Charge Minimization in Light Commercial Refrigeration Systems

Lingyan Jiang, GRA
Shuhei Shibata, Visiting Scholar
Sergio Vivanco Obeso, Visiting Scholar
Pega Hrnjak, PI
Outline

- Objectives
- Establishing a baseline
  - The original unit
  - The instrumented unit – baseline
  - Charge distribution determination of the baseline
- Modeling to identify directions in charge reduction
  - System model with a smaller round-tube condenser
  - System model with a flattened condenser
- System with a flattened condenser
  - Charge optimization experiment – compare to the baseline
- Summary and conclusions
Objectives

- Determine location of refrigerant in operation
- Develop and validate models of performance and refrigerant charge in components
- Using model identify simple ways to reduce refrigerant charge
- Modify the system and validate charge reduction
Initial experiments: baseline

- Establishing the baseline (unit as received):
  - Performance - capacity & COP
- Instrument system:
  - Install mass flow meter, pressure transducers, thermocouples, watt transducers and valves
- Perform charge optimization for instrumented system
- Validate no change in performance (Q & COP) due to instrumentation of the unit
- Determine the charge in each component: evaporator, condenser, compressor and liquid line.
The way to get the performance

\[ Q_{\text{infiltration}} = UA \times (T_{\text{amb}} - T_{\text{cab}}) \]

Where \( UA \) is determined by separate experimentation.

\[ Q_{\text{evap}} = Q_{\text{heater}} + Q_{\text{infiltration}} + Q_{\text{efan}} + Q_{\text{l&c}} \]

\[ W_{\text{sys}} = W_{\text{cp}} + W_{\text{cfan}} + W_{\text{efan}} + W_{\text{l&c}} \]

\[ \text{COP}_{\text{cycle}} = \frac{Q_{\text{evap}}}{W_{\text{cp}}} \]

\[ \text{COP}_{\text{sys}} = \frac{Q_{\text{evap}}}{W_{\text{sys}}} \]
Tubes added for instrumentation

Original

Instrumented

- Evap
- Cond
- Heater
- Capillary tube
- Filter
- Comp
- $W_{\text{system}}$
- $W_{\text{heater}}$

- Valves
- Pressure gauge
- Thermocouple
- Mass flow meter

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Modification did not affect performance

Instrumented vs. original unit

T_{amb} = 26 \, ^\circ C

Heater [W]: the net cooling capacity

Capacity & Power [W]

COPcycle
COPsys
Q_{evap}
W_{sys}
W_{comp}

0.0
0.5
1.0
1.5
2.0
2.5
3.0

0.0
0.5
1.0
1.5
2.0
2.5
3.0

Heater [W]: the net cooling capacity

Purdue conference # 2467
Charge determination procedure

- When steady state is reached:
  1. Close all valves and turn off the system simultaneously
  2. Remove refrigerant from each part to a cylinder cooled by liquid N2
  3. Dry cylinder and weigh
Charge distribution of the baseline

in steady state \( W_{\text{heater}} = 361.1 \, [W], \, T_{\text{amb}} = 25.2 \, [^\circ C], \, T_{\text{cab}} = 19.1 \, [^\circ C] \)

<table>
<thead>
<tr>
<th>Component</th>
<th>Mass</th>
</tr>
</thead>
<tbody>
<tr>
<td>Condenser</td>
<td>142.5 [g]</td>
</tr>
<tr>
<td>Evaporator</td>
<td>28.2 [g]</td>
</tr>
<tr>
<td>Liquid line (mass flow meter)</td>
<td>131.0 [g]</td>
</tr>
<tr>
<td>Compressor (accumulator)</td>
<td>35.4 [g]</td>
</tr>
<tr>
<td>Total extracted</td>
<td>337.0 [g]</td>
</tr>
<tr>
<td>Actual charge</td>
<td>350.0 [g]</td>
</tr>
<tr>
<td>Error</td>
<td>-3.7%</td>
</tr>
</tbody>
</table>
Condenser model

- Finite Volume Method (Cond is divided into 416 elements)
- $\varepsilon$-NTU method

Charge: $M = \rho V$
for single phase: $\rho(P, T)$
for two phase: $\rho = \rho_v \alpha + \rho_l (1 - \alpha)$
where $\alpha$ is void fraction.

**INPUTS:** $V_{a,c} = 3.2$ [m/s], $T_{a,c} = 26.0$ [°C]
## Correlations used in HEX models

<table>
<thead>
<tr>
<th></th>
<th>Condenser (Round tube)</th>
<th>Evaporator (Round tube plate fins)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Air side</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1-phase HTC</td>
<td>Churchill and Bernstein (1977)</td>
<td>Kim et al. (1999)</td>
</tr>
<tr>
<td><strong>Refrigerant side</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1-phase HTC</td>
<td>Gnielinski (1976)</td>
<td>Same</td>
</tr>
<tr>
<td>DP/f Churchill (1977)</td>
<td>Same</td>
<td></td>
</tr>
<tr>
<td>DP</td>
<td>Friedel (1979)</td>
<td>Same</td>
</tr>
<tr>
<td>α</td>
<td>Homogeneous, Zivi (1964), Rouhani and Axelsson (1970),</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Graham et al. (1999), ...</td>
<td></td>
</tr>
</tbody>
</table>

## System model assumptions

- Steady state
- Uniform $T_{air}$ and $V_{air}$ profiles at the inlet to both heat exchangers
- Capillary tube – isenthalpic, $\dot{m}$ everywhere the same
- Negligible oil circulation rate
**System model vs. experimental results:**

Conditions: $T_{\text{amb}} = 26.0 \, ^\circ\text{C}$, $T_{\text{cab}} = 19.1 \, ^\circ\text{C}$, $DT_1 = 20 \, ^\circ\text{C}$, $DT_5 = 12 \, ^\circ\text{C}$.

$T_{\text{ambient}} = 26^\circ\text{C}$, $P_{\text{atm}} = 101$ KPa
Effect of void fraction correlations:

Charge [g] in baseline HEXs

### Condenser

<table>
<thead>
<tr>
<th>Method</th>
<th>Charge [g]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exp</td>
<td>142.5</td>
</tr>
<tr>
<td>Homo</td>
<td>120.4</td>
</tr>
<tr>
<td>Zivi</td>
<td>158.1</td>
</tr>
<tr>
<td>RouAxe</td>
<td>171.3</td>
</tr>
<tr>
<td>Graham</td>
<td>165.2</td>
</tr>
</tbody>
</table>

### Evaporator

<table>
<thead>
<tr>
<th>Method</th>
<th>Charge [g]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exp</td>
<td>28.2</td>
</tr>
<tr>
<td>Homo</td>
<td>7.0</td>
</tr>
<tr>
<td>Zivi</td>
<td>15.5</td>
</tr>
<tr>
<td>RouAxe</td>
<td>24.1</td>
</tr>
<tr>
<td>Graham</td>
<td>23.0</td>
</tr>
</tbody>
</table>

**Charge along condenser tube**

- Homo
- Zivi
- RouAxe
- Graham

**Charge along evaporator tube**

- Homo
- Zivi
- RouAxe
- Graham

**Legend:**
- Superheated
- Two-phase
- Subcooled
We can either decreasing the diameter of the condenser tube ...

16% smaller \( d \) reduces COP 6% and charge \(~30\%\).
Or flatten the tube of the condenser

16% smaller dh keeps the same COP and reduces charge ~30%.
COP maximizing charge for system with round and flattened tube condenser

Baseline: optimal charge with the highest COP is 300 - 360 (g)

System w/ flattened condenser: optimal charge is 240 - 300 (g)

* $W_{\text{heater}} = 0 \, \text{V}$, $T_{\text{ambient}} = 26 \, ^\circ\text{C}$, cycling.

Potential charge reduction of 60 grams is reachable.
Rouhani and Axelsson (1970) and Graham et al. (1999) correlations predict well (~58 grams of charge reduction).
## Mass flux affects charge retention

<table>
<thead>
<tr>
<th>Condenser type</th>
<th>Condenser charge by model [g]</th>
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</thead>
<tbody>
<tr>
<td>Homo</td>
<td>Zivi</td>
<td>RouAxe</td>
<td>Graham</td>
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<td>120.4</td>
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<td>165.2</td>
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<tr>
<td>82.9</td>
<td>109.6</td>
<td>113.2</td>
<td>107.0</td>
<td></td>
<td></td>
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<tr>
<td>Cross sectional ratio = 0.70</td>
<td>Ratio= 0.69</td>
<td>Ratio= 0.69</td>
<td>Ratio= 0.66</td>
<td>Ratio= 0.65</td>
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</tbody>
</table>

Gr [kg/s-m²]

| | 66.4 | 93.9 |
| | Ratio= 1.43 |

Void fraction correlations that include the effect of the mass flux (Rouhani-Axelsson 1970 and Graham et al. 1999) predict greater potential for charge reduction.
Summary and conclusions

- **Experiment**: determined charge distribution in a bottle cooler experimentally. Most of the charge is retained in the **condenser**.
- **Model**: a validated system model is built to predict charge and performance. Used to analyze a system with a smaller round-tube condenser and the one with a flattened-tube condenser.
- **Charge reduction**: flattening the finless-round-tube of the heat exchanger proven to be a simple way to reduce charge without significant reduction of the system performance.
- Void fraction correlations that include the effect of the mass flux (Rouhani-Axelsson 1970 and Graham et al. 1999) predict greater potential for charge reduction.
- **Final experiments** (component charge inventory) are underway.
Thank you!

ljiang13@Illinois.edu