A New Control Mechanism for Two-Phase Ejector in Vapor Compression Cycles Using Adjustable Motive Nozzle Inlet Vortex

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Presentation Outline

• Background: opportunities and challenges with ejector cooling cycles
• Research motivation: optimize ejector cycle performance under changing working conditions/capacities (common in real world applications) by adjusting ejector motive nozzle
• New solution: vortex ejector - utilizing controllable vortex at the motive inlet of the ejector to adjust mass flow rate and condenser outlet quality/subcooling (vortex nozzle/valve has been recognized as a reliable flow modulation method as early as 1960s (Mayer, 1967; Wormley, 1969))
• Research approach:
  – Vortex nozzle tests with refrigerant (R134a)
  – Visualization and modeling of swirling low vapor quality flow expanded in the nozzle
• Conclusions
Conventional cooling cycle:
- Throttling in the expansion valve causes irreversibility
- Cycle efficiency is impaired

Ejector cooling cycle:
- Irreversibility in the expansion process is reduced
- Compressor work is saved
- Cooling capacity is increased
- Cycle efficiency is improved
(R134a ~ 5 %; CO₂ ~ 20 %)
Challenges with Ejector Cooling Cycle

- Different working conditions/capacities favor different ejector geometry
  Elbel and Hrnjak (2008); Elbel (2011);

- Slightly different geometry might result in significant difference in system COP under the same conditions
  Sumeru et al. (2012); Sarkar (2012);

- Ejector motive nozzle throat diameter (nozzle restrictiveness) is one of the key points that can significantly affect COP

  COP changed by more than 40%

<table>
<thead>
<tr>
<th>Condition 1</th>
<th>Condition 2</th>
<th>Condition 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_{\text{indoor}}$ (dry/wet bulb), °C</td>
<td>26.7/19.4</td>
<td>26.7/19.4</td>
</tr>
<tr>
<td>$T_{\text{outdoor}}$ (dry/wet bulb), °C</td>
<td>35.0/19.5</td>
<td>30.6/16.8</td>
</tr>
<tr>
<td>$p_{\text{cond}}$, MPa</td>
<td>2.4</td>
<td>2.0</td>
</tr>
</tbody>
</table>

R410A ejector air conditioning system COP with different motive nozzles under three different conditions
Hu et al. (2014)
Restrictiveness of the motive nozzle on the two-phase flow can significantly affect ejector efficiency and system performance.
Restrictiveness of the motive nozzle on the two-phase flow can significantly affect ejector efficiency and system performance.
How to Adjust Motive Nozzle Geometry (Restrictiveness on Flow)

Eurofighter Typhoon thrust nozzle
Previous Approach: Adjustable Needle

This design is complicated and costly, and more friction losses are incurred probably because of the additional surface area and turbulence introduced.
New Solution: Vortex Ejector

Utilizing an adjustable vortex at the motive inlet to control the flow expanded in the motive nozzle (no change in geometry; same effect as changing nozzle throat diameter).

Conventional ejector  Vortex ejector

Vortex ejector cooling cycle
Share of Tangential Kinetic Energy in the Available Pressure Potential Decreases the Mass Flow Rate

\[ \Delta p \approx \frac{1}{2} \rho \left( V_{\text{out}}^2 - V_{\text{in}}^2 \right) \]

\[ V_{\text{out}}^2 = V_{\text{axial, out}}^2 + V_{\text{tangential, out}}^2 \]

\[ \dot{m} \approx \rho V_{\text{axial, out}} A_{\text{out}} \]

Works for both single-phase and two-phase
Research Approach

- **Experimental investigation** of the influence of motive inlet vortex on the flow expanded in the motive nozzle with commonly used refrigerant R134a
- **Visualization** of the swirling low vapor quality flow expanded in the nozzle
- **Explanation and modeling** of the influence of motive inlet vortex on the flow expanded in the motive nozzle (ongoing)
- **Evaluation of the nozzle efficiency** with vortex control and **comparison** with other control methods; **system tests** with adjustable vortex ejector under different working conditions in the future
Vortex Nozzle

**Background and motivation**

**New solution: vortex ejector**

**Experimental facility**

**Experimental results**

**Conclusions and future work**

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**Vortex nozzle geometry**

- Nozzle inlet diameter (mm): 15.0
- Nozzle throat diameter (mm): 1.03
- Nozzle outlet diameter (mm): 1.7
- Nozzle convergent part length (mm): 9.9
- Nozzle divergent part length (mm): 40.0
- Tangential inlet inner diameter (mm): 2.0
- Vortex decay distance (mm): 138.0

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Axial inlet

Tangential inlet

Sleeve (resin)

Tee (brass)

Nozzle (resin)

3D printed prototype

Convergent-divergent nozzle (resin)
Experimental Facility for Investigation of Vortex Influence on Nozzle Restrictiveness

- Pumped-refrigerant-loop for adjustment of nozzle test conditions
- Pressures and temperatures at the axial and tangential inlets are measured; pressure at the nozzle outlet is measured
- Total mass flow rate and axial inlet mass flow rate are measured by Coriolis flow meters
- Ratio of tangential inlet mass flow rate to total mass flow rate is adjusted by two valves

\[ Vortex \ strength = \frac{\dot{m}_{tangential}}{\dot{m}_{total}} \]
Testing Conditions

- **Working fluid**: R134a
- **Different nozzle inlet pressures** are achieved by adjusting the heating water temperature and pump speed.
- **Nozzle outlet pressure** can be adjusted by a valve installed in the downstream of the nozzle.
- Flow at the nozzle inlet is **subcooled by around 0.5 °C**. No observable bubbles at the nozzle inlet (guaranteed by observing through the sight glass installed at the nozzle inlet).

### Test Matrix

<table>
<thead>
<tr>
<th>$P_{in}$ (kPa)</th>
<th>$P_{out}$ (kPa)</th>
<th>$T_{in}$ (°C)</th>
<th>$m_{total}$ (g/s)</th>
<th>Vortex strength (-)</th>
</tr>
</thead>
<tbody>
<tr>
<td>760~1059</td>
<td>407~909</td>
<td>29~41</td>
<td>6~20</td>
<td>0~1</td>
</tr>
</tbody>
</table>
Effect of Outlet Pressure on Nozzle Mass Flow Rate at Constant Inlet Pressure

**Background and motivation**

- New solution: vortex ejector

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**Experimental results**

**Conclusions and future work**

### Observations:
- Flow is choked at low outlet pressure
- Inlet vortex reduces total mass flow rate under the same inlet and outlet conditions (larger restrictiveness)

**Inlet subcooling = 0.5 °C**

Theoretically calculated incompressible single phase liquid mass flow rate

**Nozzle Inlet:** 925 kPa 36 °C

**P_{in} = 925 kPa**

- **No vortex**
- **With max vortex**

Choked at low outlet pressure (decrease in outlet pressure does not increase mass flow rate)
Preliminary Visualization Results

Clear flow in the convergent part of the nozzle

Clear flow in the convergent part of the nozzle

Inlet 925 kPa 36 C no vortex

Choked flow

Outlet pressure close to inlet pressure

Outlet pressure close to inlet pressure: flow is still clear after the throat

Choked flow (very low outlet pressure): becomes bubbly immediately after the throat

Outlet pressure close to inlet pressure: flow is still clear after the throat
Choked Mass Flow Rate with Different Inlet Vortex Strengths at Constant Inlet Pressure

Inlet subcooling = 0.5 °C

Mass flow rate can be reduced by 35 % with vortex under the same inlet and outlet conditions (large control range).

Nozzle restrictiveness on the flow is changed by vortex; the stronger the vortex is, the larger the restrictiveness is.
Nozzle Inlet Pressure Can Vary in A Wide Range with Different Inlet Vortex Strengths at Constant Total Mass Flow Rate (Choked)

Inlet subcooling = 0.5 °C

Mass flow rate ratio (vortex strength): 0.2 to 0.5
Inlet pressure: 780 kPa to 1050 kPa (large control range) for total mass flow rate = 15 g/s

Nozzle restrictiveness on the flow is changed by vortex; the stronger the vortex is, the larger the restrictiveness is.
Conclusions and Future Work

- Nozzle inlet vortex can change nozzle restrictiveness on the two-phase flow. The stronger the vortex is, the larger the restrictiveness is.
- The control range of inlet pressure and mass flow rate is large enough for real applications. Mass flow rate can be reduced by 35% with vortex under the same nozzle inlet and outlet conditions.
- Next step: Compare the efficiency of vortex ejector with other control methods to see if it reduces the frictional losses for the same range of flow control.
- Goal: By adjusting the restrictiveness of motive nozzle on the flow expanded through it, ejector cycle performance can be optimized for different working conditions/capacities and the improvements could be more than 40%. 
Thank you for your attention!

Any questions?

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- Email: jzhu50@illinois.edu

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