Analytical model of a multichannel double tube CO2 gas-cooler for a water heater

2017. 5. 18
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Introduction

- Background
- Literatures review
- Objective
Natural refrigerant, CO$_2$

- **Low GWP**
  - 1/1000 of GWP compared with HFC refrigerants

- **Economical price**
  - Approximately 1/50 of the cost compared to newly developed HFO refrigerants

- **Excellent efficiency**
  - Similar cooling and heating efficiency compared to R22 (HCFC refrigerant)

* 출처: P. Neksa(2002), CO$_2$ heat pump systems
Characteristic of CO₂ cycle

- **Supercritical cycle**
  - Low critical temperature(31.1°C @7.3MPa)

- **Temperature gliding**
  - Temperature of CO₂ is continuously changed during the Gas-cooling process

- **High isentropic efficiency**
  - Lower compression ratio compared with HFC's refrigerants

* Luca Cecchinato(2010), A critical approach to the determination of optimal heat rejection pressure in transcritical systems
CO\textsubscript{2} heat pump water heater and Gas-cooler

- **Produce high temperature water using supercritical CO\textsubscript{2} cycle**
  - Due to large temperature glide of CO\textsubscript{2} in the supercritical region, hot water can be generated efficiently

- **Double-tube heat exchanger applied as a gas-cooler**
  - Important component affecting the system performance
  - Heat exchange of water-CO\textsubscript{2} by applying gas-cooler designed as counter flow
  - Advantages such as simple shape, economical production cost, high pressure resistance

- **Commercialization of the CO\textsubscript{2} heat pump water heater**
Literature review

- Friedrich Kauf (1999)
  - Develop the correlation to calculate the optimal gas-cooler pressure according to ambient temperature

- Cecchinato et al. (2010)
  - Develop the model of the CO$_2$-water gas-cooler
  - Determine the optimal gas-cooler pressure for the maximum heating capacity

- Sanchez et al. (2012)
  - Development and validation of a 15 kW double tube gas-cooler simulation model
  - Calculate COP and thermal effectiveness of the gas-cooler

- Previous research have focused on air-CO$_2$ gas-cooler
- Most of the studies were about a single inner tube water-CO$_2$ gas cooler or a large capacity commercial heat pump water heater

- Studies about multichannel gas-cooler used in the domestic heat pump water heater are scarce
**Objective**

**CO₂ gas-cooler**
- Cooling process at supercritical region
- Key role of system performance

**Double tube heat exchanger**
- Excellent pressure resistance
- Simple shape

**Optimization of the double tube water-CO₂ gas-cooler**
- Independent variable: Gas-cooler sectional area ratio, GCAR \( = \frac{A_{\text{CO₂}}}{A_{\text{total}}} \)
- Control variable: Heat transfer area
- Dependent variable: Capacity, COP, Thermal effectiveness (\( \varepsilon \))

![Cross sectional view of double tube the gas-cooler having different sectional area ratio](image-url)

**Fig.** Cross sectional view of double tube the gas-cooler having different sectional area ratio
Experiment and Modeling

- Experimental setup
- Experimental range
- System modeling
Experimental setup

Fig. Schematic diagram of the experimental setup
Double tube gas-cooler used in the experiment

![Diagram of gas-coolers](image)

**Fig. Schematic diagram of the water-CO₂ double tube gas-cooler used in the experiments.**

**Table. The Geometrical information of the gas-coolers used in the experiments.**

<table>
<thead>
<tr>
<th>Geometrical variable</th>
<th>Gas-cooler 1</th>
<th>Gas-cooler 2</th>
<th>Gas-cooler 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outer tube diameter (D₀, mm)</td>
<td>25.4</td>
<td>6.35</td>
<td>3.15</td>
</tr>
<tr>
<td>Outer tube thickness (Th₀, mm)</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Inner tube diameter (Dᵰ, mm)</td>
<td>9.52</td>
<td>6.35</td>
<td>3.15</td>
</tr>
<tr>
<td>Inner tube thickness (Thᵰ, mm)</td>
<td>0.6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Inner tube number (n)</td>
<td>2</td>
<td>4</td>
<td>8</td>
</tr>
<tr>
<td>Gas-cooler length (L, m)</td>
<td>2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Heat exchange surface area (Aₛf, m²)</td>
<td>0.119</td>
<td>0.159</td>
<td>0.158</td>
</tr>
<tr>
<td>Cross-sectional area ratio, GCAR (σ)</td>
<td>0.216</td>
<td>0.166</td>
<td>0.047</td>
</tr>
</tbody>
</table>
**Parameter range of the experiment**

Table. The parameter range of the experiment.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Min</th>
<th>Max</th>
<th>Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_{gc}$ (kPa)</td>
<td>7466</td>
<td>9601</td>
<td>±40 kPa</td>
</tr>
<tr>
<td>$P_{ev}$ (kPa)</td>
<td>2998</td>
<td>6750</td>
<td>±40 kPa</td>
</tr>
<tr>
<td>$T_{CO_2, gc, i}$ ($^\circ$C)</td>
<td>50.9</td>
<td>92.8</td>
<td>±0.5 °C</td>
</tr>
<tr>
<td>$T_{CO_2, gc, o}$ ($^\circ$C)</td>
<td>18.5</td>
<td>48.8</td>
<td>±0.5 °C</td>
</tr>
<tr>
<td>$T_{w, gc, i}$ ($^\circ$C)</td>
<td>13.7</td>
<td>33.9</td>
<td>±0.5 °C</td>
</tr>
<tr>
<td>$T_{w, gc, o}$ ($^\circ$C)</td>
<td>19.9</td>
<td>45.9</td>
<td>±0.5 °C</td>
</tr>
<tr>
<td>$\dot{m}_{CO_2}$ (kg/s)</td>
<td>0.0126</td>
<td>0.0401</td>
<td>±0.5 % of reading</td>
</tr>
<tr>
<td>$\dot{V}_{w}$ (l/min)</td>
<td>3.98</td>
<td>8.11</td>
<td>±0.35 % of reading</td>
</tr>
<tr>
<td>Compressor speed (rpm)</td>
<td>2700</td>
<td>3600</td>
<td>-</td>
</tr>
<tr>
<td>Re$_{co2}$</td>
<td>82846</td>
<td>519464</td>
<td>-</td>
</tr>
<tr>
<td>Re$_w$</td>
<td>1462</td>
<td>5194</td>
<td>-</td>
</tr>
<tr>
<td>Charge amount of CO$_2$ (g)</td>
<td>600</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>
Modeling of the gas-cooler

- **Input**
  - $T_{wi}$, $P_{ev}$, $V_w$, rpm, gas-cooler geometry

- **Output**
  - $Q$, COP, $\varepsilon_{gc}$, $P_{gc}$, $T_{wo}$

- **Finite volume method**
  - Total segment number: 50
  - Tube-by-tube method applied

- **Heat transfer correlation of gas-cooler**
  - $\text{CO}_2$: Gnielinski
  - Water: Gnielinski (Turbulent) and Stephan (Laminar)

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Fig. Flow chart of the gas-cooler model
Results and Discussion

- Validation
- Analysis result
Validation of the gas-cooler model

- **Validation**
  - To validate the simulation model, simulation results were compared with the experimental data (103 data cases)

- **Maximum deviation**
  - Heating capacity : 15.6 %
  - Water outlet temperature : 2.62 °C

Fig. Comparison of the measured water temperature at the gas-cooler outlet with the predictions.
Gas-cooler performance according to GCAR

- **Effects of the GCAR on the thermal effectiveness**
  - The thermal effectiveness of the gas-cooler increase as the GCAR decrease
  - \[ \varepsilon = \frac{\dot{Q}_{gc, actual}}{\dot{Q}_{gc, max}} = \frac{h_{CO_2, gc, i} - h_{CO_2, gc, o}}{h_{CO_2, gc, i} - h_{CO_2}} \]
  - The increase rate is larger at the lower water inlet temperature
  - As the GCAR decreases, the overall heat transfer coefficient increases
  - The increase in overall heat transfer coefficient contributes to the thermal efficiency improvement of the gas cooler

Fig. Effects of the cross-sectional area ratio on gas-cooler (a) thermal effectiveness and (b) overall heat transfer coefficient (Pgc=9.5 MPa, rpm=3600, Vw=4 l/min).
Gas-cooler performance according to GCAR

Effects of the GCAR on the heating capacity

- The variation of the heating capacity shows similar trend with the thermal effectiveness
- When the water inlet temperature is 15 °C, the heating capacity decrease as decrease the GCAR
- The worse of the heating capacity is caused by decline of the mass flow rate of CO₂

Fig. Effects of the cross-sectional area ratio on gas-cooler (a) heating capacity and (b) mass flow rate (P_{gc}=9.5 MPa, rpm=3600, V_w=4 l/min).
Gas-cooler performance according to GCAR

**Effects of the GCAR on the heating capacity**

- The mass flow rate of CO₂ is influenced by the evaporating pressure of the cycle.
- The reason for the reduction of the evaporating pressure is due to the mass distribution in the cycle.
- As the water inlet temperature is lower and the thermal effectiveness is higher, the amount of CO₂ in the gas-cooling process increases.
- Relatively, the amount of refrigerant in the evaporating process decreases, causing the reduction of the evaporating pressure.

Fig. Effects of the cross-sectional area ratio on gas-cooler (a) heating capacity and (b) mass flow rate (\(P_{gc}=9.5\) MPa, rpm=3600, \(V_w=4\) l/min).
Conclusions
Conclusions

- **CO₂ heat pump water heater modeling**
  - Numerical model of the CO₂ gas-cooler was developed by using the finite volume method
  - The model was validated based on the measured data for the three different gas-cooler with different GCAR (Gas-cooler cross sectional area ratio)
  - The maximum relative deviation of the heating capacity is 15.6 %

- **Effects of the GCAR on heating capacity and thermal effectiveness**
  - The heating capacity and the thermal effectiveness increase as the GCAR decrease due to the increase of overall heat transfer coefficient
  - The GCAR should be lower for the higher thermal effectiveness
  - The increase of amount of CO₂ in the gas-cooling process due to the high density of CO₂ cause the lowering of the heating capacity by decrease of the evaporating pressure
Thank you!

Q&A