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Refrigeration and Air Conditioning
High Performance Buildings

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

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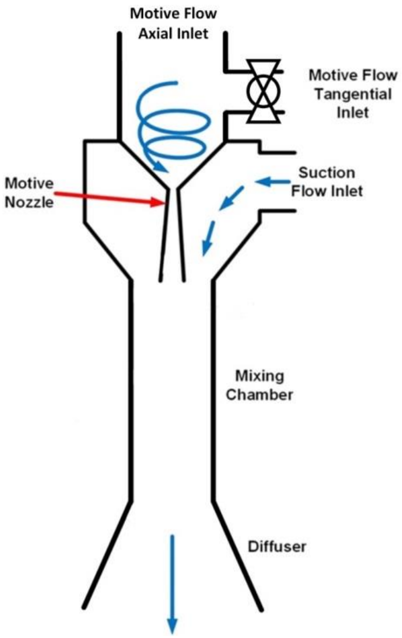
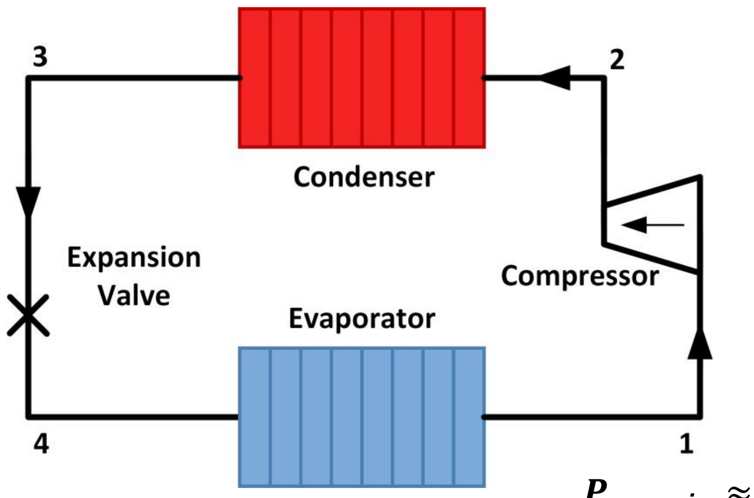
Presentation Outline

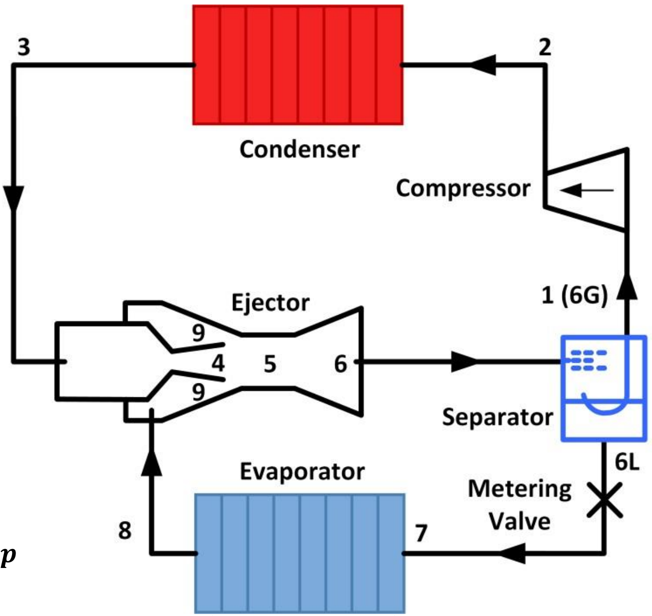
- Background: opportunities and challenges with ejector cooling cycles
- Research motivation: optimize ejector cycle performance under changing working conditions/capacities (common in real world applications) by adjusting ejector motive nozzle
- New solution: vortex ejector - utilizing controllable 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



Benefits of Ejector Cooling Cycle



$P_{comp,in} \approx P_{evap}$



$P_{comp,in} > P_{evap}$

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 %; CO_2 ~ 20 %)

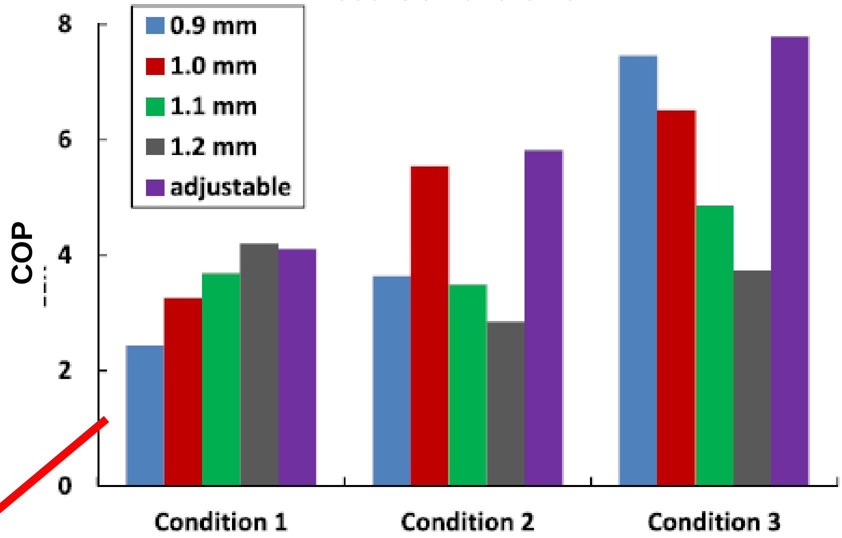
Challenges with Ejector Cooling Cycle

- 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 %

	Condition 1	Condition 2	Condition 3
T_{indoor} (dry/wet bulb), °C	26.7/19.4	26.7/19.4	26.8/19.5
$T_{outdoor}$ (dry/wet bulb), °C	35.0/19.5	30.6/16.8	27.8/14.9
p_{cond}, MPa	2.4	2.0	1.9

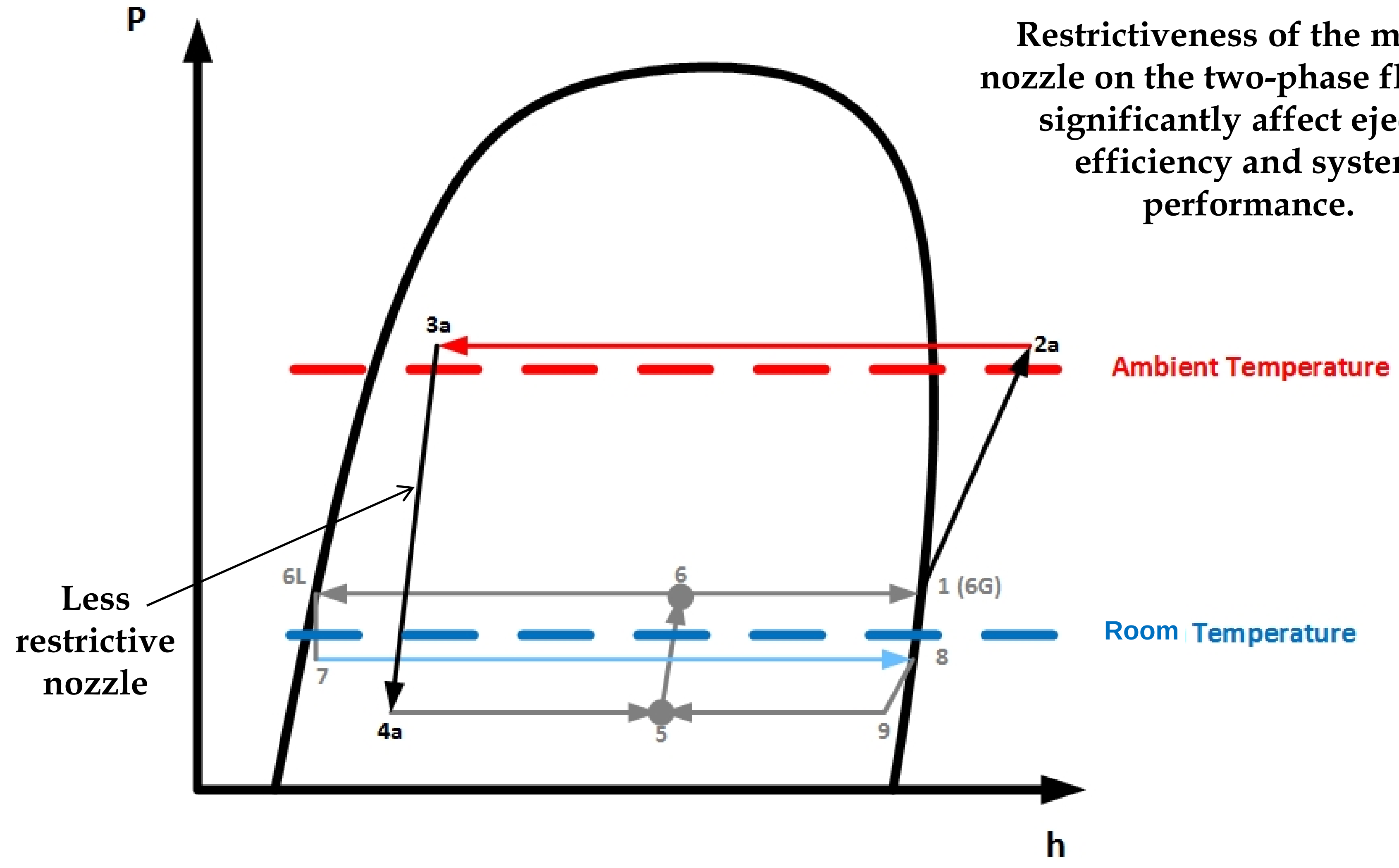
Test Conditions



R410A ejector air conditioning system COP with different motive nozzles under three different conditions Hu *et al*. (2014)

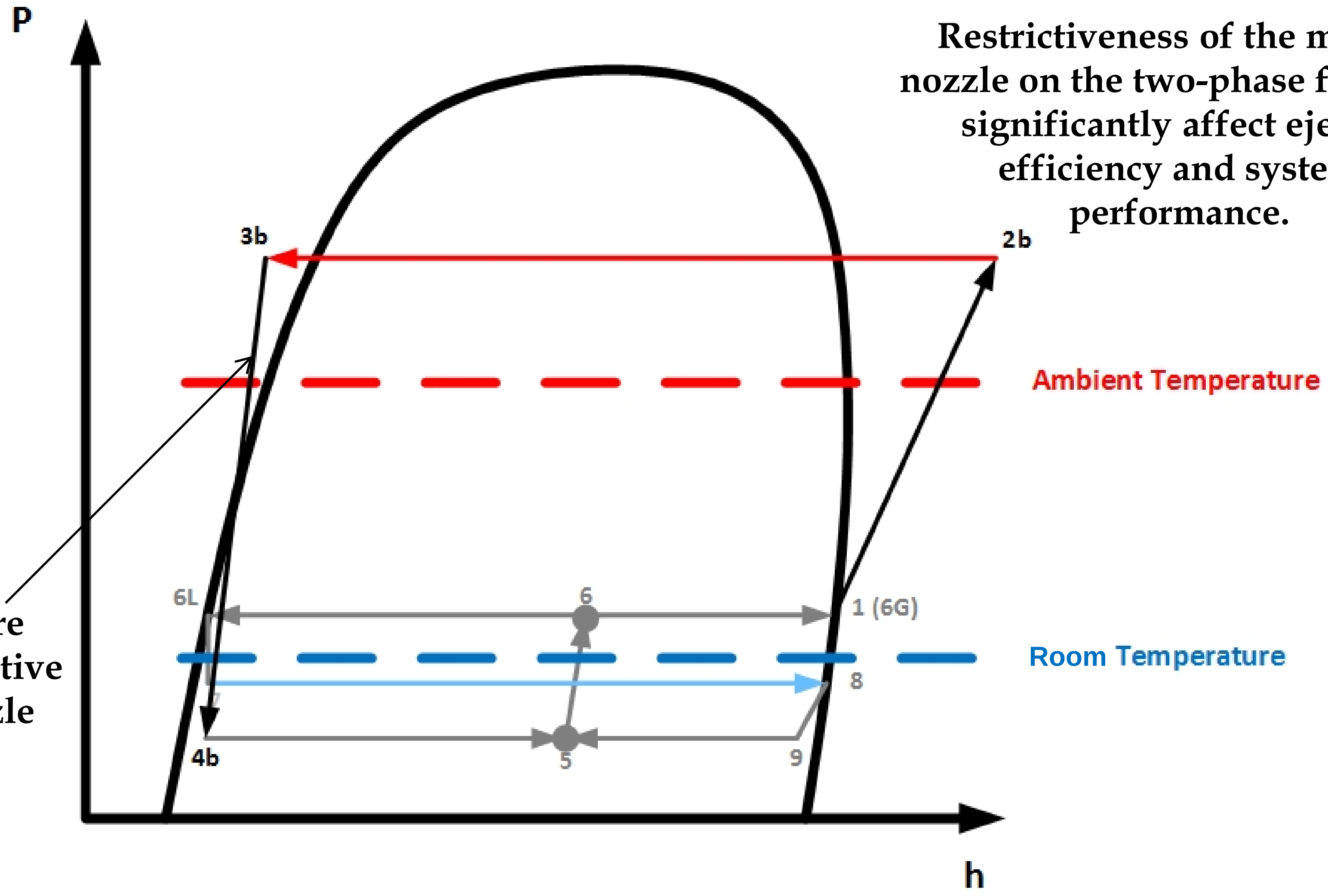
Challenges with Ejector Cooling Cycle

Restrictiveness of the motive nozzle on the two-phase flow can significantly affect ejector efficiency and system performance.



Less restrictive nozzle

Challenges with Ejector Cooling Cycle



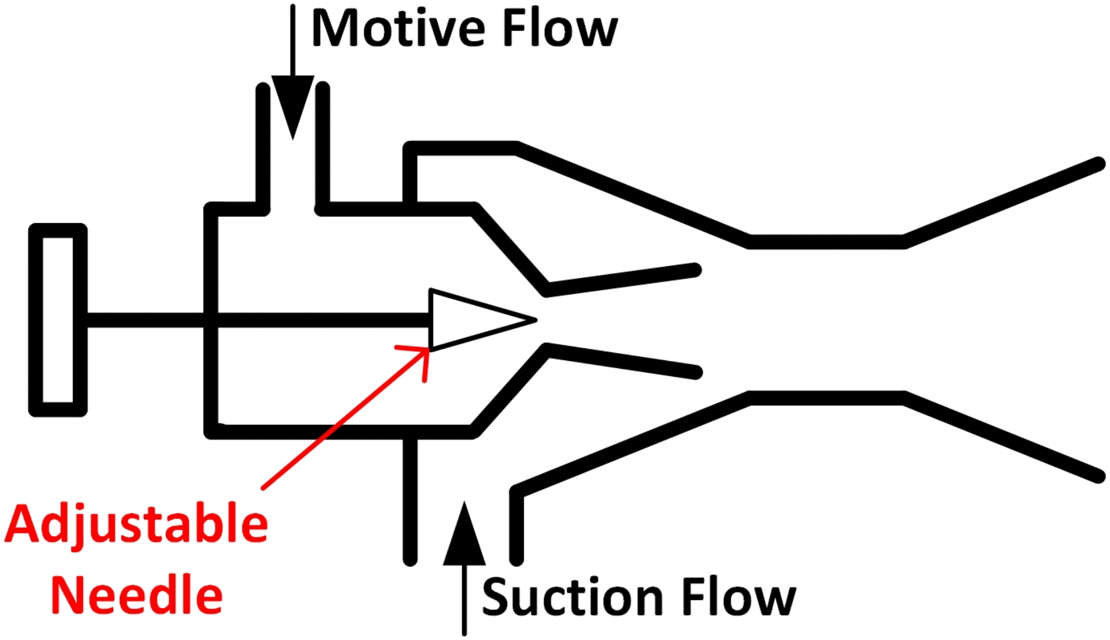
Restrictiveness of the motive nozzle on the two-phase flow can significantly affect ejector efficiency and system performance.

More restrictive nozzle

How to Adjust Motive Nozzle Geometry (Restrictiveness on Flow)

Eurofighter Typhoon thrust nozzle
http://www.military.com/video/aircraft/engines/eurofighter-thrust-vectoring-nozzle/2907034546001

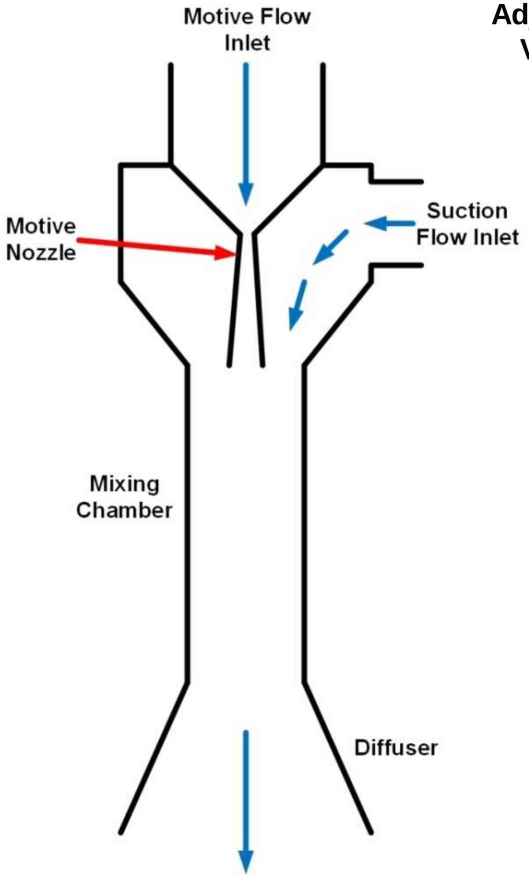
Previous Approach: Adjustable Needle



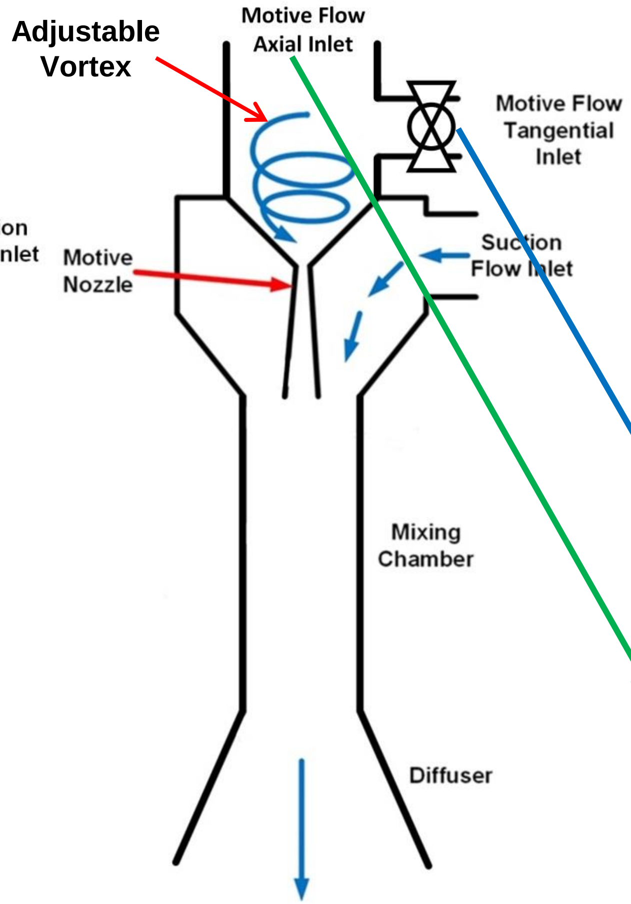
This design is complicated and costly, and more friction losses are incurred probably because of the additional surface area and turbulence introduced.

New Solution: Vortex Ejector

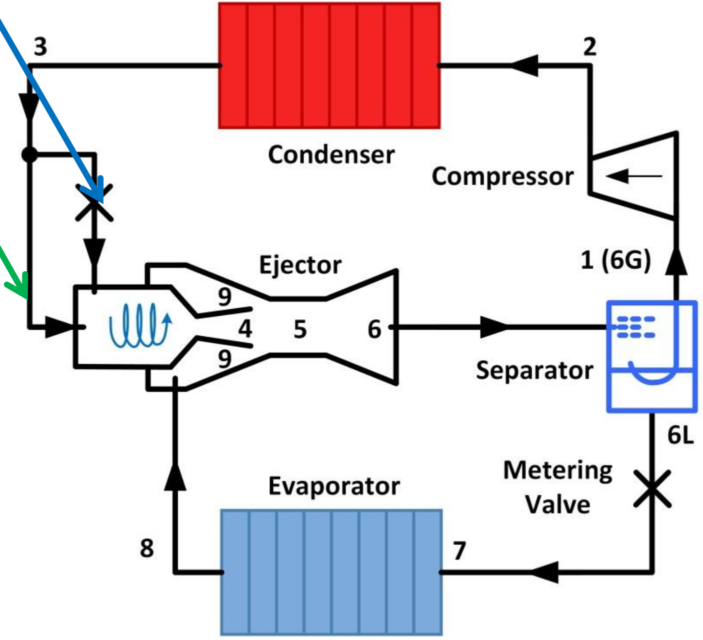
Utilizing an adjustable vortex at the motive inlet to control the flow expanded in the motive nozzle (no change in geometry; same effect as changing nozzle throat diameter)



Conventional ejector

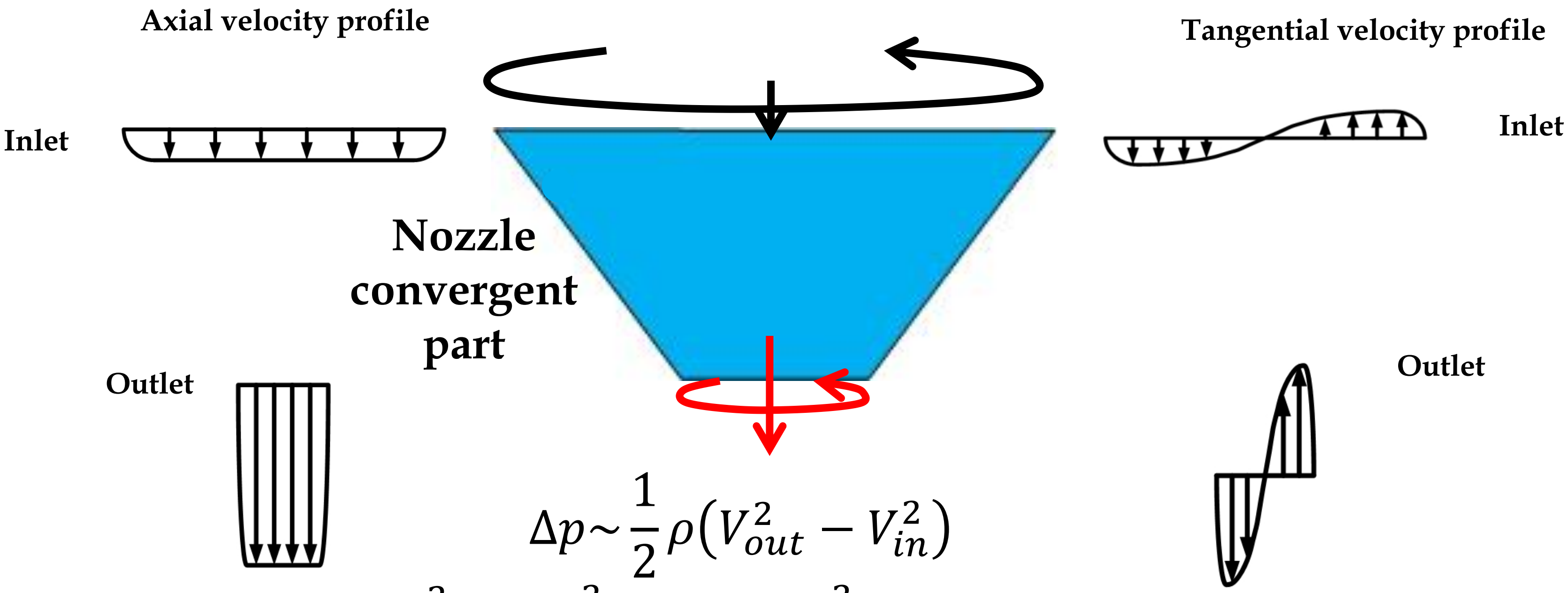


Vortex ejector



Vortex ejector cooling cycle

Share of Tangential Kinetic Energy in the Available Pressure Potential Decreases the Mass Flow Rate



Axial velocity profile

Tangential velocity profile

Inlet

Inlet

Nozzle convergent part

Outlet

Outlet

$$\Delta p \sim \frac{1}{2}\rho\left(V_{out}^2 - V_{in}^2\right)$$

$$V_{out}^2 = V_{axial,out}^2 + V_{tangential,out}^2$$

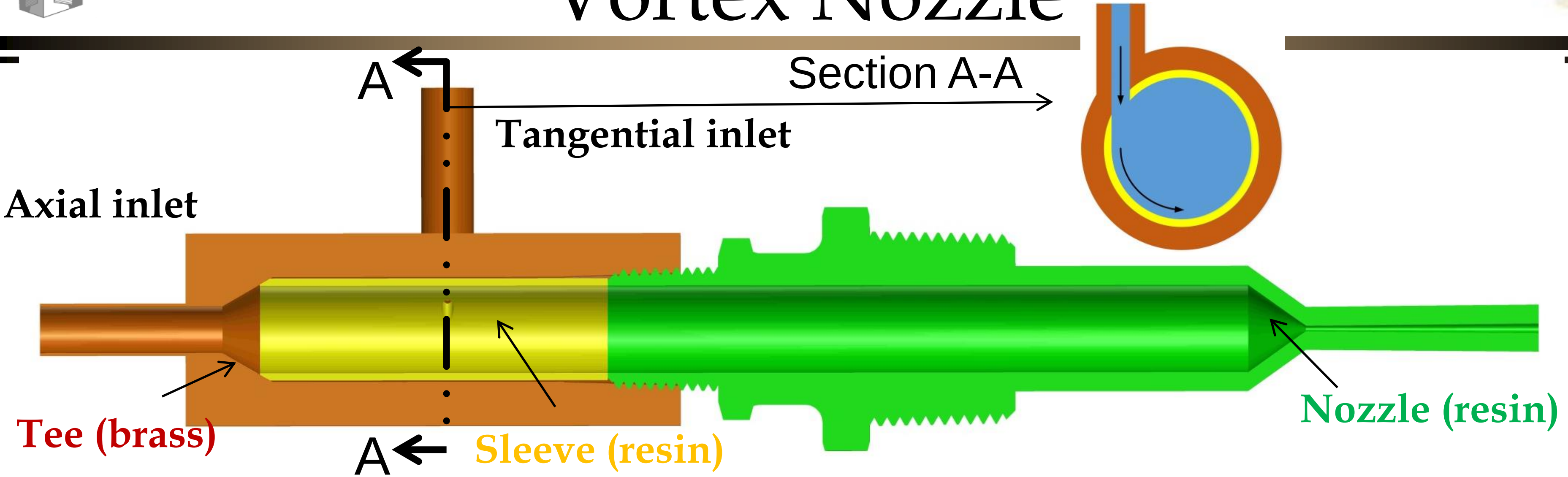
$$\dot{m} \sim \rho V_{axial,out} A_{out}$$

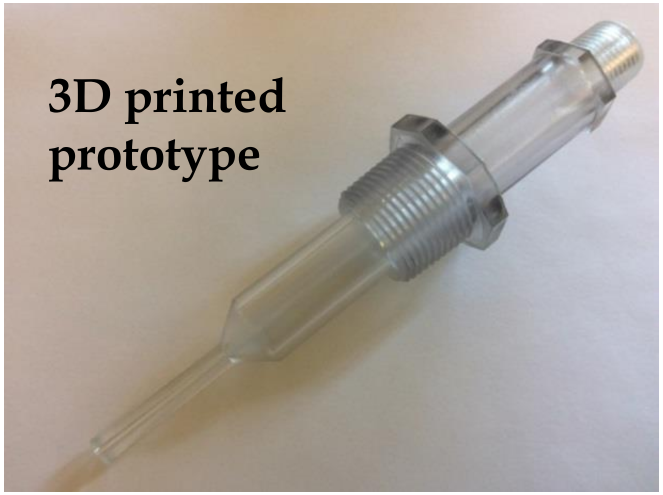
Works for both single-phase and two-phase

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





Convergent-divergent nozzle (resin)

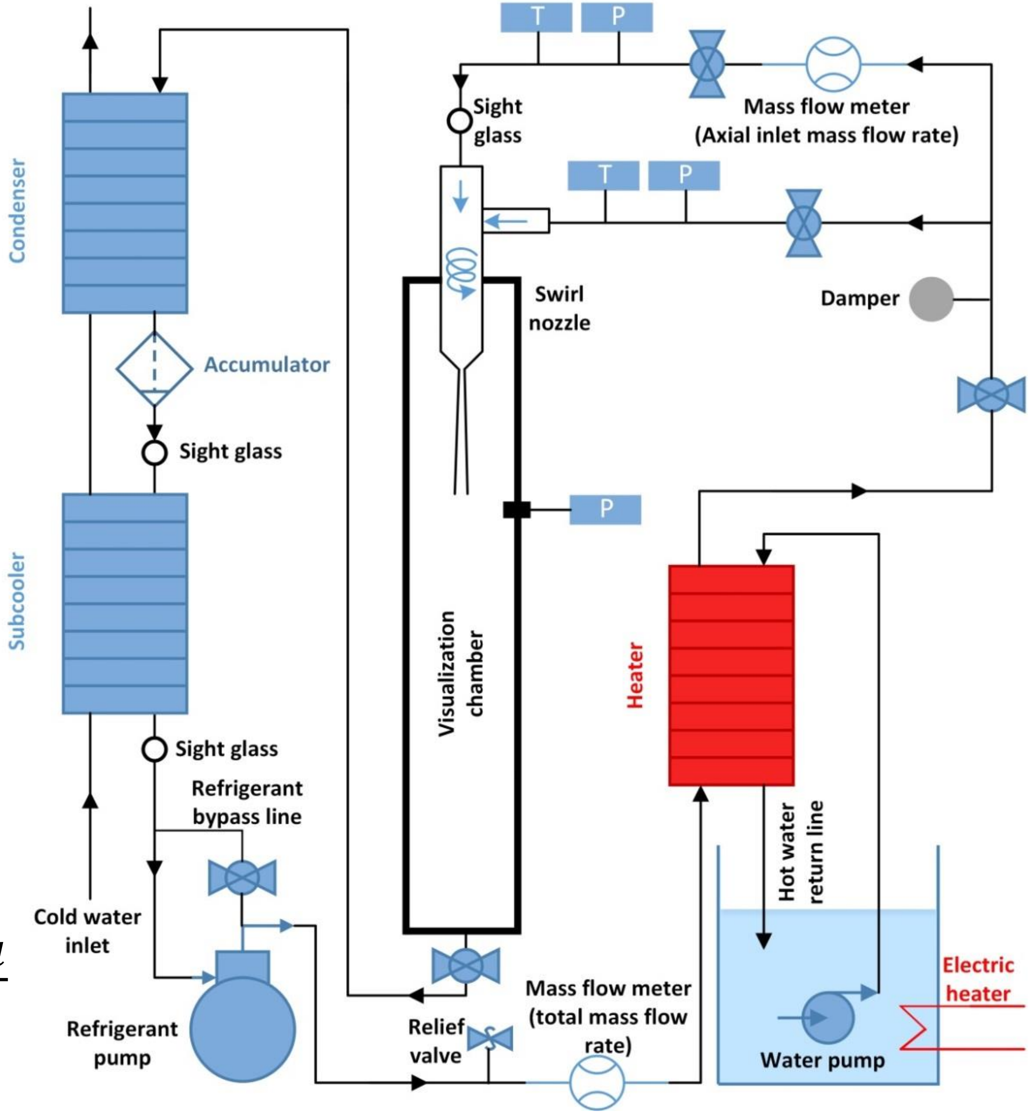
Nozzle inlet diameter (mm)	15.0
Nozzle throat diameter (mm)	1.03
Nozzle outlet diameter (mm)	1.7
Nozzle convergent part length (mm)	9.9
Nozzle divergent part length (mm)	40.0
Tangential inlet inner diameter (mm)	2.0
Vortex decay distance (mm)	138.0

Vortex nozzle geometry

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

$$Vortex\ strength = \frac{\dot{m}_{tangential}}{\dot{m}_{total}}$$



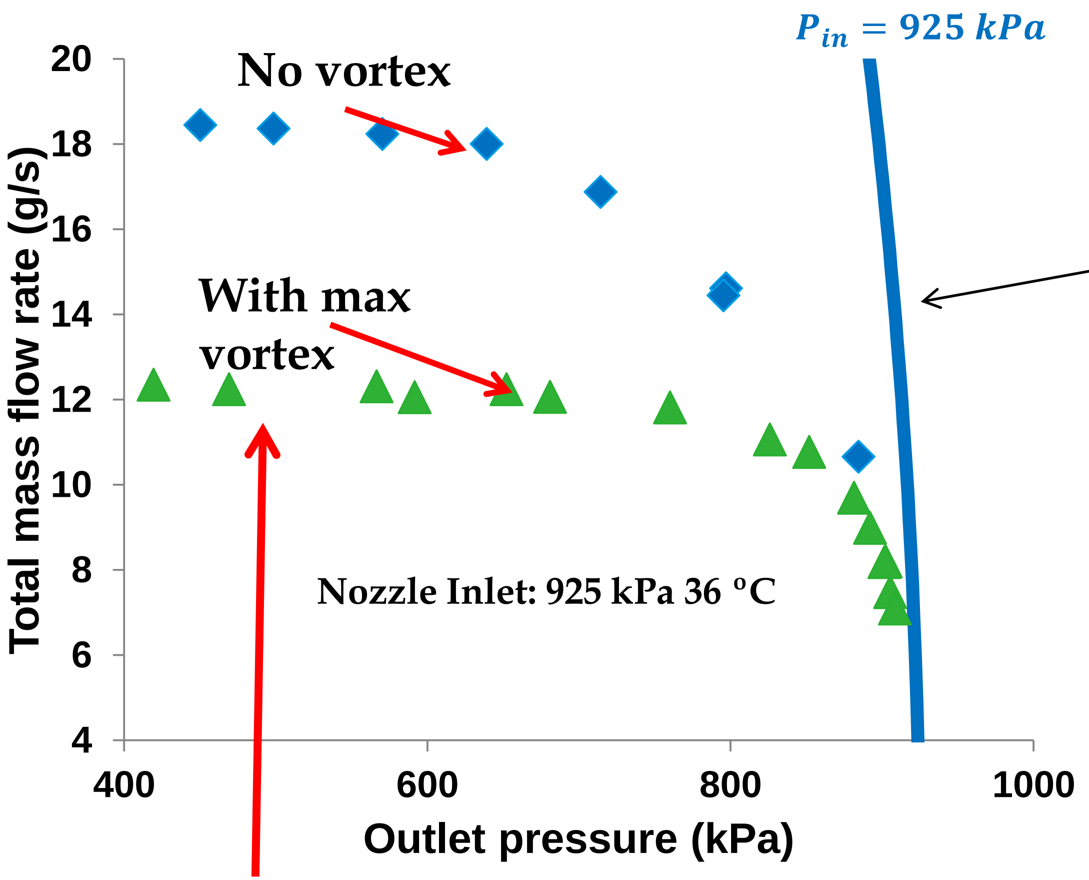
Testing Conditions

- 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

P_{in} (kPa)	P_{out} (kPa)	T_{in} (°C)	$\dot{m}_{total}$ (g/s)	Vortex strength (-)
760~1059	407~909	29~41	6~20	0~1

Effect of Outlet Pressure on Nozzle Mass Flow Rate at Constant Inlet Pressure



Inlet subcooling = 0.5 °C

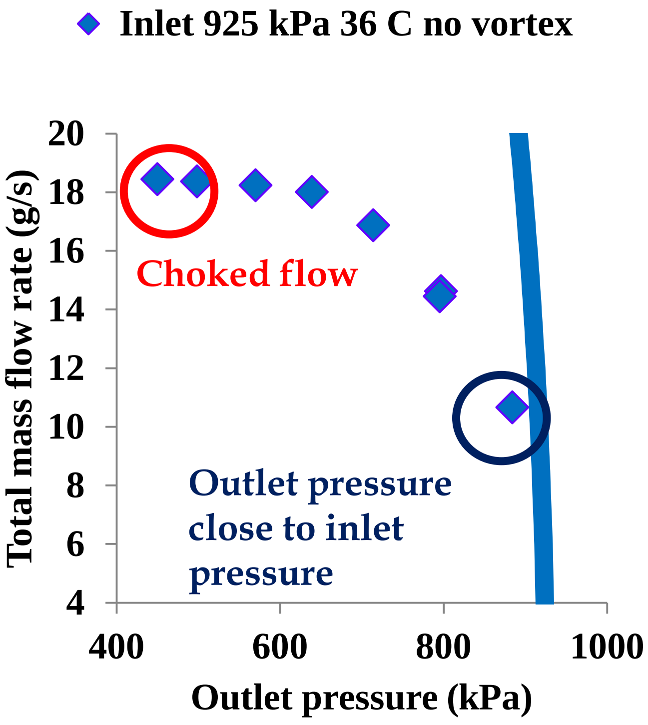
Theoretically calculated incompressible single phase liquid mass flow rate

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

Observations:

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

Preliminary Visualization Results

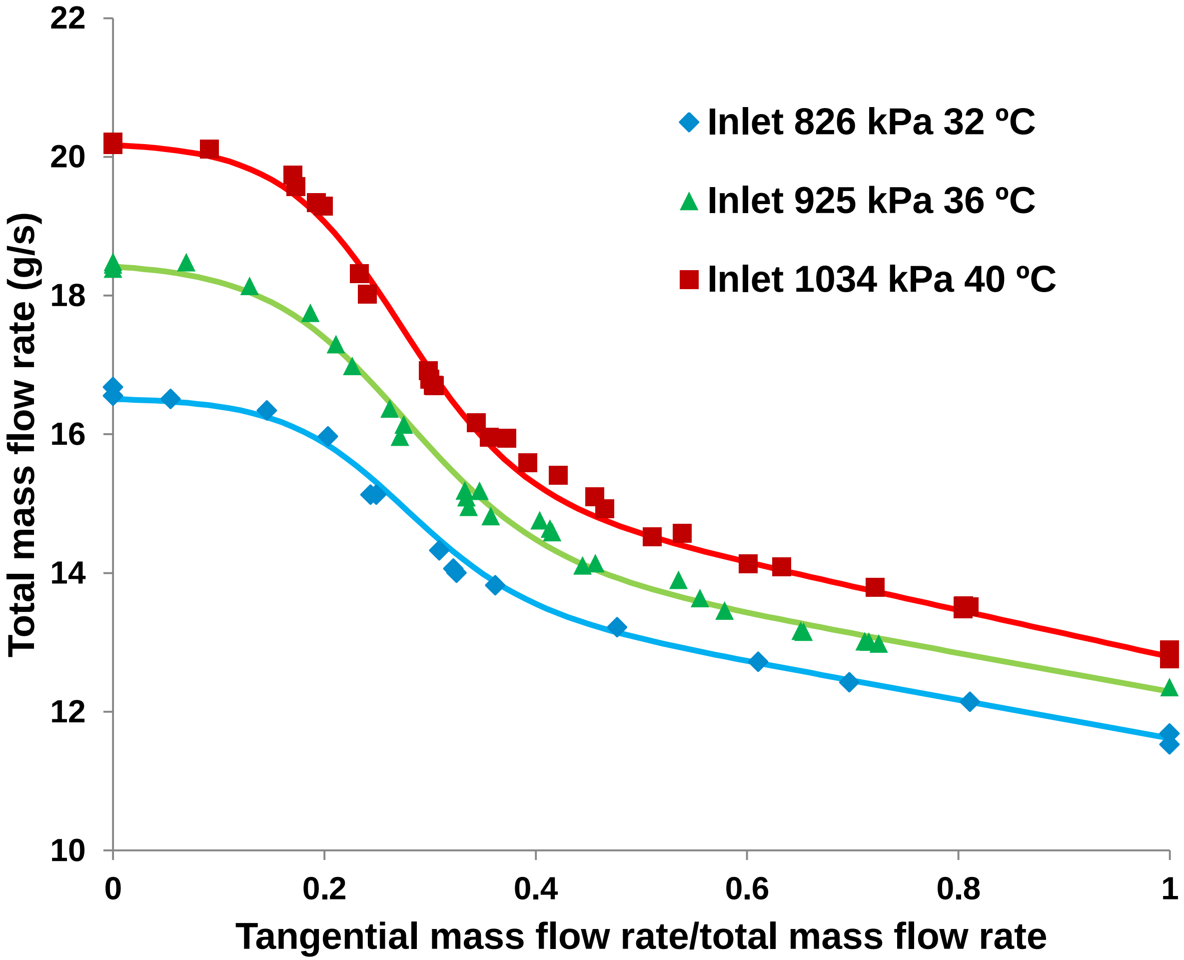


Clear flow in the convergent part of the nozzle

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

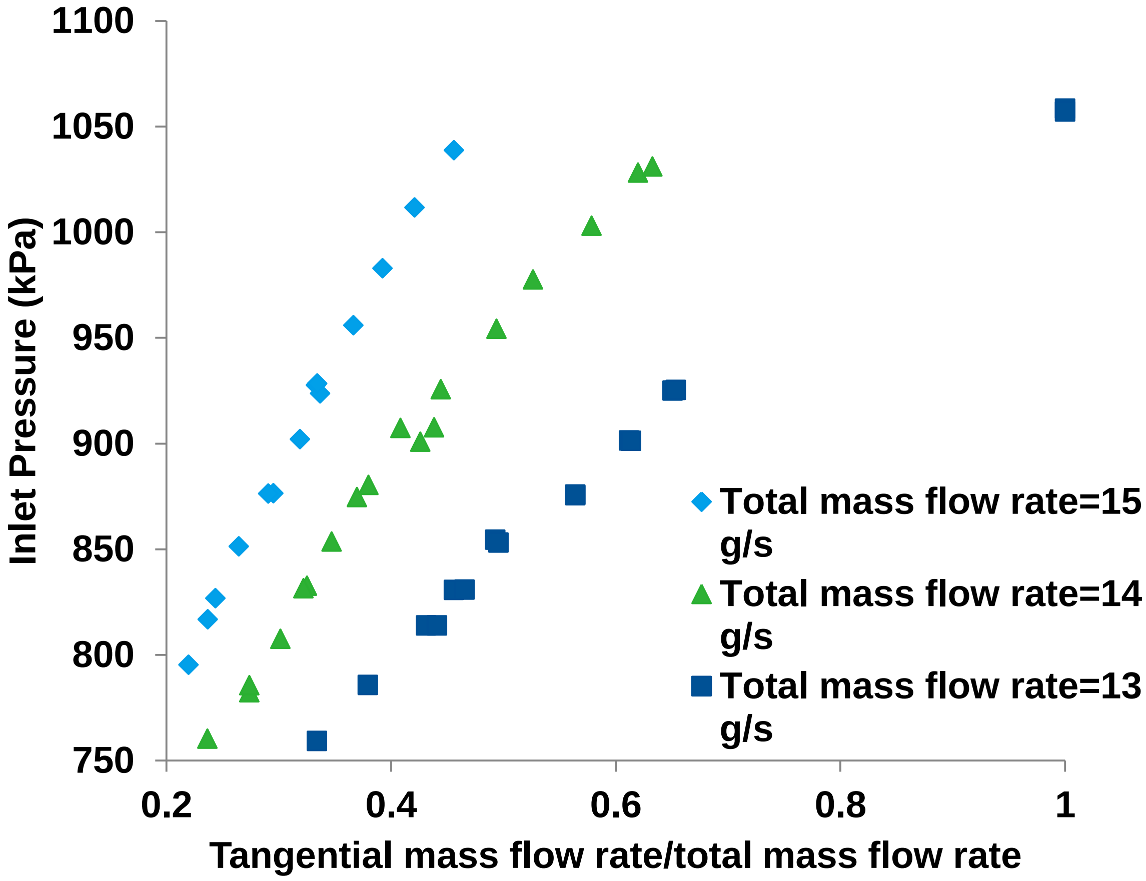


Inlet subcooling = 0.5 °C

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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References

1. Gay, N. H., “Refrigerating System,” U.S. Patent 1,836,318, 1931.

2. Disawas, S. and Wongwises, S., “Experimental investigation on the performance of the refrigeration cycle using a two-phase ejector as an expansion device,” International Journal of Refrigeration, 27(6): 587-594, 2004.

3. Lawrence, N., and Elbel, S., “Experimental and Numerical Study on the Performance of R410A Liquid Recirculation Cycles with and without Ejectors," 15th International Refrigeration and Air Conditioning Conference at Purdue, West Lafayette, IN, USA, Paper 2187, 2014.

4. Ozaki, Y., Takeuchi, H., and Hirata, T., “Regeneration of expansion energy by ejector in CO2 cycle,” 6th IIR Gustav Lorentzen Conference on Natural Working Fluid, Glasgow, UK, 11-20, 2004.

5. Banasiak, K., Hafner, A., and Andresen, T., “Experimental and numerical investigation of the influence of the two-phase ejector geometry on the performance of the R744 heat pump,” International Journal of Refrigeration, 35(6): 1617-1625, 2012.

6. Elbel, S. and Hrnjak, P., “Experimental validation of a prototype ejector designed to reduce throttling losses encountered in transcritical R744 system operation,” International Journal of Refrigeration, 31(3): 411-422, 2008.

7. Elbel, S., “Historical and present developments of ejector refrigeration systems with emphasis on transcritical carbon dioxide air-conditioning applications,” International Journal of Refrigeration, 34(7): 1545-1561, 2011.

8. Harrell, G. S., and Kornhauser, A. A., “Performance tests of a two-phase ejector,” American Society of Mechanical Engineers, New York, NY, United States, 1995.

9. Lawrence, N. and Elbel S., “Experimental investigation of a two-phase ejector cycle suitable for use with low-pressure refrigerants R134a and R1234yf,” International Journal of Refrigeration, 38: 310-322, 2014.

References

10. Sumeru, K., Nasution, H., and Ani, F. N., "A review on two-phase ejector as an expansion device in vapor compression refrigeration cycle," Renewable and Sustainable Energy Reviews, 16(7): 4927-4937, 2012.

11. Sarkar, J., "Ejector enhanced vapor compression refrigeration and heat pump systems - A review," Renewable and Sustainable Energy Reviews, 16(9): 6647-6659, 2012.

12. Hu, J., Shi, J., Liang, Y., Yang, Z., and Chen, J., "Numerical and experimental investigation on nozzle parameters for R410A ejector air conditioning system," International Journal of Refrigeration, 40: 338-346, 2014.

13. Henry, R. E., and Fauske, H. K., "The two-phase critical flow of one-component mixtures in nozzles, orifices, and short tubes," Journal of Heat Transfer, 93(2): 179-187, 1971.

14. Schrock, V. E., Starkman, E. S., and Brown, R. A., "Flashing flow of initially subcooled water in convergent–divergent nozzles," Journal of Heat Transfer, 99(2): 263-268, 1977.

15. Plesset, M. S., and Zwick, S. A., "The growth of vapor bubbles in superheated liquids," Journal of Applied Physics, 25(4): 493-500, 1954.

16. Florschuetz, L. W., Henry, C. L., and Khan, A. R., "Growth rates of free vapor bubbles in liquids at uniform superheats under normal and zero gravity conditions," International Journal of Heat and Mass Transfer, 12(11): 1465-1489, 1969.

17. Ruckenstein, E., and Davis, E. J., "The effects of bubble translation on vapor bubble growth in a superheated liquid," International Journal of Heat and Mass Transfer, 14(7): 939-952, 1971.

18. Mayer, E. A., "Large-signal vortex valve analysis," Advances in Fluidics, 233-249, 1967.

19. Wormley, D. N., "An analytical model for the incompressible flow in short vortex chambers," Journal of Basic Engineering, 91(2): 264-272, 1969.