_{l,o}) + \dot{m}_{g,i}(e_{g,i} - e_{l,i}) \]

Empirical correlations

\[ \tau_w = \frac{f \dot{m}^2}{8 \rho A^2} \]

\[ f = f_1 \phi_{fr}^2 \]

\[ f_1 = \frac{0.079}{Re^{0.25}} \text{ (Blasius equation)} \]

\[ \phi_{fr}^2 = \frac{E + \frac{3.42FH}{Fr_{h}^{0.045}We_{l}^{0.0035}}}{\frac{0.045}{Fr_{h}} \cdot \frac{0.0035}{We_{l}}} \]

Lin, TFESC2015, August 2015
Flow pattern maps

Kattan-Thome-Favrat (KTF) flow pattern Map:

Dry angles:

\[
\theta_{dry} = \theta_{strat}
\]

\[
\theta_{strat} = 2\pi - 2 \left\{ \frac{\pi(1-\varepsilon) + \left(\frac{3\pi}{2}\right)^{1/3} \left[1 - 2(1-\varepsilon) + (1-\varepsilon)^{2/3} - \varepsilon^{1/3}\right]}{1 - \frac{1}{200}(1-\varepsilon)(1-2(1-\varepsilon))[1+4((1-\varepsilon)^2 + \varepsilon^2)]} \right\}
\]

\[
\theta_{dry} = \theta_{strat} \frac{\dot{m}_{high} - \dot{m}}{\dot{m}_{high} - \dot{m}_{low}} \quad \text{for} \quad x < x_{\text{max}}
\]

\[
\theta_{dry} = (2\pi - \theta_{\text{max}}) \frac{x - x_{\text{max}}}{1 - x_{\text{max}}} + \theta_{\text{max}} \quad \text{for} \quad x > x_{\text{max}}
\]

Lin, TFESC2015, August 2015
Heat transfer coefficient

Heat transfer coefficient based on flow pattern:

\[ \alpha = \frac{\theta_{\text{dry}} \alpha_g + (2\pi - \theta_{\text{dry}}) \alpha_1}{2\pi} \]

Gas phase: \( \alpha_g = 0.023 \text{Re}^{0.8} \text{Pr}^{0.4} \frac{k_g}{d} \) \( \text{Dittus-Boelter (1930)} \)

Liquid phase: \( \alpha_1 = (\alpha_{\text{nb}}^3 + \alpha_{\text{cb}}^3)^{1/3} \) \( \alpha_{\text{cb}} = 0.0133 \text{Re}_1^{0.69} \text{Pr}_1^{0.4} \frac{k_i}{\delta} \) \( \text{Kattan (1998)} \)

For each element:

\[ \alpha_{\text{nb}} = 55 p_r^{0.12} (-\log p_r)^{-0.55} M^{-0.5} q_w^{0.67} \text{ Cooper (1984)} \]

A heat transfer coefficient profile in radial direction

All elements

3D heat transfer coefficient profile

Example: Absorber tube

Boundary conditions:

1D model (Matlab code)
- Inlet condition: Temperature, flow rate, pressure
- Heat losses: $\dot{q}_{\text{losses}} = 0.8(T - T_s)\sigma(\epsilon \cdot T_s^4 + h_{\text{nc}}(T_W - T_o))$

3D model (Fluent)
- Inner wall: heat transfer coefficient and fluid temperature
- Outer wall: Concentrated solar power (typical distribution)
- Tube wall: heat flux
- Wall ends: Non-slip and adiabatic
- Outside wall: Non-slip and adiabatic
- Pressure outlet

Heat losses: $\dot{q}_{\text{losses}} = 0.8\sigma T_s^4 + h_{\text{nc}}(T_W - T_o)$

$\overline{Nu} = \begin{cases} 
0.60 + \frac{0.387 Ra^{1/6}}{[1+(0.559 / Pr)^{9/16}]^{8/27}} \quad , \quad Ra \leq 10^{12} 
\end{cases}$

Churchill and Chu (1975)

Lobon et al. (2014)
Model validation

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tube length</td>
<td>510 m</td>
</tr>
<tr>
<td>Inner radius</td>
<td>0.05 m</td>
</tr>
<tr>
<td>Outer radius</td>
<td>0.07 m</td>
</tr>
<tr>
<td>Inlet temperature</td>
<td>478.15 K</td>
</tr>
<tr>
<td>Mass flow rate</td>
<td>0.47 kg/s</td>
</tr>
<tr>
<td>Direct normal isolation</td>
<td>822 W/m²</td>
</tr>
<tr>
<td>Optical efficiency</td>
<td>0.632</td>
</tr>
<tr>
<td>Inlet pressure</td>
<td>3.43 MPa</td>
</tr>
<tr>
<td>Heat loss (liquid)</td>
<td>1278 W/m²</td>
</tr>
<tr>
<td>Heat loss (two phase)</td>
<td>1828 W/m²</td>
</tr>
<tr>
<td>Heat loss (vapor)</td>
<td>2323 W/m²</td>
</tr>
</tbody>
</table>

Performance evaluation

- Solar thermal efficiency:
  \[ \eta_t = 1 - \frac{\dot{Q}_{\text{heat loss}}}{\dot{Q}_{\text{solar,receiver}}} \]

- Maximum wall-fluid temperature difference: \( \Delta T_{\text{max}} \)

- Mean heat transfer coefficient in two-phase flow region: \( \bar{h}_{tp} \)
# Baseline and reference case parameters

<table>
<thead>
<tr>
<th>Simulation parameter</th>
<th>Ref.</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Direct normal irradiance, DNI</td>
<td>1</td>
<td>kWm(^{-2})</td>
</tr>
<tr>
<td>Concentration</td>
<td>1000</td>
<td></td>
</tr>
<tr>
<td>Inlet pressure</td>
<td>15</td>
<td>bar</td>
</tr>
<tr>
<td>Mass flux</td>
<td>200</td>
<td>kgm(^{-2})s(^{-1})</td>
</tr>
<tr>
<td>Inner tube diameter</td>
<td>10</td>
<td>mm</td>
</tr>
<tr>
<td>Wall thickness</td>
<td>1</td>
<td>mm</td>
</tr>
<tr>
<td>Ambient temperature, (T_0)</td>
<td>298.15</td>
<td>K</td>
</tr>
<tr>
<td>Target temperature</td>
<td>1000</td>
<td>K</td>
</tr>
<tr>
<td>PV efficiency, (\eta_{pv})</td>
<td>15%</td>
<td></td>
</tr>
<tr>
<td>Solar field optical efficiency, (\eta_{op})</td>
<td>50%</td>
<td></td>
</tr>
</tbody>
</table>
Design guidelines

**Inlet pressure**

- **ηₜ**
- **$\bar{h}_p$**
- **$\Delta T_{max}$**

**Tube inner diameter**

- **ηₜ**
- **$\bar{h}_p$**
- **$\Delta T_{max}$**

- **Tube length**

- **Thermal efficiency, $\eta_t$**
- **Averaged heat transfer coefficient (two-phase region), $\bar{h}_p$**
- **Maximum wall-fluid temperature difference, $\Delta T_{max}$**

Lin, TFESC2015, August 2015
Design guidelines

**Concentration ratio**

- Tube length: 12 m
- Tube length: 7 m

**Mass flux**
Design guidelines

- **Thermal efficiency, $\eta_t$**
- **Averaged heat transfer coefficient (two-phase region), $\bar{h}_{tp}$**
- **Maximum wall-fluid temperature difference, $\Delta T_{max}$**

![Graph showing mass fraction of CO\(_2\) vs. $\eta_t$, $\bar{h}_{tp}$, and $\Delta T_{max}$](image)
# Optimized design

<table>
<thead>
<tr>
<th>Optimized Parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inlet pressure</td>
<td>15bar</td>
</tr>
<tr>
<td>Tube inner diameter</td>
<td>12mm</td>
</tr>
<tr>
<td>Tube thickness</td>
<td>1mm</td>
</tr>
<tr>
<td>Concentration ration</td>
<td>750</td>
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<tr>
<td>Mass flux</td>
<td>350 kgm(^{-2})s(^{-1})</td>
</tr>
<tr>
<td>Target outlet temperature</td>
<td>10000K</td>
</tr>
<tr>
<td>Tube length</td>
<td>6.0225m</td>
</tr>
<tr>
<td>CO(_2) mass fraction</td>
<td>0</td>
</tr>
</tbody>
</table>

\[ \eta = 38.8\% \]

\[ \Delta T_{\text{max}} = 410.7\K \]

\[ h = 34102.8\text{W/m}^2\text{K} \]
Optimized design?

- Efficiency variation with irradiance changes

\[ \eta_t = 1 - \frac{\dot{Q}_{\text{heat loss}}}{\dot{Q}_{\text{solar,receiver}}} \]
Summary and conclusion

- Development of a novel **general receiver model** to predict performance of multi-tube receiver for concurrent steam and CO₂ heating

- Model integrates:
  - 1D multi-phase single-tube model
  - detailed 3D multi-tube cavity model

- Various geometrical as well as operational conditions were investigated and optimized.
  - Inlet pressure has minor effect on the efficiency.
  - Larger tube diameter leads to higher thermal efficiency but longer tube length and higher $\Delta T_{\text{max}}$.
  - Low concentration is preferred.
  - High mass flux leads to better efficiency.
  - Mix CO₂ and H₂O could enhance the thermal efficiency.

- Experiment will be conducted to modified the flow pattern under high flux with non-uniformity.
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