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Why and When Expansion Work Recovery Makes Sense

ILLINOIS

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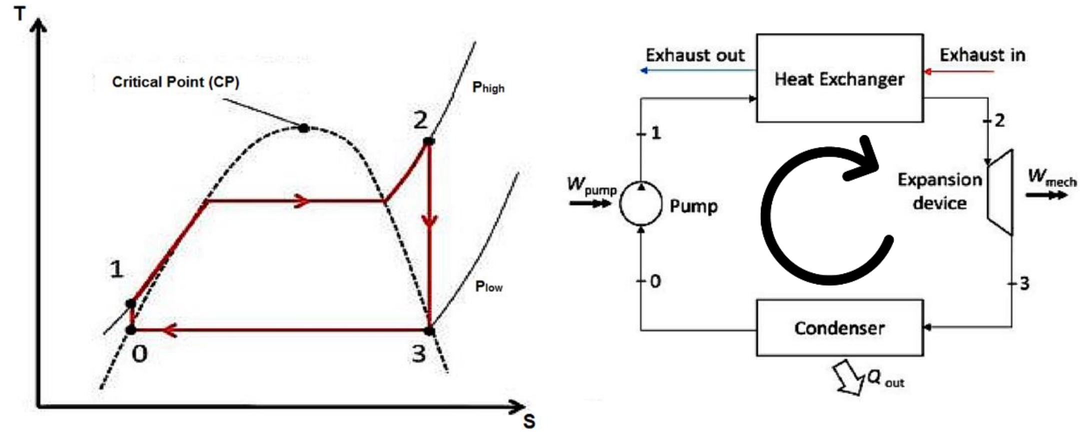
Presentation Outline

- Thermodynamic cycles:
  - Power generation vs. cooling
- Throttling loss and work recovery potential
- Comparison of expander and ejector
- Ejector
  - Cycle implementation
- Summary & conclusions

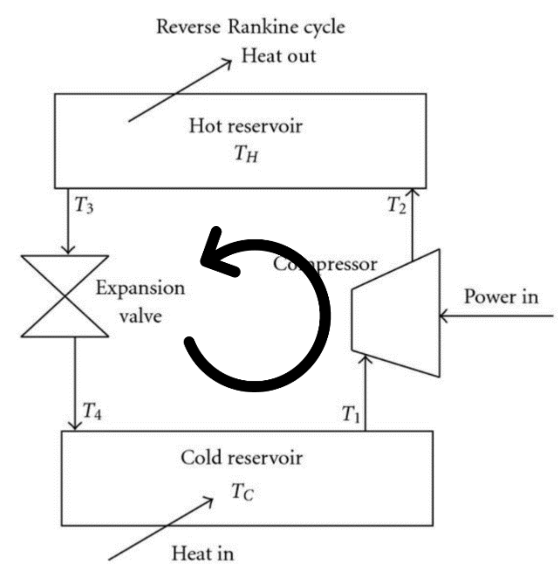
Background on Rankine Cycle

- Rankine Power Cycle
  - Purpose: convert heat into power
  - Turbine expands in vapor region to generate power

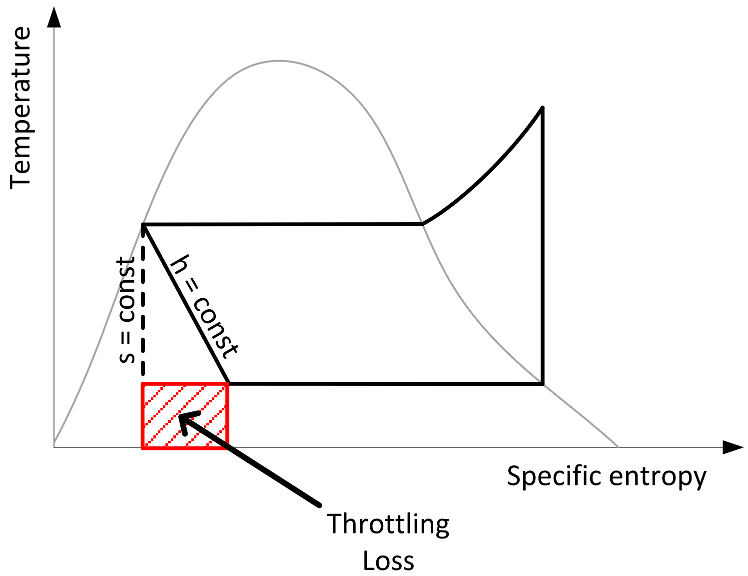


(a) (b)

- Reverse Rankine Cooling Cycle
  - Convert mechanical power into cooling (or heating)
  - Throttling valve is used instead of turbine to expand liquid
  - Could use expansion machine, but typically not done due to cost



Throttling Loss and Work Recovery



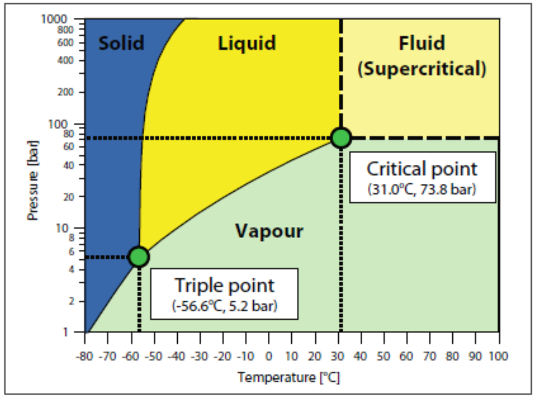
Difference between isentropic and isenthalpic expansion defines throttling loss

Greater throttling loss provides greater opportunity for work recovery

- Work recovery improves cycle performance:
  - Reduced compressor work
  - Increased cooling capacity
- Throttling loss varies greatly depending on fluid properties and operating conditions
- Several devices capable of recovering expansion work (by approaching isentropic expansion):
  - Two-phase ejector
  - Expander
  - (Vortex tube)

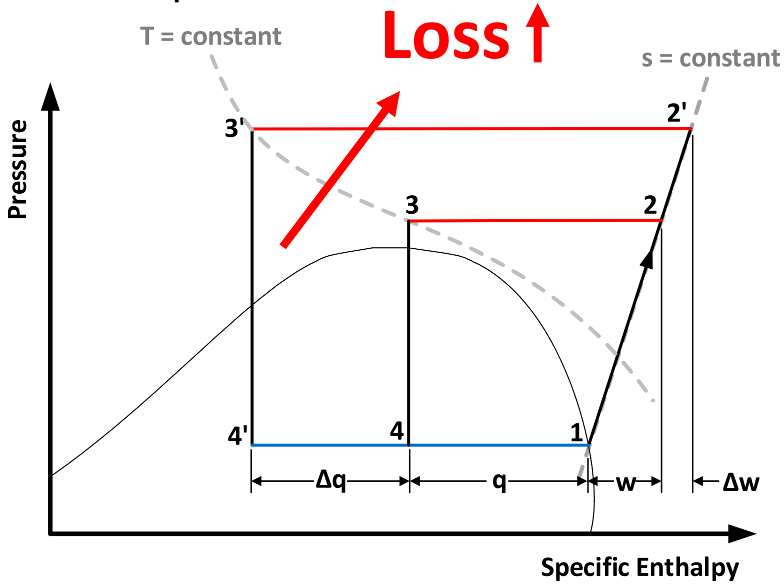
Transcritical CO_2 Refrigeration Cycle

Source: www.Danfoss.com

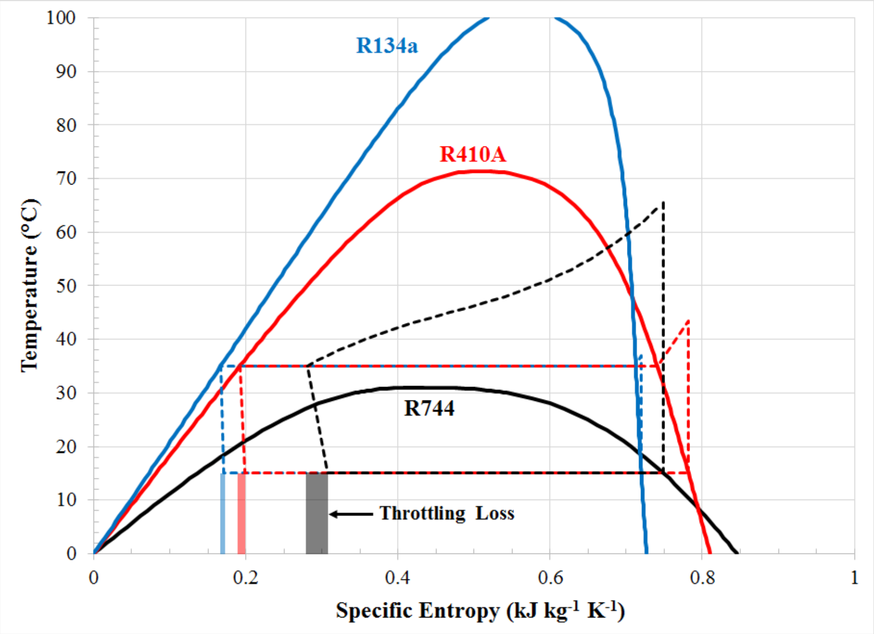


- Has excellent thermophysical properties
  - High thermal conductivity, low viscosity, …
- Has low critical temperature (only 31°C)
  - Cannot differentiate between vapor and liquid above critical point, i.e. no condensation but instead gas cooling
- Runs as a transcritical cycle at elevated ambient temperatures
  - That is what's causing the efficiency loss in AC operation

- High-side pressure used to maximize system performance
- Higher ambient requires higher P_{high}, loss increases



COP Improvement Through Work Recovery Depends on Refrigerant



- CO_2 has larger throttling loss than any other refrigerant
- Needs help at high ambient temperatures
- Work recovery potential increases as high and low temperatures are further apart

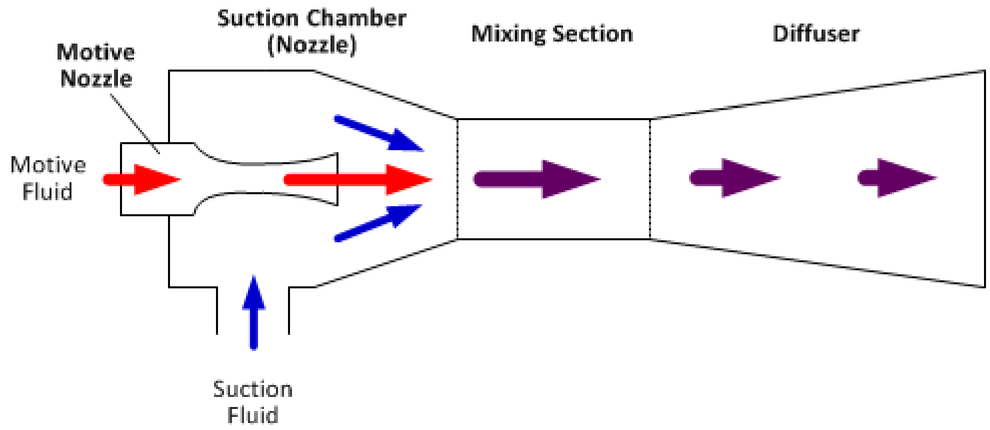
Thermodynamic cycle conditions/assumptions:

- Q_{evap} = 2 kW; T_{evap} = 15°C
- R134a/R410A: T_{cond} = 35°C, ΔT_{SC} = 0 K
- CO_2: P_{gc} = 90 bar, $T_{gc,out}$ = 35°C

Refrigerant	Specific Throttling Loss (kJ kg^{-1})	Mass Flow Rate (g s^{-1})	Total Throttling Loss (kW)	Maximum COP Improvement (%)
CO_2 (no IHX)	7.10	17.0	0.121	56.5
CO_2 (ε_{IHX} = 0.6)	5.54	13.8	0.076	38.8
R410A	1.95	11.9	0.023	17.6
R134a	1.27	12.7	0.016	12.4

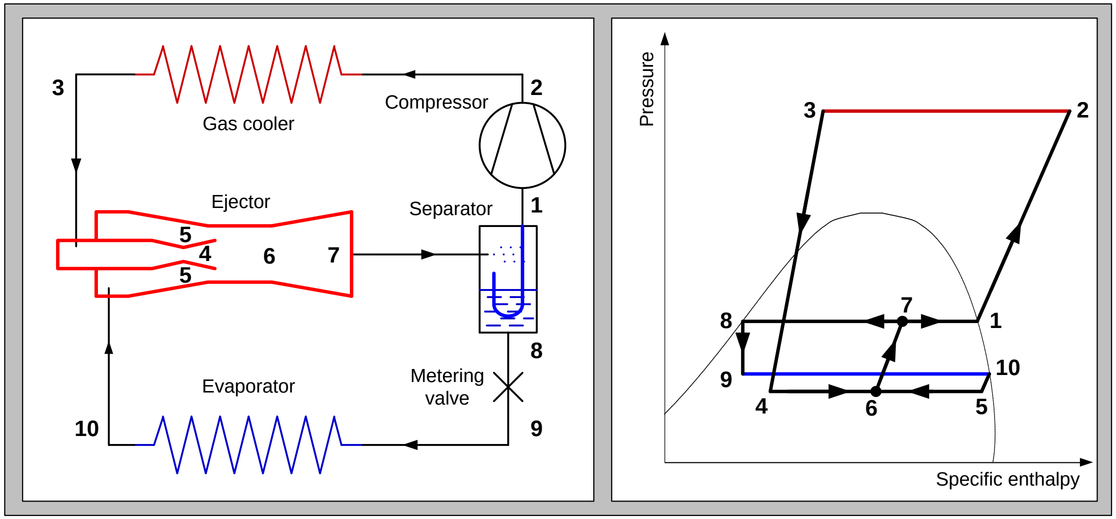
Two-phase Ejector for Expansion Work Recovery

- High-energetic motive stream accelerated in motive nozzle (low static pressure, high kinetic energy)
- Suction flow pre-accelerated in suction nozzle to reduce mixing losses caused by shearing
- Low-energy suction stream is entrained, accelerated by momentum transfer; velocities equalize during mixing, pressure rise in mixing chamber (possibility of shocks)
- Deceleration in subsonic diffuser; further increase of static pressure



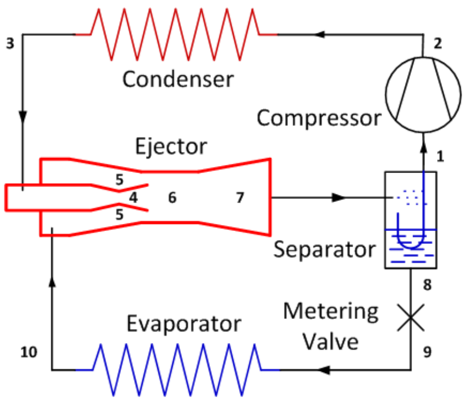
How to Implement Two-phase Ejector?

- Standard two-phase ejector cycle: high-pressure fluid from the gas cooler is used to increase the pressure of the vapor from the evaporator.

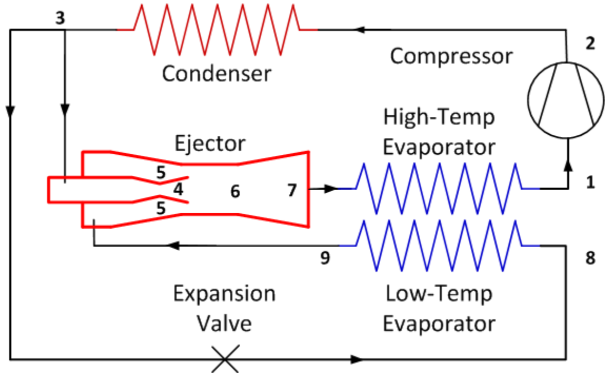


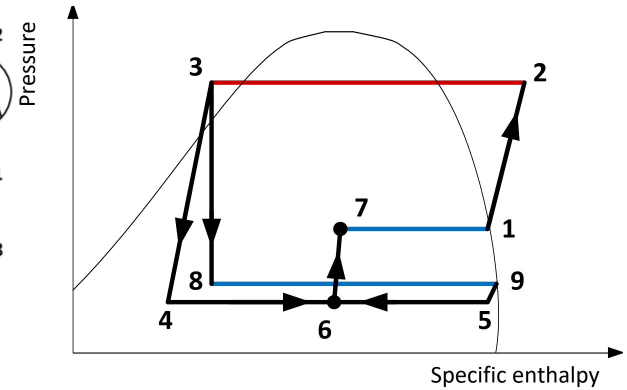
- Improvement mechanisms of ejector cycle compared to conventional expansion valve cycle:
  - Reduced compressor work (ejector provides pressure lift)
  - Potentially improved evaporator performance (liquid feeding)
  - Higher compressor efficiency (lower pressure ratio)
  - Lower compressor discharge temperature
  - Improved evaporator distribution

Different Ways to Implement Two-phase Ejectors



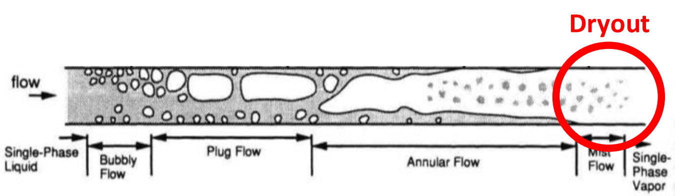
Standard Ejector Cycle

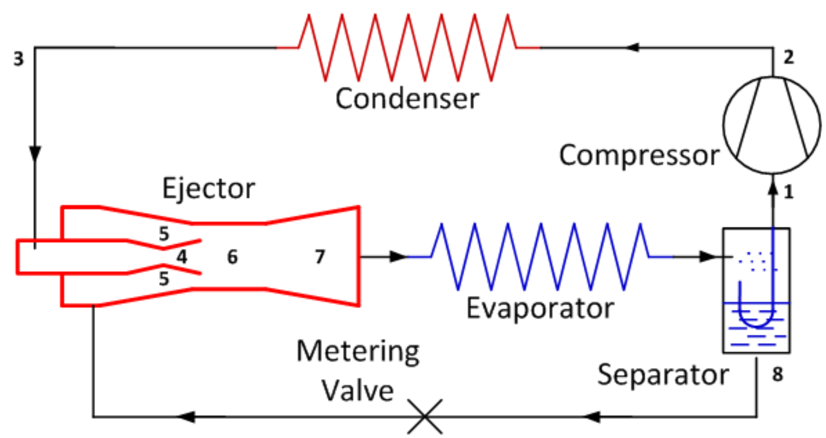




COS Ejector Cycle (multi-temperature)

Liquid recirculation cycle

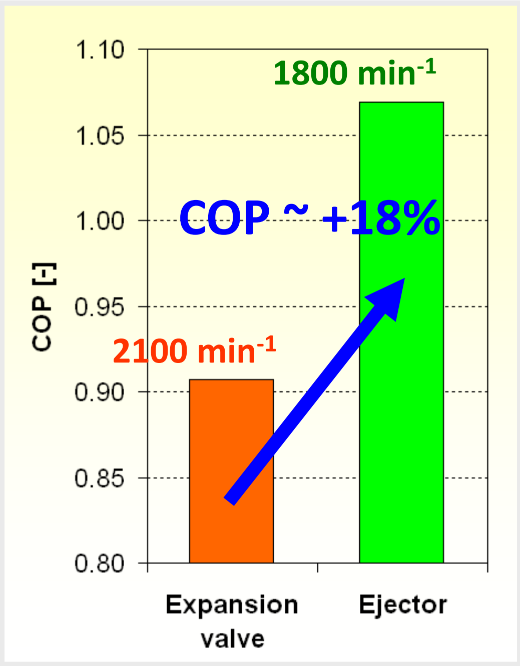




- Flooded evaporator eliminates dryout:
  - Improved heat transfer coefficient at end of evaporator
  - Elimination of superheat and reduced ΔT between refrigerant and air

What Influences the COP Improvement that an Ejector Cycle can Achieve?

- Review paper* on recent ejector studies showed experimental studies generally observe the following COP improvements with and ejector:
  - 15 - 30 % with CO_2
  - 10 - 15 % with R410A
  - ~ 5 % with R134a and R1234yf
- CO_2 applications that benefit most from two-phase ejectors
  - Air-conditioning at high ambient temperature
  - Commercial refrigeration
  - Low temperature heat pumps
  - Heat pump water heaters, …



CO_2 system at matched 4.8 kW capacity
T_{amb} = 45°C, T_{evap} = 5°C

* Elbel, S., Lawrence, N., 2016, Review of recent developments in advanced ejector technology, *Int. J. Refrigeration*, 62: 1-18.

Summary and Conclusions

- Conventional cooling cycles use isenthalpic throttling instead of expansion turbine (cost)
- Fluids with large throttling losses (e.g. transcritical CO_2) greatly benefit from expansion work recovery
  - Work recovery provides cycle efficiency boost at high ambient temperatures
- Large difference between ambient and evaporation temperature increases work recovery potential
- Expander and ejectors can provide work recovery
  - COP gains of 10 to 30%
- Ejector appears to be most cost effective solution
- First commercial applications
  - Supermarkets, some automotive, industrial refrigeration, …
- More research needed: controls, efficiency, design for part-load, …

Thank You for Your Attention!

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