Experimental Analysis of R134a and R1234ze(E) Flow Boiling Inside a Roll Bond Evaporator

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Outline

- **Introduction**: why this work?
- **Experimental set up**: where this work?
- **Operating conditions**: how this work?
- **Analysis of the results**: what did we measure?
- **Two phase flow correlation**: simplified design point of view
- **Conclusions**: a brief summary
Domestic refrigerators:
more than 80 million units/year

ROLL BOND EVAPORATOR

Increase efficiency
→ Variable refrigerant flow rate modulation

EU F- Gas Regulation
→ Jan 2015: Refrigerants with GWP>150 can not be used anymore

Introduction 1/2
Several steady state conditions at different mass flow rates

- Infrared images
- Overall thermal performances
- Average HTC S

Substitute for R134a (most used refrigerant in this application)

- Isobutane – Propane (FLAMMABLE)
- HFO 1234ze(E) GWP < 1
Experimental Set-Up 1/3

Off-the-shelf roll bond evaporator

- layer of insulation (one adiabatic face)
- 16 T-type thermocouples

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ratio external/internal heat transfer area</td>
<td>1.69</td>
</tr>
<tr>
<td>Plate length L [m]</td>
<td>0.42</td>
</tr>
<tr>
<td>Plate width W [m]</td>
<td>0.52</td>
</tr>
<tr>
<td>Plate thickness [mm]</td>
<td>0.8</td>
</tr>
<tr>
<td>Tube section perimeter 2P [mm]</td>
<td>34.7</td>
</tr>
<tr>
<td>Tube section area [mm$^2$]</td>
<td>12.6</td>
</tr>
<tr>
<td>Tube length l [m]</td>
<td>7.44</td>
</tr>
</tbody>
</table>
Experimental Set-Up 2/3

Experimental rig

Roll Bond Evaporator

Legend:
- p: absolute pressure transducer
- dp: differential pressure transducer
- t: T-type thermocouple
- m: Coriolis mass flow meter

Infrared camera: front face temperature distribution
Experimental Set-Up 3/3

Roll bond evaporator

Climatic chamber
### Operating Conditions

Climatic chamber: air temperature 3°C, air velocity <1 m s⁻¹

<table>
<thead>
<tr>
<th>Experimental data sets</th>
<th>t cond</th>
<th>x in</th>
<th>G</th>
<th>Q</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Condensation</td>
<td>Inlet vapor</td>
<td>Refrigerant</td>
<td>Heat flow</td>
</tr>
<tr>
<td></td>
<td>temperature</td>
<td>quality</td>
<td>mass flux</td>
<td>rate</td>
</tr>
<tr>
<td>°C</td>
<td>[-]</td>
<td>[kg/(m²s)]</td>
<td>[W]</td>
<td></td>
</tr>
<tr>
<td><strong>R134a (t_{evap} = -15°C)</strong></td>
<td>40 — 42</td>
<td>0.26 — 0.32</td>
<td>11 — 49</td>
<td>24 — 90</td>
</tr>
<tr>
<td><strong>R134a (t_{evap} = -20°C)</strong></td>
<td>40 — 43</td>
<td>0.27 — 0.35</td>
<td>11 — 60</td>
<td>24 — 106</td>
</tr>
<tr>
<td><strong>R1234ze(E) (t_{evap} = -15°C)</strong></td>
<td>41 — 42</td>
<td>0.27 — 0.28</td>
<td>10 — 50</td>
<td>21 — 87</td>
</tr>
<tr>
<td><strong>R1234ze(E) (t_{evap} = -20°C)</strong></td>
<td>40 — 41</td>
<td>0.28 — 0.30</td>
<td>10 — 56</td>
<td>21 — 100</td>
</tr>
</tbody>
</table>

- **G min**: minimum compressor rpm value;
- **G max**: no more superheating available at the suction line.
Analysis of the results 1/6

Heat flow rate $Q$:  
$$ Q = \dot{m} \left( h_{out} - h_{in} \right) $$

![Graph showing heat flow rate vs. refrigerant mass flow rate for different refrigerants and temperature evaporation points](image-url)
Thermal camera images 2/6

(a) $\dot{m}=0.51 \text{ kg h}^{-1}$
(b) $\dot{m}=0.76 \text{ kg h}^{-1}$
(c) $\dot{m}=0.99 \text{ kg h}^{-1}$
(d) $\dot{m}=1.27 \text{ kg h}^{-1}$
Thermal camera images 3/6

\( \dot{m} = 1.55 \text{ kg h}^{-1} \)

\( \dot{m} = 1.76 \text{ kg h}^{-1} \)

\( \dot{m} = 2.07 \text{ kg h}^{-1} \)

\( \dot{m} = 2.24 \text{ kg h}^{-1} \)
Analysis of the results 4/6

Overall heat transfer coefficient: $U = \frac{Q}{A \left( t_a - t_r \right)}$ where: $A = L \cdot W$

![Graph showing the relationship between specific heat flux and $U$ for different refrigerants at two evaporation temperatures.]

- $U_{-15^\circ C} = +13\% U_{-20^\circ C}$
Average **air side** heat transfer coefficient:

\[
\alpha_a = \frac{Q}{A (t_a - t_w)} \quad \text{mean value 22.0 W/(m}^2\text{K)}
\]

\[
\text{dev standard 2.1W/(m}^2\text{K)}
\]

Average **refrigerant side** heat transfer coefficient:

\[
\alpha_r = \frac{1}{\left(\frac{1}{U} - \frac{1}{\alpha_a}\right)\left(\frac{A_{tot}}{A_{tube}}\right)}
\]

• no fouling resistance
• no wall resistance
Analysis of the results 6/6

HTC_{-15°C} = +32% HTC_{-20°C}
Two phase flow correlation

→ No dedicated HTC models

- Not linear circuitry lay-out;
- Low mass flux \([\text{from} \ 10 \ \text{to} \ 60 \ \text{kg} \ \text{m}^{-2} \ \text{s}^{-1}]\);
- Low heat flux \([\text{from} \ 160 \ \text{to} \ 820 \ \text{W} \ \text{m}^{-2}]\);
- Low Reynolds number \([\text{Re}_{\text{LP}} \ \text{below} \ 150}]\);

→ Chen correlation (1966): - high pool boiling contribution;
    - poor convective boiling effect.

Simplified model for roll bond design: **Cooper (1984)**

\[
\alpha_{tp} = 55 \ p^* \left(0.12 - 0.2 \ \log_{10} R_p\right) \ \left(-\log_{10} p^*\right)^{-0.55} \ q^{0.67} \ M^{-0.5}
\]

Relative deviation: 7 % for R134a
                  3 % for R1234ze(E)
Conclusions

1. Variable mass flow rates analysis:
   - Refrigerant capacity is a linear function of mass flow rate;
   - Air side coefficient: almost constant (22 W m\(^{-2}\) K\(^{-1}\));
   - Overall HTC and Refrigerant HTC:
     - slightly lower for \(t_{\text{evap}} = -20^\circ\text{C}\);
     - compared against Cooper correlation (1984)
       \(\rightarrow\) relative deviation 5%.
   - Recently tested also: R1234yf, R600a and R600.

2. R134a vs. R1234ze(E):
   - the two refrigerants have similar heat transfer performances;
   - R1234ze(E) environmentally friendly substitute of R134a from the evaporator design point of view.
Thank you for your attention

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Further analysis

REFRIGERANT HTC (W/m²K)

SPECIFIC HEAT FLUX (W/m²)

- R134a (Tevap = -15°C)
- R1234ze(E) (tevap = -15°C)
- R1234yf (tevap = -15°C)
- R600a (Tevap = -15°C)
- R600 (tevap = -15°C)
- R1234yf (tevap = -20°C)
- R134a (Tevap = -20°C)
- R1234ze(E) (tevap = -20°C)

$\textit{t}_{\text{evap}} = -15°C$

$\textit{t}_{\text{evap}} = -20°C$
Average air side HTC

- R134a (tevap=-15°C)
- R134a (tevap=-20°C)
- R1234ze(E) (tevap=-15°C)
- R1234ze(E) (tevap=-20°C)

Mean value: 22.0 W/(m²K)
St. dev: 2.08 W/(m²K)
# Uncertainty

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Infrared camera (Agema 550)</td>
<td>± 0.1 K</td>
</tr>
<tr>
<td>T-type thermocouple</td>
<td>± 0.1 K</td>
</tr>
<tr>
<td>Climatic chamber (Weiss WK111)</td>
<td>± 1 K (spatial)</td>
</tr>
<tr>
<td></td>
<td>± 0.3 K (time)</td>
</tr>
<tr>
<td>Coriolis flowmeter</td>
<td>± 0.1 % reading</td>
</tr>
<tr>
<td>Pressure transducer</td>
<td>± 0.075 % fs. (fs. 20 bar)</td>
</tr>
<tr>
<td>Specific enthalpy</td>
<td>± 1 %</td>
</tr>
<tr>
<td>Evaporator cooling capacity</td>
<td>± 2.9 %</td>
</tr>
<tr>
<td>Overall heat transfer coefficient</td>
<td>± 7.6 %</td>
</tr>
<tr>
<td>Air heat transfer coefficient</td>
<td>± 2.0 %</td>
</tr>
<tr>
<td>Refrigerant HTC</td>
<td>± 20.0 %</td>
</tr>
</tbody>
</table>

Kline and McClintok (1954)
Cooper correlation $t_{\text{evap}} = -15^\circ\text{C}$
Relative deviation

<table>
<thead>
<tr>
<th>Correlation</th>
<th>R134a</th>
<th>R1234ze(E)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cooper (1984)</td>
<td>7%</td>
<td>3%</td>
</tr>
<tr>
<td>Chen (1966)</td>
<td>130%</td>
<td>150%</td>
</tr>
<tr>
<td>Chato (1997)</td>
<td>106%</td>
<td>98%</td>
</tr>
<tr>
<td>Smith et al. (1993)</td>
<td>109%</td>
<td>-30%</td>
</tr>
<tr>
<td>Zhang et al. (2005)</td>
<td>179%</td>
<td>175%</td>
</tr>
<tr>
<td>Shah (1976)</td>
<td>132%</td>
<td>131%</td>
</tr>
<tr>
<td>Forster and Zuber</td>
<td>23.5%</td>
<td>-9.3%</td>
</tr>
</tbody>
</table>
Experimental set up
Refrigerant pressure drop

- R134a (tevap=-15°C)
- R134a (tevap=-20°C)
- R1234ze(E) (tevap=-15°C)
- R1234ze(E) (tevap=-20°C)

**Graph:**
- **Y-axis:** Pressure Drop (bar)
- **X-axis:** Refrigerant Mass Flow Rate (kg/h)

July 16, 2014
Compressor

Rotary model made by Aspen.
Brushless DC Motor (24V)
Speed: 2100-6500 RPM
Size: 1.9 cm³
Chen correlation (1966)

Local two phase flow boiling coefficient:

\[ \alpha_{tp} = S \alpha_{nb} + F \alpha_{cb} \]

Where:
- \( S \) nucleate boiling suppression factor
- \( F \) two-phase multiplier
- \( \alpha_{nb} \) nucleate boiling HTC (Forster and Zuber, 1955)
- \( \alpha_{cb} \) convective boiling HTC (Dittus-Boelter, 1930)

\[ S = 1 \]

\[ \alpha_{nb} \) (Forster and Zuber): relative deviation: 23.5% R134a
-9.3% R1234ze(E)
Roll bond design

\[ q = \frac{Q}{Pl} \]

\[ A = LW \]