A NEW CONTROL MECHANISM FOR TWO-PHASE EJECTOR IN VAPOR COMPRESSION CYCLES FOR AUTOMOTIVE APPLICATIONS USING ADJUSTABLE MOTIVE NOZZLE INLET SWIRL

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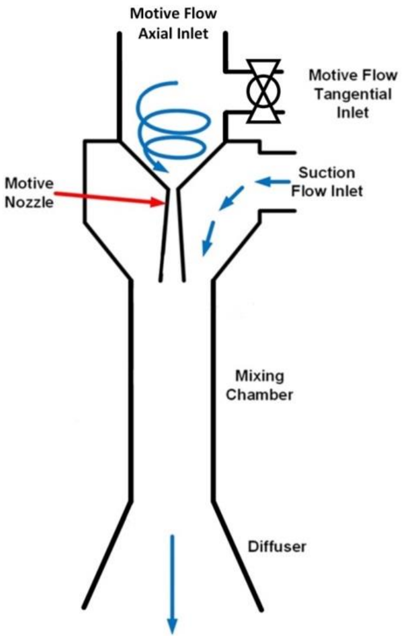
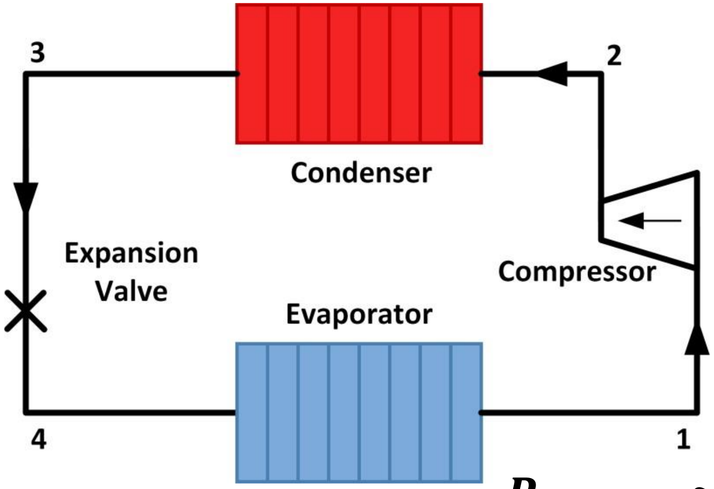
Presentation Outline

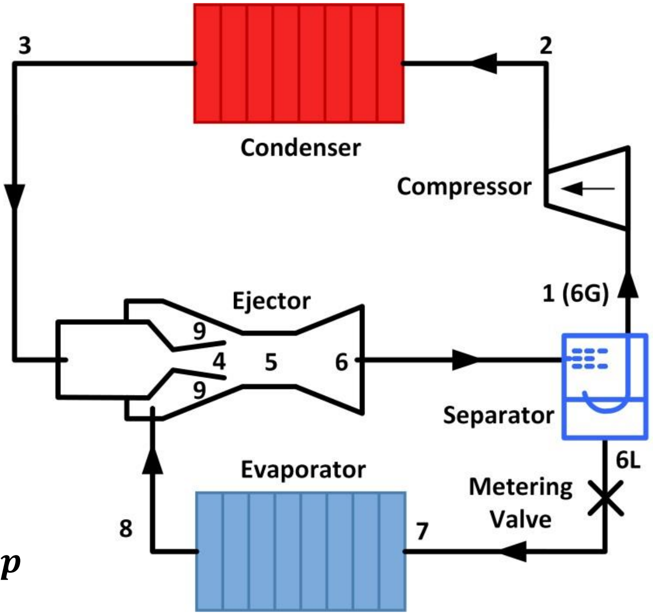
- Background: opportunities and challenges with ejector cooling cycles
- Research motivation: optimize ejector cycle performance under changing working conditions/capacities (common in automotive applications) by adjusting ejector motive nozzle
- New solution: swirl ejector - utilizing controllable swirl at the motive inlet of the ejector to adjust mass flow rate and condenser outlet quality/subcooling (Swirl nozzle/valve has been recognized as a reliable flow modulation method as early as 1960s (Mayer, 1967; Wormley, 1969))
- Research approach:
  - Swirl nozzle tests with refrigerant (R134a)
  - Visualization and modeling of low-quality flow expanded in the nozzle
- Conclusions



Benefits of Ejector Cooling Cycles



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



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

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

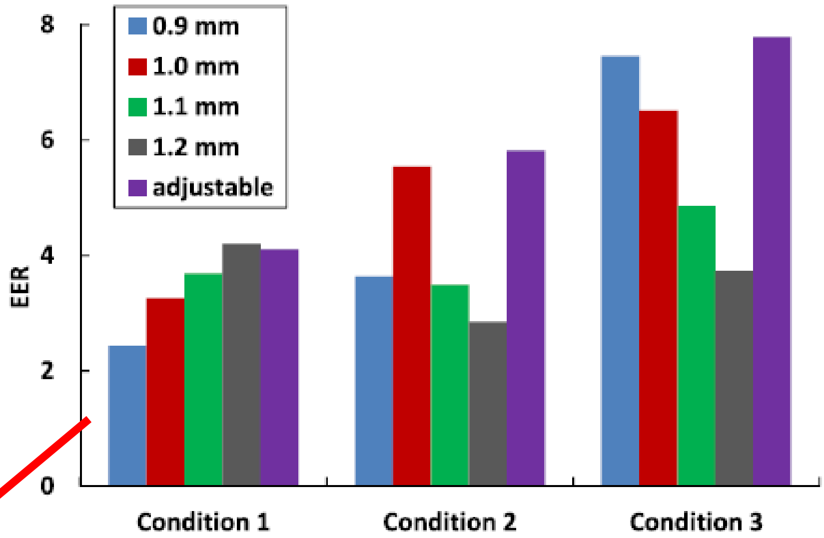
  Sumeru *et al*. (2012); Sarkar (2012);

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

  COP changed by more than 40 %

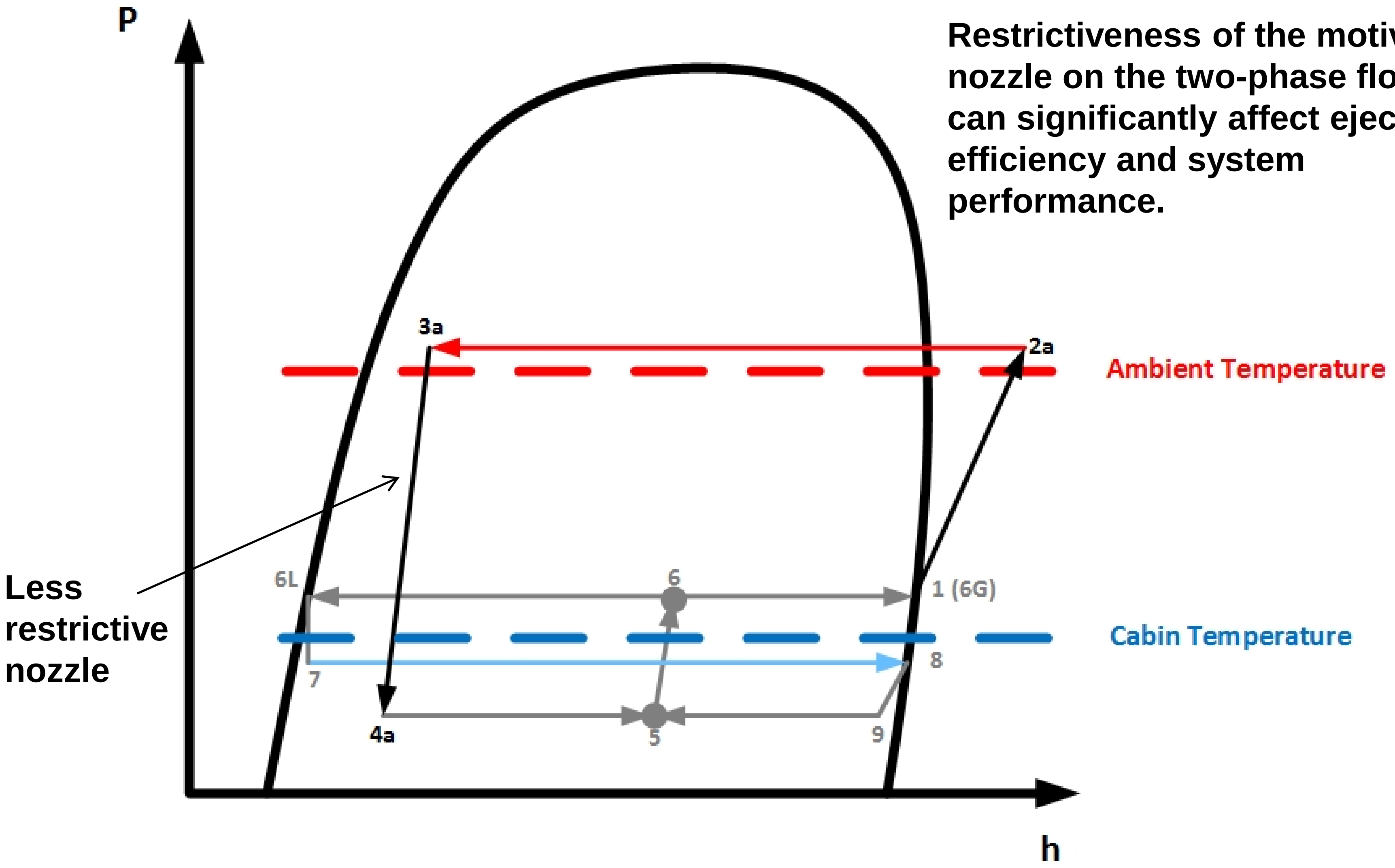
	Condition 1	Condition 2	Condition 3
T_{indoor}(dry/wet bulb), ºC	26.7/19.4	26.7/19.4	26.8/19.5
$T_{outdoor}$(dry/wet bulb), ºC	35.0/19.5	30.6/16.8	27.8/14.9
p_{cond}, MPa	2.4	2.0	1.9

Test Conditions



R410A ejector air conditioning system COP with different motive nozzle throat diameters 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.

Challenges with Ejector Cooling Cycle

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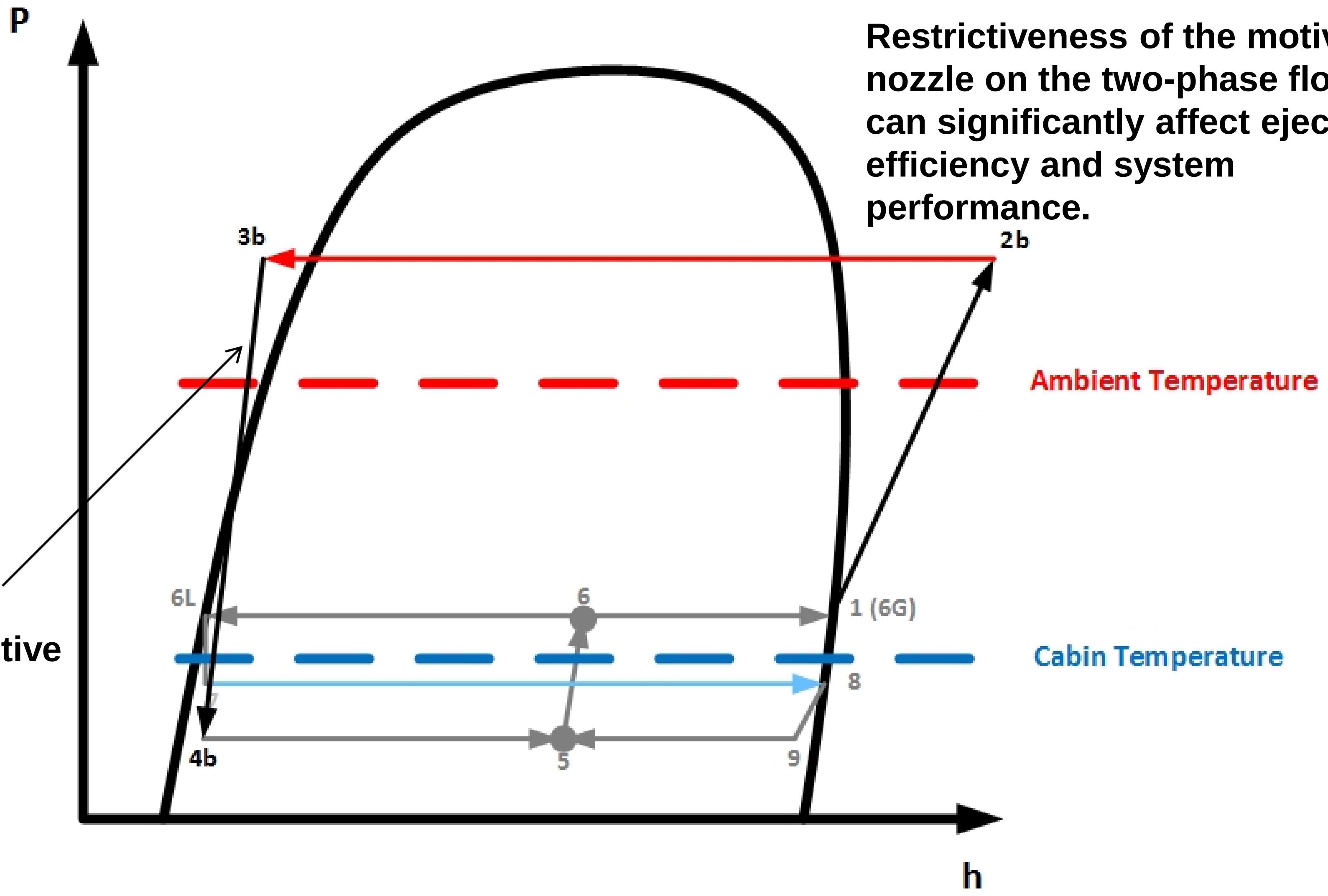
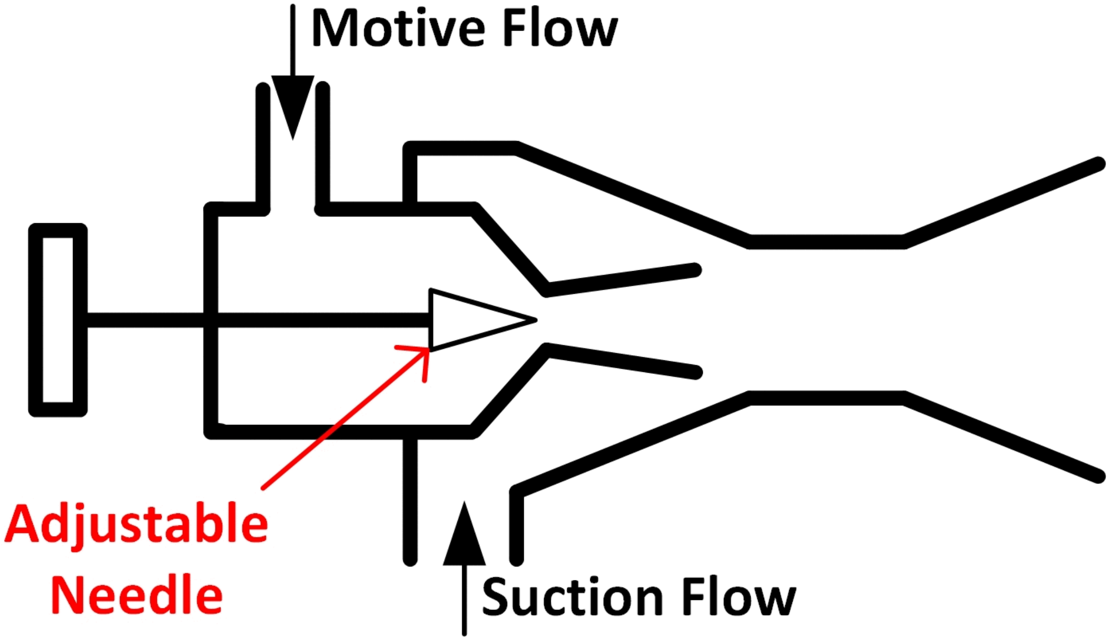


More restrictive nozzle

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

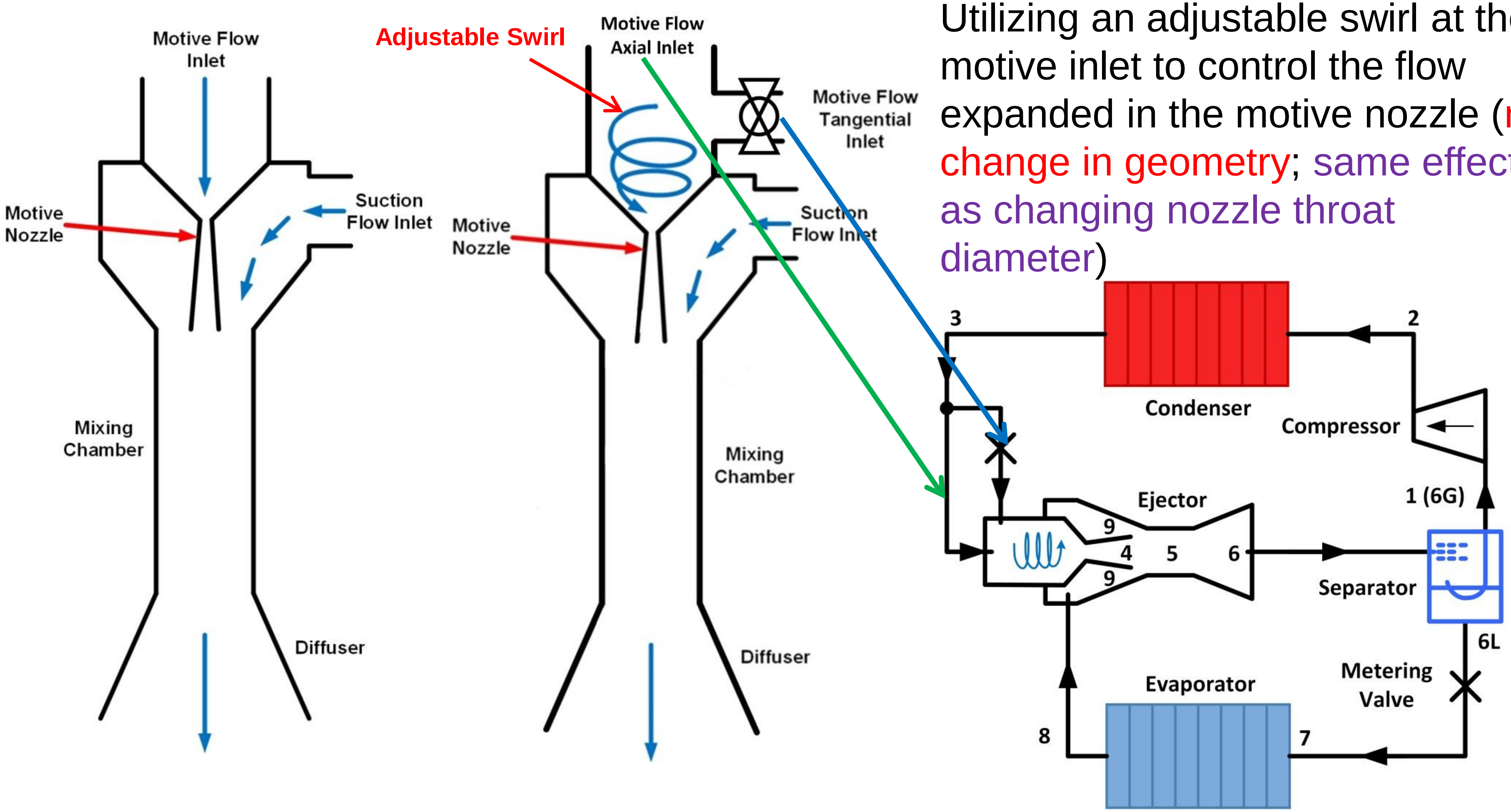
Previous Approach: Adjustable Needle



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

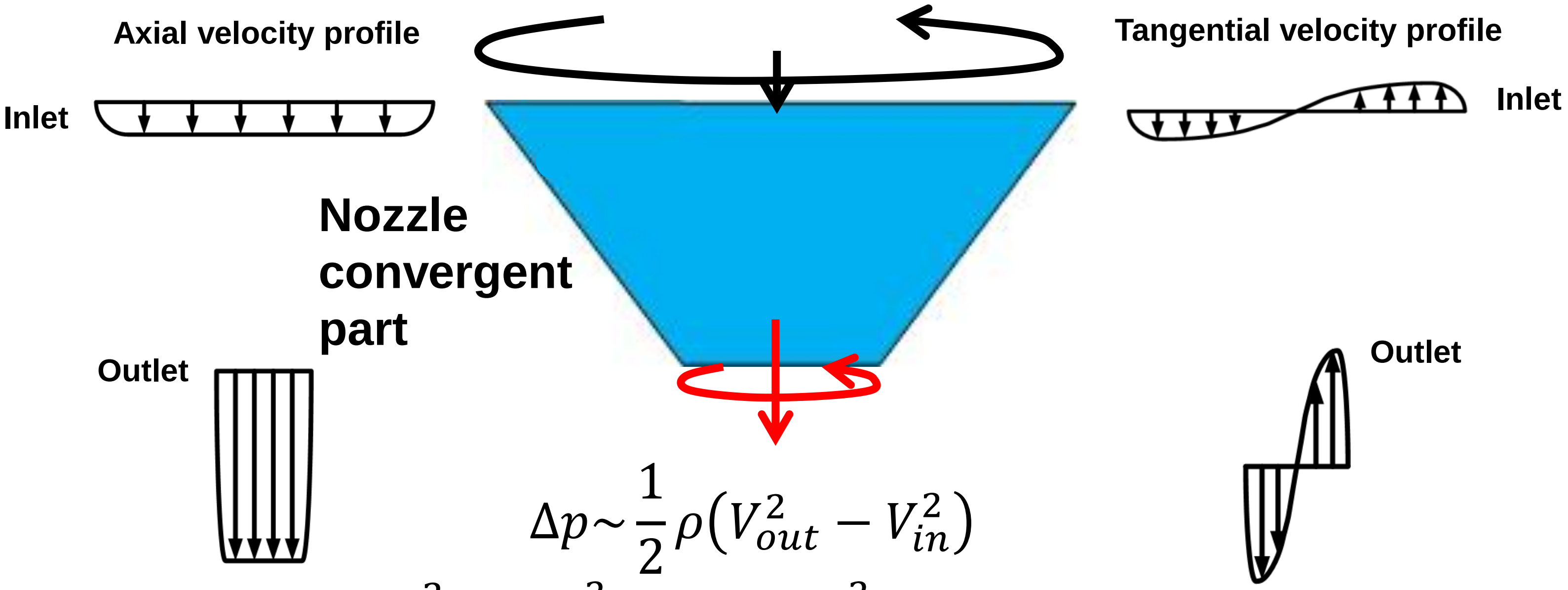
New Solution: Swirl Ejector

Utilizing an adjustable swirl 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 **Swirl ejector** **Swirl ejector cooling cycle**

Hypothesis 1: Share of Tangential Kinetic Energy in the Available Pressure Potential Decreases the Mass Flow Rate



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

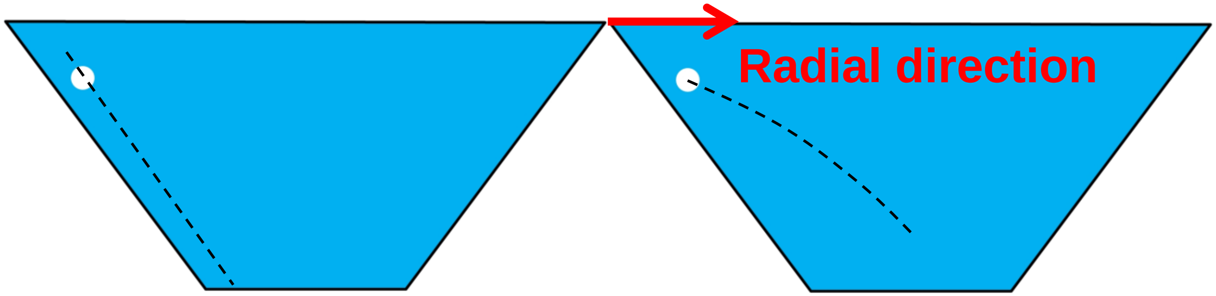
$$V_{out}^2 = V_{axial,out}^2 + V_{tangential,out}^2$$

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

Works for both single-phase and two-phase

Hypothesis 2: Swirl Boosts Vapor Bubble Growth

Nozzle convergent part



No Swirl

With stronger swirl, more relative motion is created between bubbles and surrounding liquid in radial direction

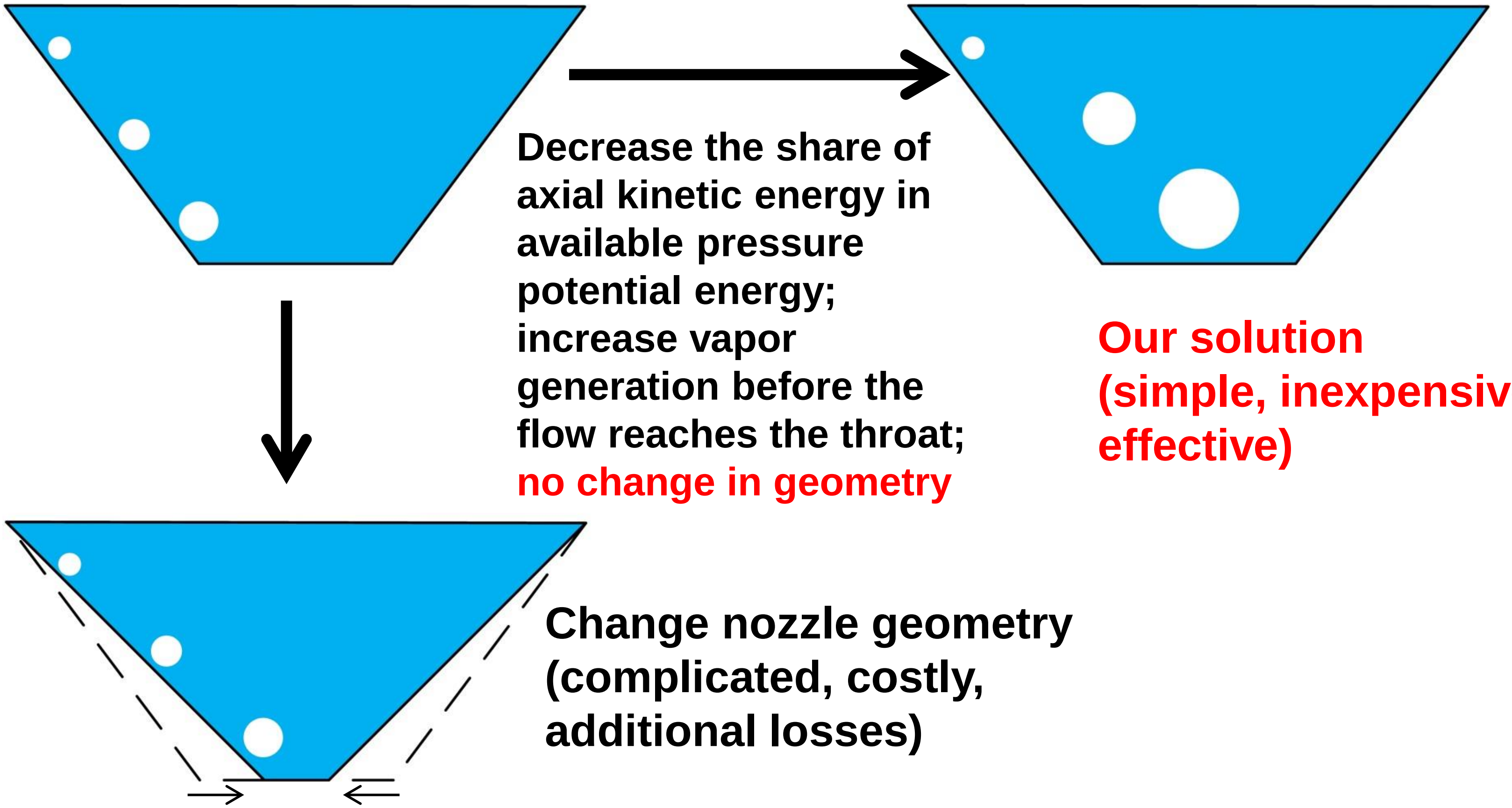
- Two-phase flow during expansion is usually not in equilibrium (Bubble growth takes time)

$$\frac{d(m_{bubble})}{dt}h_{lv} = 4\pi R_{bubble}^{2}\bar{h}(T_{liquid,\infty} - T_{s})$$

$$\overline{Nu}_{sphere} = \frac{\bar{h}D_{bubble}}{k} = 2 + \left[0.4Re^{\frac{1}{2}} + 0.06Re^{\frac{2}{3}}\right]Pr^{0.4}\left(\frac{\mu_{liquid,\infty}}{\mu_{liquid,s}}\right)^{\frac{1}{4}} \qquad Re \sim V_{relative}$$

- The stronger the swirl is the faster bubbles grow
- Works for two-phase flow

How to Make Nozzle Have More Restrictiveness on The Two-Phase Flow?



Decrease the share of axial kinetic energy in available pressure potential energy; increase vapor generation before the flow reaches the throat; no change in geometry

Our solution (simple, inexpensive, effective)

Change nozzle geometry (complicated, costly, additional losses)

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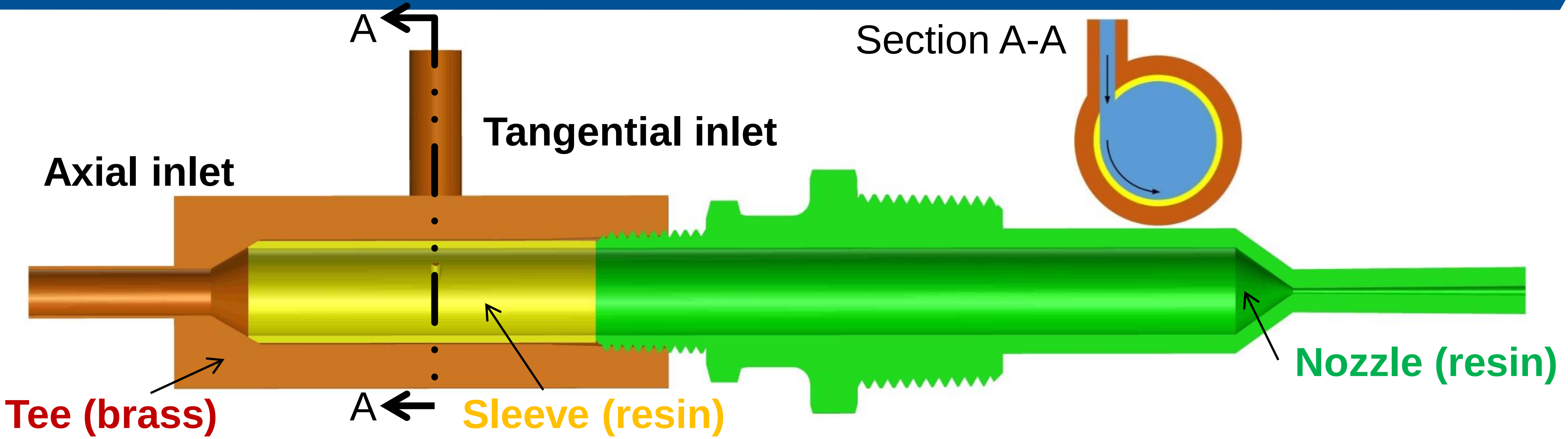
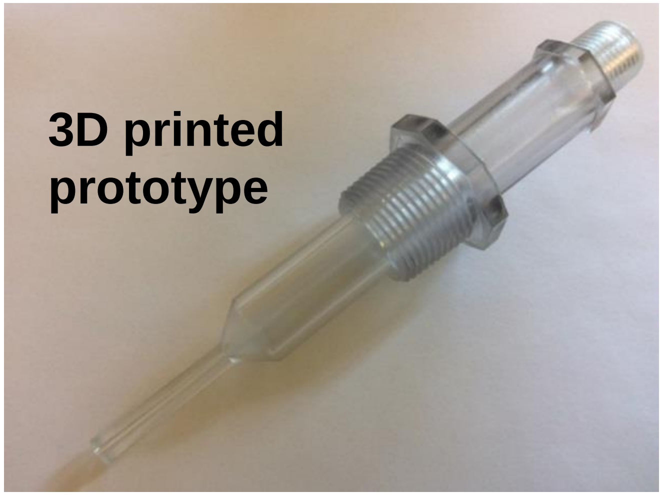
Research Approach

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

Swirl Nozzle





Convergent-divergent nozzle (resin)

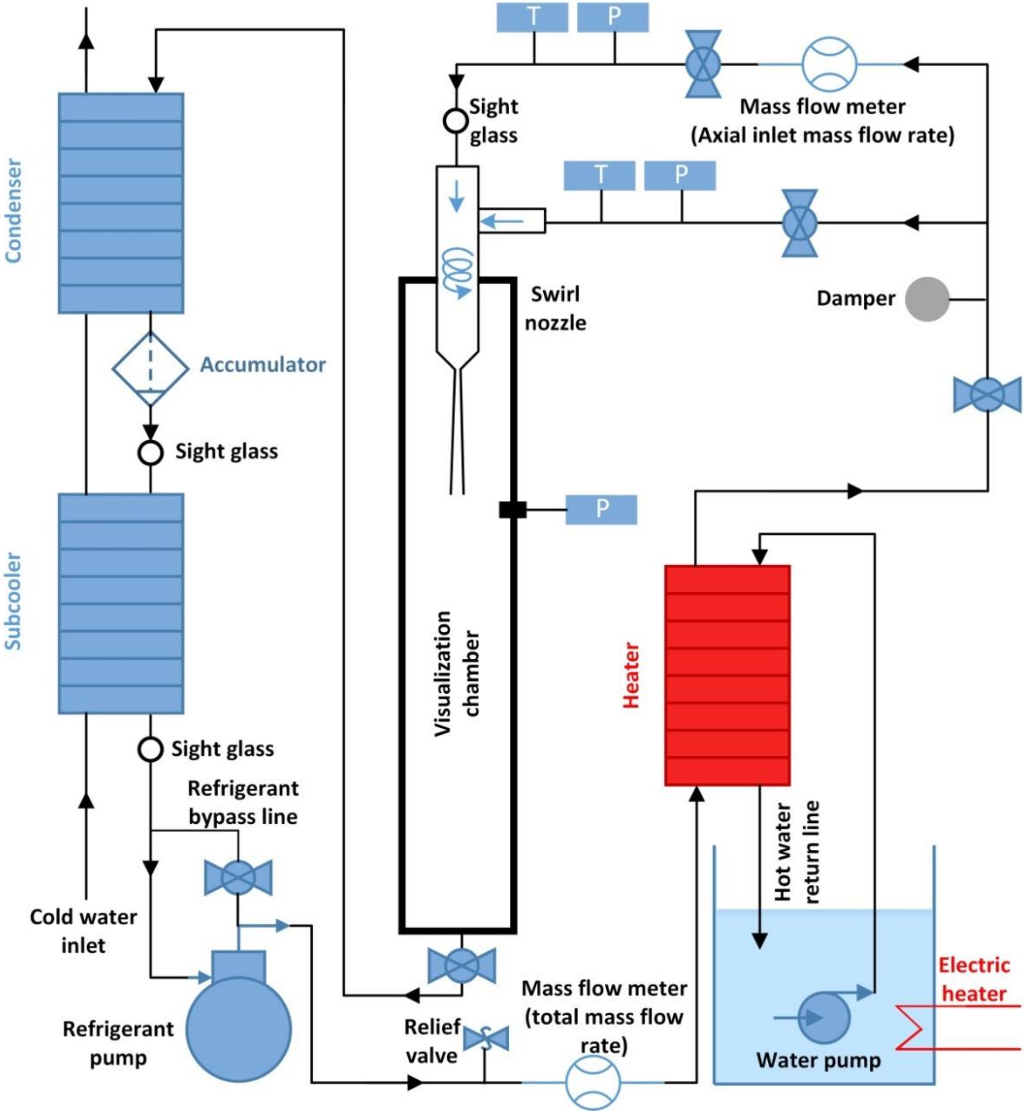
Nozzle inlet diameter (mm)	15.0
Nozzle throat diameter (mm)	1.0
Nozzle outlet diameter (mm)	1.7
Nozzle convergent part length (mm)	9.9
Nozzle divergent part length (mm)	40.0
Tangential inlet inner diameter (mm)	2.0
Swirl decay distance (mm)	138.0

Swirl nozzle geometry

Experimental Facility for Investigation of Swirl 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

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



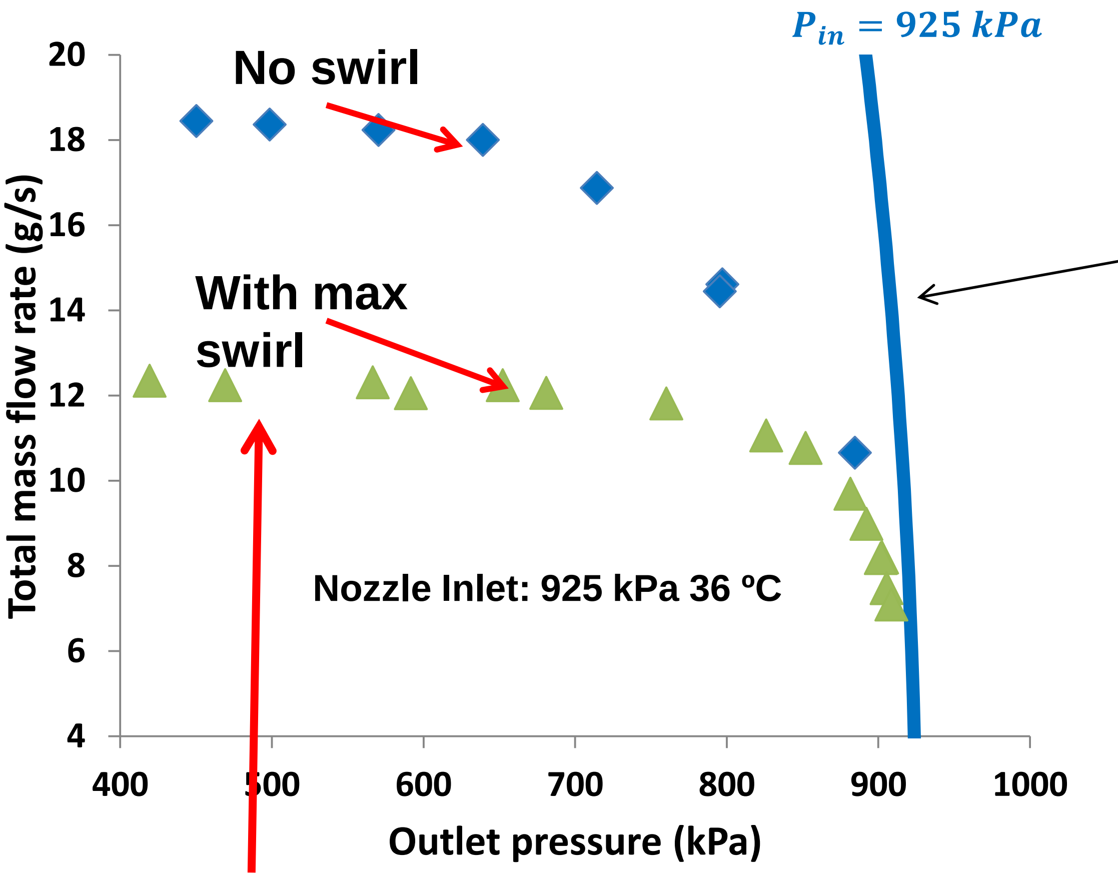
Testing Conditions

- 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 ºC. 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} (ºC)	$\dot{m}_{total}$ (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 ºC

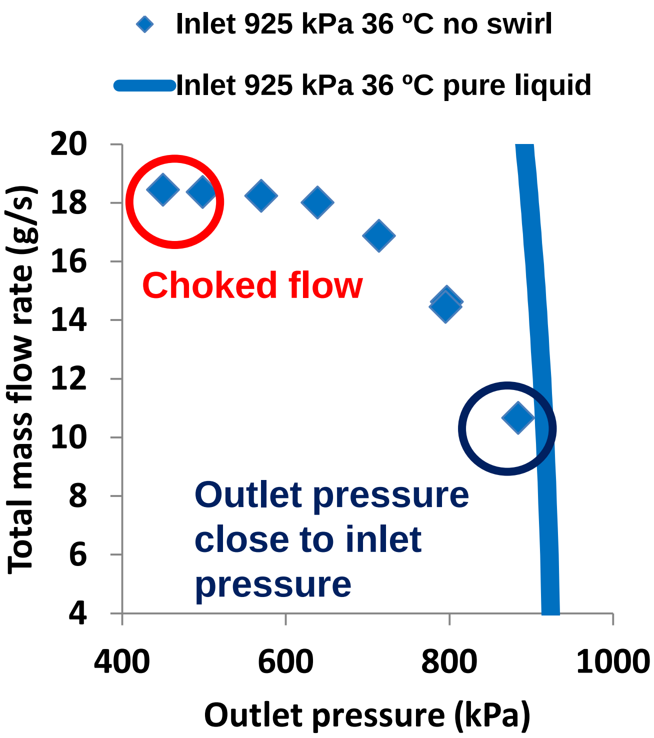
Theoretically calculated incompressible single phase liquid mass flow rate

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

Observations:

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

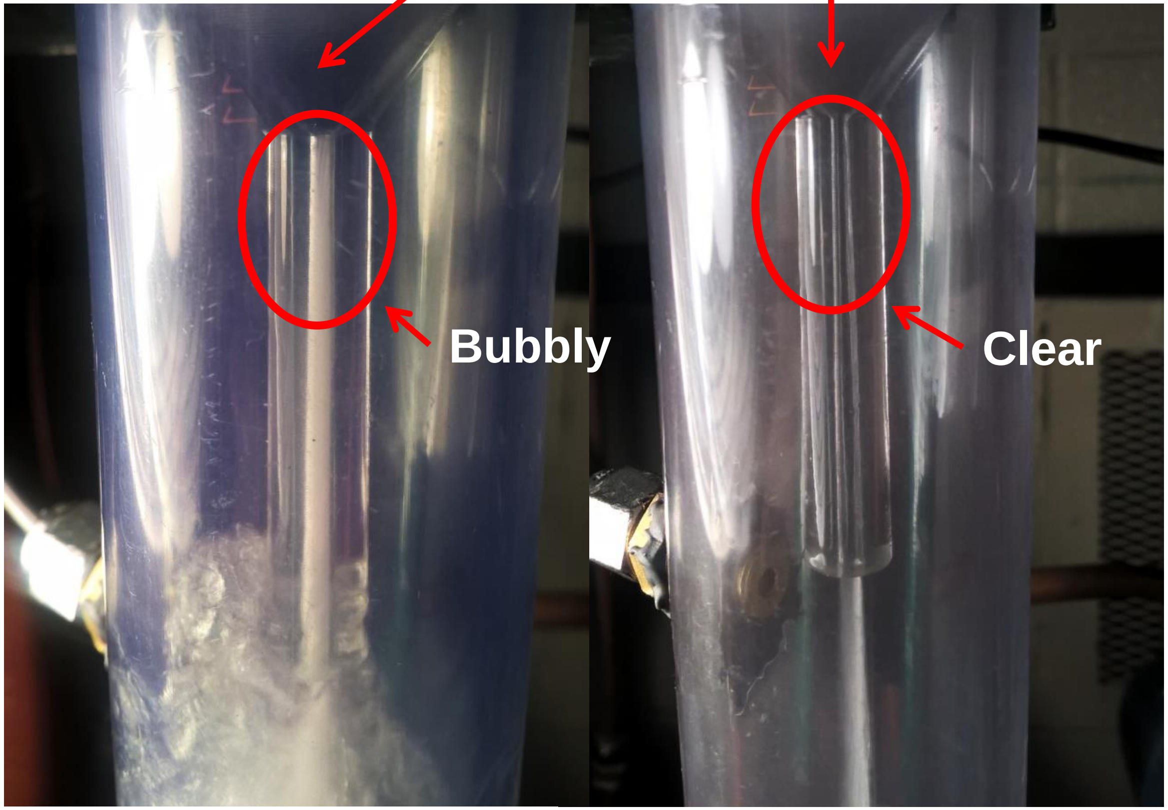
Preliminary Visualization Results



Choked flow

Outlet pressure close to inlet pressure

Clear flow in the convergent part of the nozzle



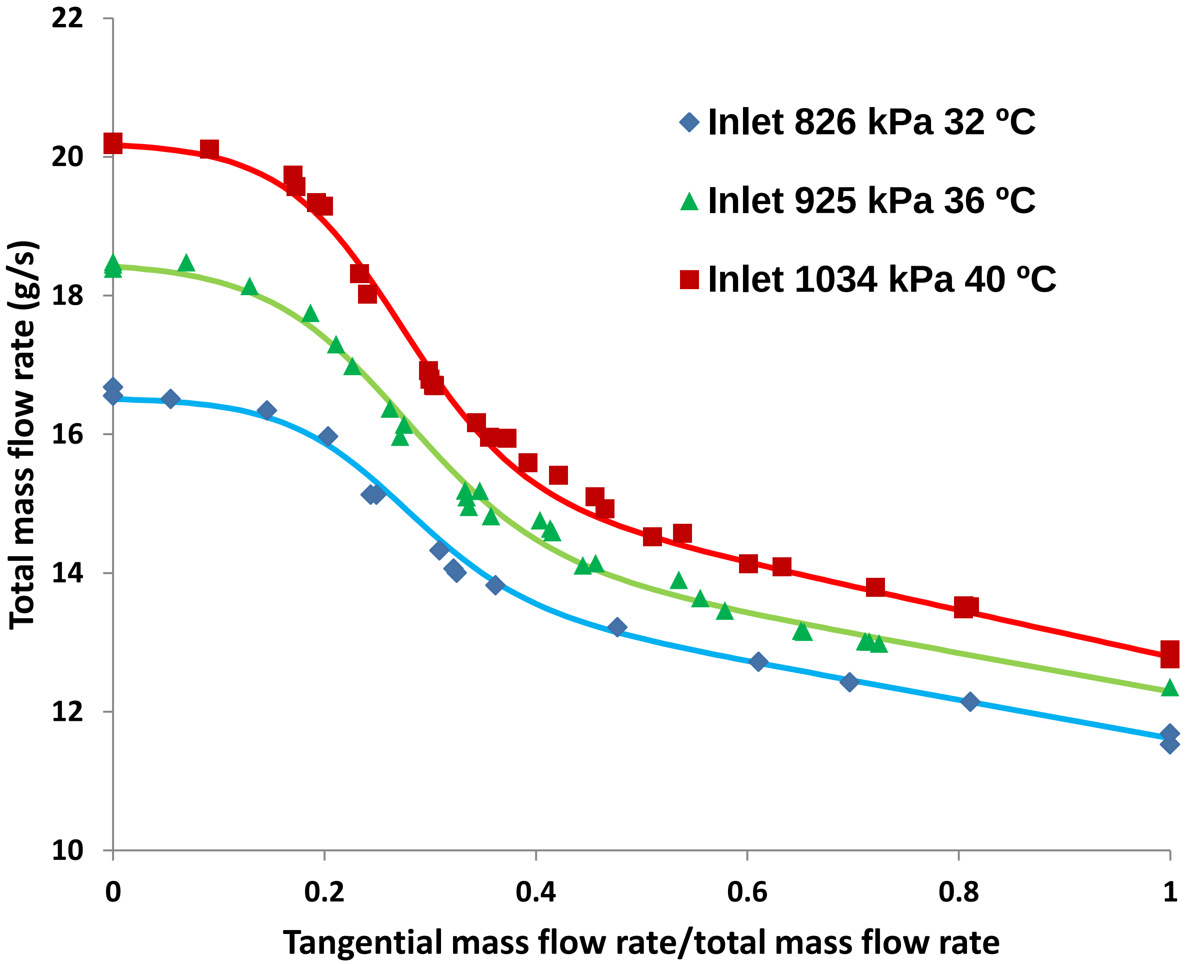
Bubbly

Clear

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 Swirl Strengths at Constant Inlet Pressure

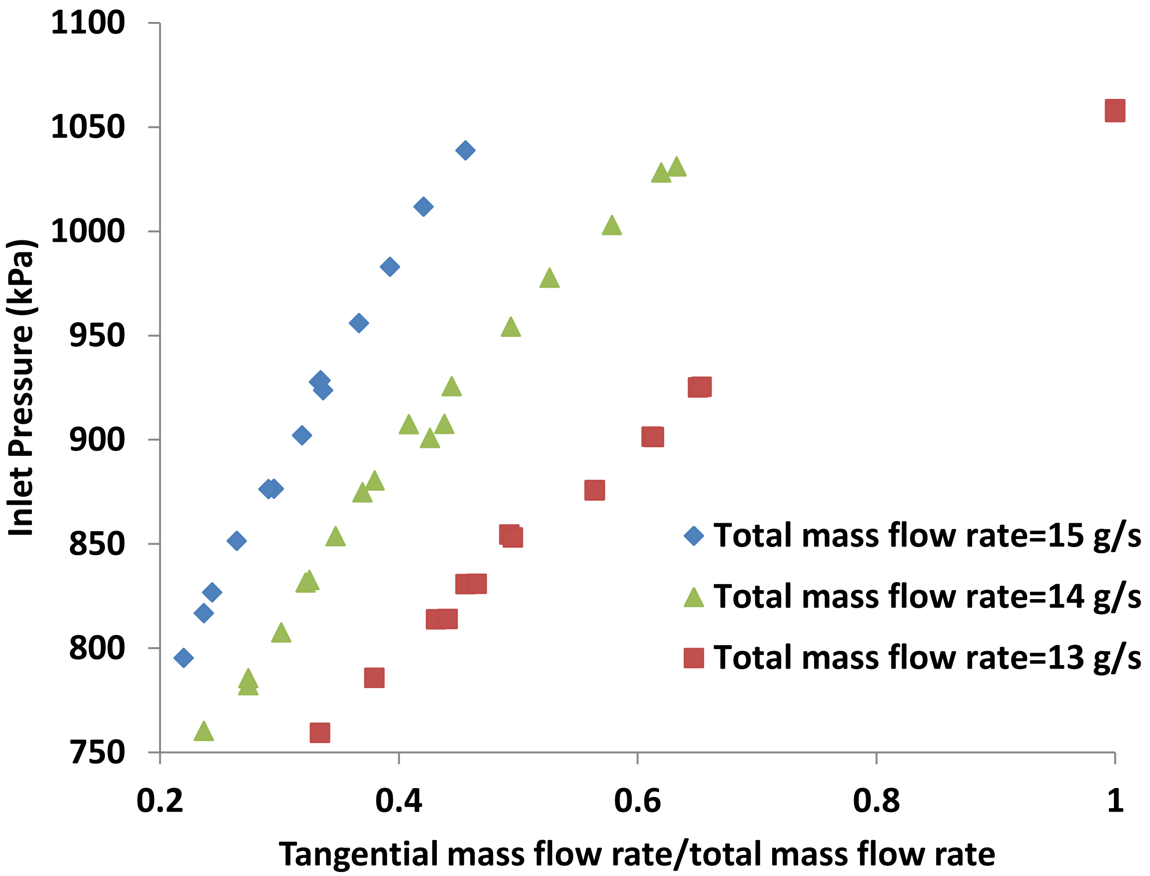


Inlet subcooling = 0.5 °C

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

Nozzle restrictiveness on the flow is changed by swirl; the stronger the swirl is, the larger the restrictiveness is.

Nozzle Inlet Pressure Can Vary in A Wide Range with Different Inlet Swirl Strengths at Constant Total Mass Flow Rate



Inlet subcooling = 0.5 ºC

Mass flow rate ratio (swirl 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 swirl; the stronger the swirl is, the larger the restrictiveness is.

Summary and Conclusions

- Nozzle inlet swirl can change nozzle restrictiveness on the two-phase flow. The stronger the swirl 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 swirl under the same nozzle inlet and outlet conditions.
- Next step: Compare the efficiency of swirl 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?

- Presenter: Jingwei Zhu
- Email: jzhu50@illinois.edu
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