Propane as Refrigerant for Heat Pump Water Heaters

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Agenda

• Background and objective
• Evaluation based on Thermophysical Properties
• Performance Modeling
• Experimental Evaluation/Validation (+Charge reduction)
• Field Validation
• Conclusions
Background
Objective

Identify appropriate substitute for R-134a as HFCs will phase out:

• Evaluate the potential of Propane (R290) to replace R134a for a residential hybrid HPWH while ensuring compliance with safety standards

+ Low GWP, no direct environmental impact
+ No major modification of existing system is desired
+ Performance FHR and UEF should be comparable
− Refrigerants flammability poses a concern!!
## A- Evaluation based on Thermophysical Properties

<table>
<thead>
<tr>
<th></th>
<th>R134a</th>
<th>R290</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Formula</strong></td>
<td>CH$_2$FCF$_3$</td>
<td>C$_3$H$_8$</td>
</tr>
<tr>
<td><strong>CAS number</strong></td>
<td>811-97-2</td>
<td>74-98-6</td>
</tr>
<tr>
<td><strong>Molecular mass (g/mol)</strong></td>
<td>102</td>
<td>44</td>
</tr>
<tr>
<td><strong>Ozone depletion potential</strong></td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td><strong>Global warming potential, GWP$_{100}$</strong></td>
<td>1300$^a$</td>
<td>&lt;3$^a$</td>
</tr>
<tr>
<td><strong>Safety classification$^b$</strong></td>
<td>A1</td>
<td>A3</td>
</tr>
<tr>
<td><strong>Critical temperature (K)$^c$</strong></td>
<td>374.21</td>
<td>369.89</td>
</tr>
<tr>
<td><strong>Critical pressure (MPa)$^c$</strong></td>
<td>4.06</td>
<td>4.25</td>
</tr>
<tr>
<td><strong>Saturation pressure at 280.37 K (MPa)</strong></td>
<td>0.3774</td>
<td>0.5879</td>
</tr>
<tr>
<td><strong>Enthalpy of vaporization at 280.37 K (kJ/kg)</strong></td>
<td>193.17</td>
<td>364.46</td>
</tr>
<tr>
<td><strong>Vapor density at 280.37 K (kg/m$^3$)</strong></td>
<td>18.66</td>
<td>12.75</td>
</tr>
<tr>
<td><strong>Volumetric capacity at 280.37 K (kJ/m$^3$)</strong></td>
<td><strong>3604.55</strong></td>
<td><strong>4646.87</strong></td>
</tr>
<tr>
<td><strong>Saturation pressure at 341.48 K (MPa)</strong></td>
<td>2.04</td>
<td>2.50</td>
</tr>
</tbody>
</table>

$^a$ IPCC 5$^{th}$ report, chapter 8 (Myhre et al., 2013)  
$^b$ ANSI/ASHRAE standard 34-2013 (A, nontoxic; 1, nonflammable; 3, flammable)  
$^c$ REFPROP 9.1 (Lemmon et al., 2013)
B- Performance Modeling- Design Parameters

- Heat pump T-stat at the top: on at 115 °F, off at 125 °F.
- Electric element at the top: on at 110 °F, off at 125 °F.
- Two different condenser coil wrap patterns

<table>
<thead>
<tr>
<th>Case number</th>
<th>Wrap pattern</th>
<th>Tank insulation effectiveness (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Parallel-counterflow</td>
<td>90</td>
</tr>
<tr>
<td>2</td>
<td>Parallel-counterflow</td>
<td>95</td>
</tr>
<tr>
<td>3</td>
<td>Counterflow</td>
<td>90</td>
</tr>
<tr>
<td>4</td>
<td>Counterflow</td>
<td>95</td>
</tr>
</tbody>
</table>

Condenser wrap configurations: (a) counterflow, (b) parallel-counterflow
## Performance Evaluation Criteria

<table>
<thead>
<tr>
<th>FHR greater or equal to (gals)</th>
<th>FHR less than (gals)</th>
<th>Draw pattern for 24-hr UEF</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>20</td>
<td>Point of use</td>
</tr>
<tr>
<td>20</td>
<td>55</td>
<td>Low usage</td>
</tr>
<tr>
<td>55</td>
<td>80</td>
<td>Medium usage</td>
</tr>
<tr>
<td>80</td>
<td>Max</td>
<td>High usage</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Draw Number</th>
<th>Time During Test (hh:mm)</th>
<th>Volume (gals/L)</th>
<th>Flow Rate (GPM/LPM)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>00:00</td>
<td>15.0 (56.8)</td>
<td>1.7 (6.5)</td>
</tr>
<tr>
<td>2</td>
<td>00:30</td>
<td>2.0 (7.6)</td>
<td>1 (3.8)</td>
</tr>
<tr>
<td>3</td>
<td>01:40</td>
<td>9.0 (34.1)</td>
<td>1.7 (6.5)</td>
</tr>
<tr>
<td>4</td>
<td>10:30</td>
<td>9.0 (34.1)</td>
<td>1.7 (6.5)</td>
</tr>
<tr>
<td>5</td>
<td>11:30</td>
<td>5.0 (18.9)</td>
<td>1.7 (6.5)</td>
</tr>
<tr>
<td>6</td>
<td>12:00</td>
<td>1.0 (3.8)</td>
<td>1 (3.8)</td>
</tr>
<tr>
<td>7</td>
<td>12:45</td>
<td>1.0 (3.8)</td>
<td>1 (3.8)</td>
</tr>
<tr>
<td>8</td>
<td>12:50</td>
<td>1.0 (3.8)</td>
<td>1 (3.8)</td>
</tr>
<tr>
<td>9</td>
<td>16:00</td>
<td>1.0 (3.8)</td>
<td>1 (3.8)</td>
</tr>
<tr>
<td>10</td>
<td>16:15</td>
<td>2.0 (7.6)</td>
<td>1 (3.8)</td>
</tr>
<tr>
<td>11</td>
<td>16:45</td>
<td>2.0 (7.6)</td>
<td>1.7 (6.5)</td>
</tr>
<tr>
<td>12</td>
<td>17:00</td>
<td>7.0 (26.5)</td>
<td>1.7 (6.5)</td>
</tr>
</tbody>
</table>

Total Volume Drawn Per Day: 55 gallons (208 L)
The **First Hour Rating (FHR)** is a measure of the available hot water capacity of the water heater (in gallons).

**Uniform Energy Factor (UEF)**

\[
\text{UEF} = \sum_{k=1}^{n} \frac{M_k c_p (T_s - T_i)}{W_i}
\]

Compressor Discharge Temperature and Refrigerant Charge Inventory

Direct refrigerant replacement leads to a major charge reduction

Lower compressor discharge is advantageous for direct replacement

Average stored water temperature for propane is comparable to R134a.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>R134a</th>
<th>Propane (R290)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Optimum refrigerant charge</td>
<td>1.68 lbs</td>
<td>0.85 lbs</td>
</tr>
<tr>
<td>First Hour Rating (FHR)</td>
<td>66 gallons</td>
<td>64 gallons</td>
</tr>
<tr>
<td>Unified Energy Factor</td>
<td>3.44</td>
<td>3.60</td>
</tr>
</tbody>
</table>
Opportunities for Charge Reduction

- Refrigerants with higher volumetric capacity
- Component modifications- Design improvement of heat exchangers
- Deployment of improved compressor design
- System modifications- Wrapped vs. split configurations

A refrigerant's charge less than 150 grams has been recommended for all indoor applications.
Preliminary Developments for Charge Reduction

- Baseline R134a Compressor (R134a)
- Large Compressor (Propane)
- Small Compressor (Propane)
- R134a Compressor (drop-in Propane)
- Current progress-optimised component design

Charge Reductions:
- 43% charge reduction
- 47% charge reduction
- >66% charge reduction

DOE compliance and noncompliance markers are indicated.

Uniform Energy Factor (UEF) vs. Refrigerant charge (Grams)
D- Field Validation

Field study at Yarnell House - side by side comparison

Instrumentation strategy for heat pump water heating system

Field evaluation has been in progress for over three months
D- Field Validation

Power consumption comparison
Conclusions

• R290 (Propane) is a feasible working fluid for residential HPWHs (smaller platforms in general).

• Minimum system modifications can enable acceptable performance. Developments are focused on system charge reductions.

• A review of maximum charge limit (indoor applications) can enable broader opportunities.

Propane is a great fluid for specific platforms. However, “One size fits all” is NOT a viable approach!!
Acknowledgements

Joseph Rendall, Ahmed Elatar, Jian Sun, Bo Shen (ORNL)

DOE Building Technologies Office (BTO)

A.O. Smith