Experimental investigations on a transcritical CO₂ refrigeration plant and theoretical comparison with an ejector-based one

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Paphos, 17/10/2018
Facts and figures about refrigeration

• 3 billion units worldwide

• 300 billion USD global annual sales

• 12 million people employed worldwide

Data refer to refrigeration, air conditioning & heat pumps
[IIR, 2015]
Facts and figures about refrigeration

• Electricity consumption 295 Mtoe (17.2% of global amount)

• 1680 MtCO$_2$ indirect emissions

• 2.1 MtCO$_2$ total carbon footprint

(6.5% of global amount)

Data refer to refrigeration, air conditioning & heat pumps
[IIR, 2015]
Outline

• The role of CO₂ in the refrigeration sector
• Experimental setup and baseline campaign
• Thermodynamic model of the ejector-based layout
• Energy and exergy comparison
• Future work
R744 (CO₂) as refrigerant

**pros**
- “Green” refrigerant GWP = 1; ODP = 0
- Natural refrigerant
- Low-cost
- Not toxic, not flammable, odorless
- Thermodynamic properties

**cons**
- Higher maximum pressure
- Increased leaks
- Greater system complexity
- Higher investment costs
- Not recommended for warm areas

F-Gas Reduction
EU Regulation n°. 517/2014
Experimental setup

Rated power is 18kW thermal and 12kW electric

G. Bianchi – Brunel University London
Experimental setup

<table>
<thead>
<tr>
<th>n°</th>
<th>Instrument</th>
<th>Accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>PT1000 RTDs</td>
<td>0.1 K</td>
</tr>
<tr>
<td>1</td>
<td>K-thermocouple</td>
<td>2.2 K</td>
</tr>
<tr>
<td>1</td>
<td>Foxboro IMT25 Mass Flow (Water/glycol)</td>
<td>0.25%</td>
</tr>
<tr>
<td>1</td>
<td>SITRANS FC MASS 6000 IP67 (CO2)</td>
<td>10% max</td>
</tr>
</tbody>
</table>
Experimental setup

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Experimental campaign

\[ y = 0.1177x^2 - 5.3056x + 136.42 \quad R^2 = 0.9748 \]

\[ y = 0.0053x^2 - 0.3398x + 7.3823 \quad R^2 = 0.8241 \]

\[ y = 0.1177x^2 - 5.3056x + 136.42 \quad R^2 = 0.9748 \]

\[ y = -0.0007x^2 + 0.0615x - 0.8024 \quad R^2 = 0.9714 \]

\[ y = 0.0035x^2 - 0.2734x + 7.1993 \quad R^2 = 0.931 \]

- Higher external temperature
- Higher operating pressures to realize the transcritical cycle
- Compressor needs more power
- COP decreases

- Gas cooler outlet temperature increases
- Higher quality at the receiver
- COP decreases

\[ COP = \left(1 - X_7\right) \frac{h_4 - h_2}{h_3 - h_4} \]

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Reference test case - Energy analysis

\[ T_{\text{ext}} = 33.5^\circ C \]

\[ m_{\text{comp}} = 0.103 \, \text{kg/s} \]

\[ m_{\text{evap}} = 0.055 \, \text{kg/s} \]

\[ \text{COP} = 1.83 \]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>External temperature</td>
<td>33.5°C</td>
</tr>
<tr>
<td>CO₂ Mass Flow Rate</td>
<td>0.10 kg/s</td>
</tr>
<tr>
<td>Discharge temperature</td>
<td>115.0°C</td>
</tr>
<tr>
<td>Gas cooler outlet temperature</td>
<td>36.5°C</td>
</tr>
<tr>
<td>Gas cooler pressure</td>
<td>90.9 bar</td>
</tr>
<tr>
<td>Suction pressure</td>
<td>25.3 bar</td>
</tr>
<tr>
<td>Suction temperature</td>
<td>5.6°C</td>
</tr>
<tr>
<td>Superheat</td>
<td>15.7°C</td>
</tr>
<tr>
<td>Receiver pressure</td>
<td>34.8 bar</td>
</tr>
<tr>
<td>Evaporating pressure</td>
<td>25.3 bar</td>
</tr>
<tr>
<td>Evaporating temperature</td>
<td>-10.2°C</td>
</tr>
<tr>
<td>Gas cooler thermal power</td>
<td>28.0 kW</td>
</tr>
<tr>
<td>CO₂ critical pressure</td>
<td>73.8 bar</td>
</tr>
<tr>
<td>CO₂ critical temperature</td>
<td>31.1°C</td>
</tr>
</tbody>
</table>
Reference test case - Exergy analysis

Irreversibility breakdown

- GC: 42.58%
- ICMT: 27.19%
- EEV: 1.47%
- Evap: 7.43%
- Comp: 21.32%

Exergy efficiency: 29.4%

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Ejector-based layout

- Constant pressure mixing device
- Model developed in Matlab coupled with NIST database

Entrainment ratio
$$\mu = \frac{m_{evap}}{m_{comp}}$$

Ejector efficiency
$$\eta_{ej} = \mu \frac{(h_{3,isent} - h_3)}{h_7 - h_6}$$

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Regardless of the entrainment ratio the temperature of the \( \text{CO}_2 \) at the exit of the compressor is lower of about 15-25 K, producing a lower compression work up to 22 kJ/kg.
The entrainment ratio of the ejector affects the vapor quality downstream the ejector and, in turn, the ejector efficiency and the COP.
Ejector-based results

Irreversibility breakdown

<table>
<thead>
<tr>
<th>Component</th>
<th>Reference</th>
<th>Ejector retrofit</th>
</tr>
</thead>
<tbody>
<tr>
<td>COP</td>
<td>1.83</td>
<td>2.64 (+44%)</td>
</tr>
<tr>
<td>Exergy efficiency</td>
<td>29.4%</td>
<td>34.8% (+18%)</td>
</tr>
</tbody>
</table>
Conclusions

• Development of an industrial-scale facility for experimental CO₂ refrigeration research
• First experimental campaign at different external temperatures and exergy analyses
• Theoretical modelling of a constant pressure mixing ejector layout

• The comparison between experimental cases and ejector-based case highlights good improvements of Coefficient of Performance up to 40% and maximum temperatures lower of about 15-25K
• For 33.5°C, ejector-based exergy efficiency improves to 34.8% from 29.4%

• Future activities will aim at an experimental assessment of the ejector and other energy saving and recovery technologies
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