Improving Vapor Compression System Efficiency through Advanced Vapor Compression Technologies

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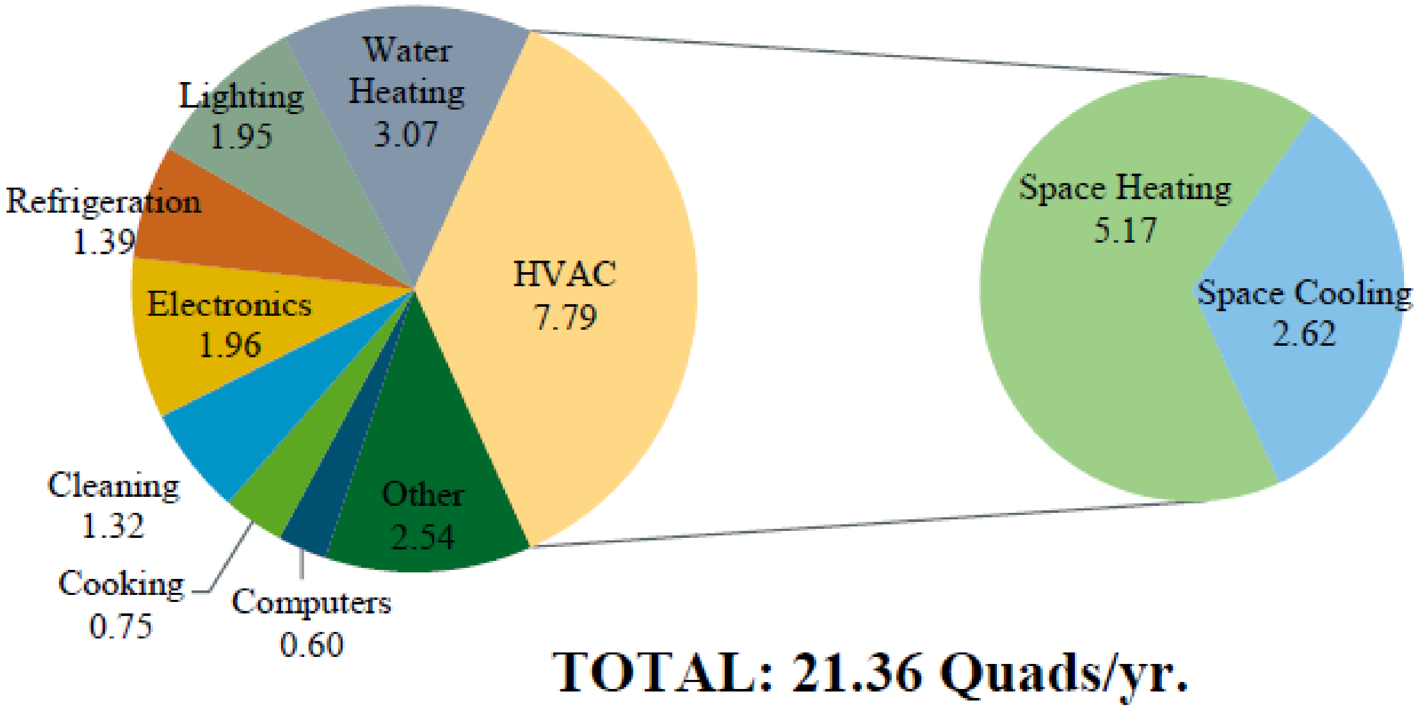
Outline

- Introduction
- In Search of Carnot Efficiency
  - Irreversibilities of a Vapor Compression Cycle
  - Suction-to-Liquid Line Heat Exchange
  - Multi-Stage Compression with Intercooling
  - Refrigerant Injected Compression with Economization
  - Liquid Flooded Compression with Internal Regeneration
  - Quasi-isothermal Compression with Cylinder Cooling and Internal Regeneration
- Summary and Perspectives

Introduction

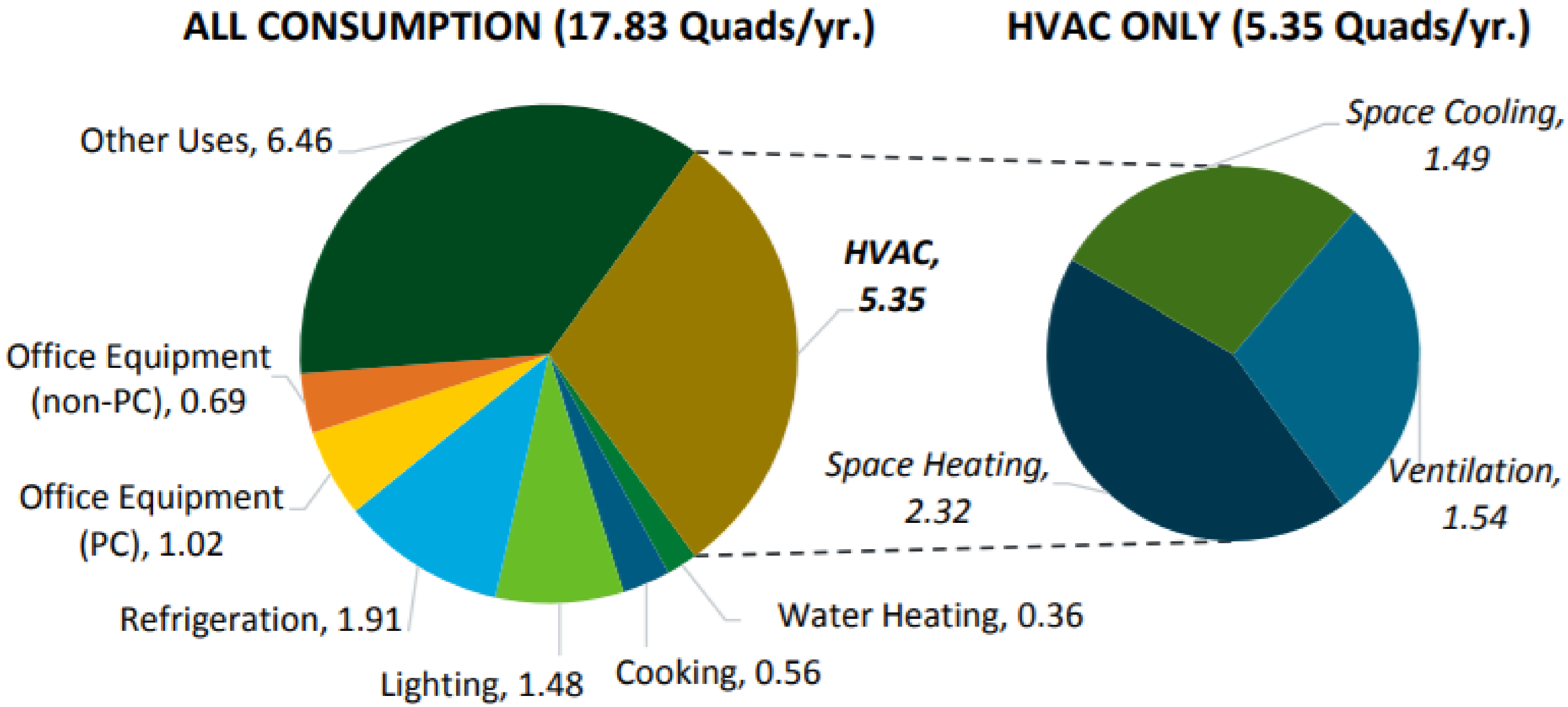
- Residential buildings
  - Primary energy consumption by end use, Quads/yr. (Quadrillion Btu/yr)



(Source: EIA Annual Energy Outlook, 2017)

Introduction (cont'd)

- Commercial buildings
  - Primary energy consumption by end use, Quads/yr. (Quadrillion Btu/yr)



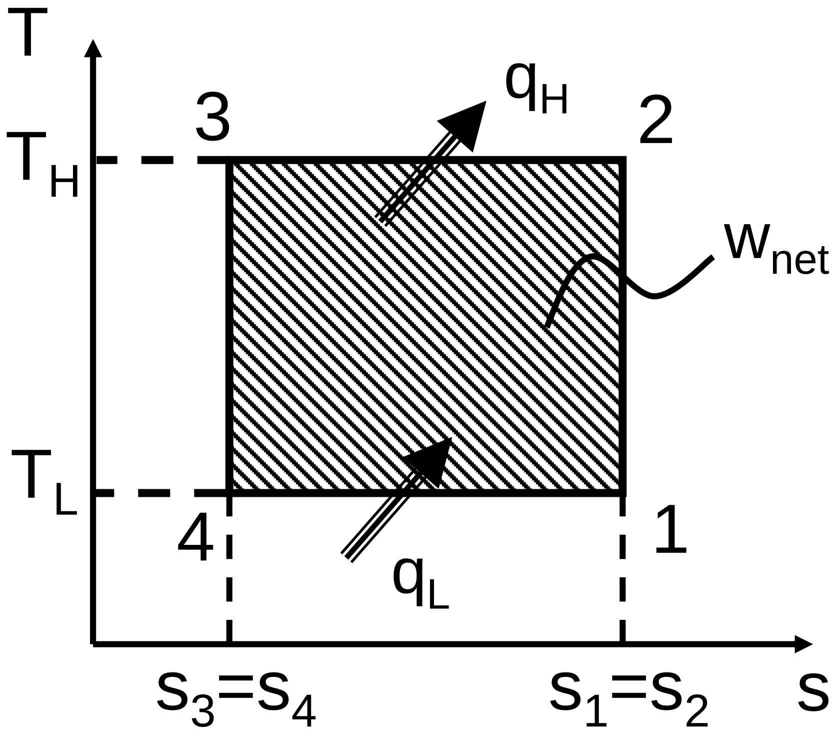
(Source: EIA Annual Energy Outlook, 2017)

Outline

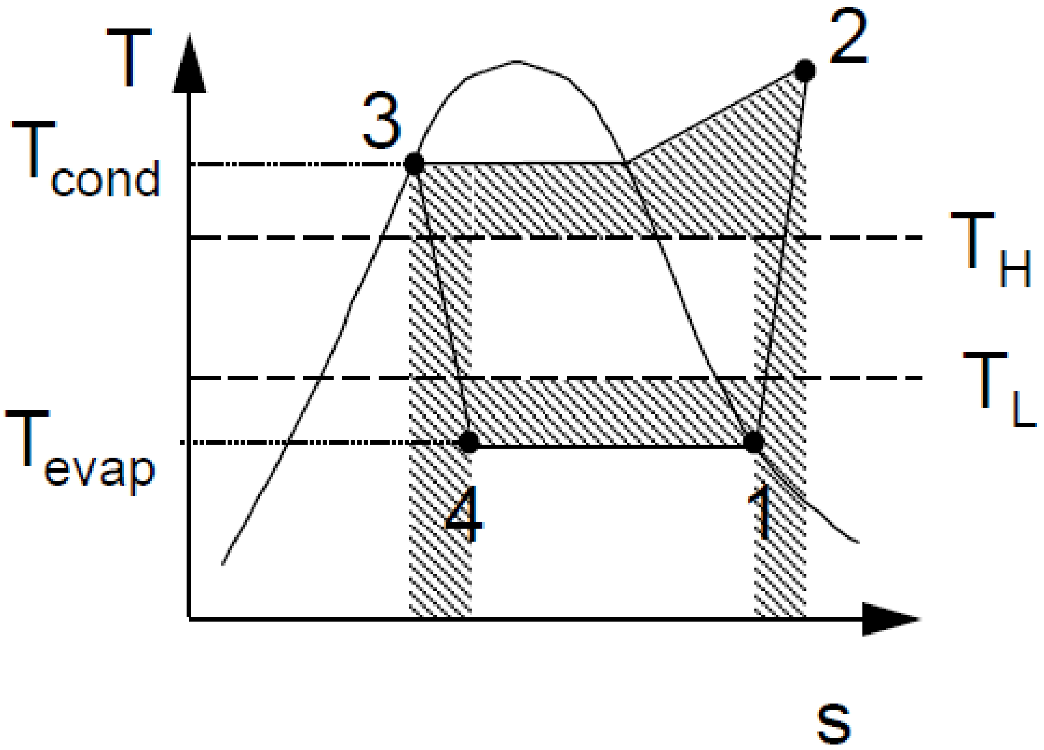
In Search of Carnot Efficiency

Irreversibilities in a Vapor Compression Cycle

- Carnot Cycle vs Real Cycle with Irreversibilities



1 - 2: reversible & adiabatic compression
2 - 3: reversible & isothermal heat rejection
3 - 4: reversible & adiabatic expansion
4 - 1: reversible & isothermal heat addition

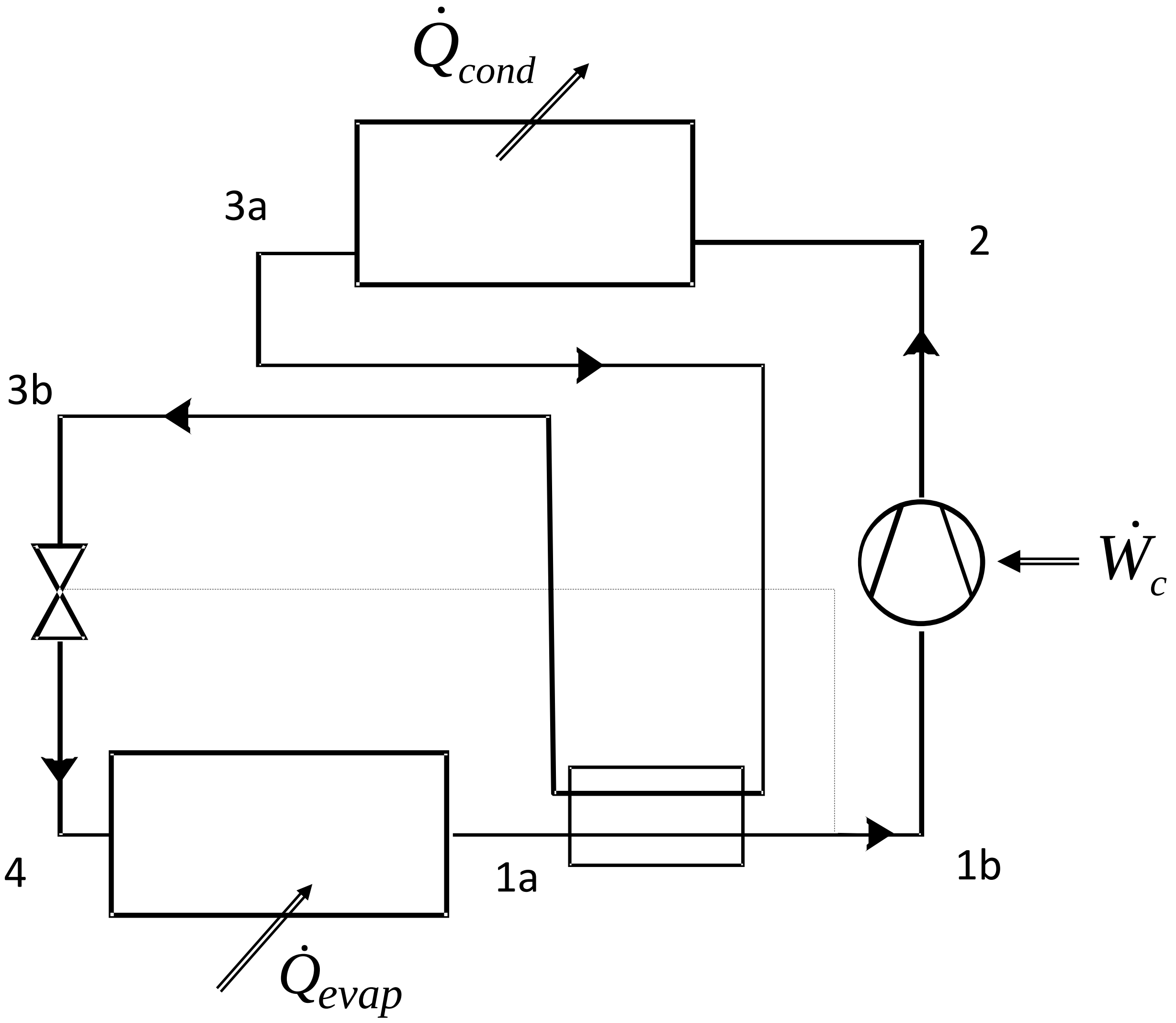


Compression losses
Desuperheating losses
Heat exchange losses
Expansion losses

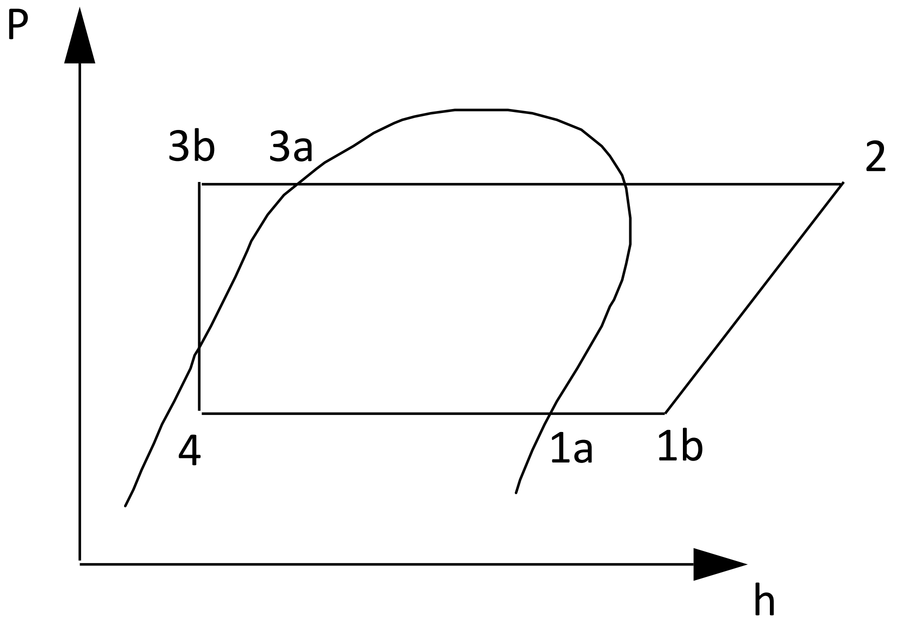
In Search of Carnot Efficiency

Suction-to-Liquid Line Heat Exchange

In Search of Carnot Efficiency
Suction-to-Liquid Line Heat Exchange



In Search of Carnot Efficiency
Suction-to-Liquid Line Heat Exchange (cont'd)



Effect on cooling capacity?

1.) Increases superheat → increases specific volume at state 1
→ reduces mass flow rate → decreases cooling capacity

2.) Increases subcooling → decreases enthalpy at state 4
→ increases Δh across evaporator → increases cooling capacity

→ net result depends on refrigerant characteristics

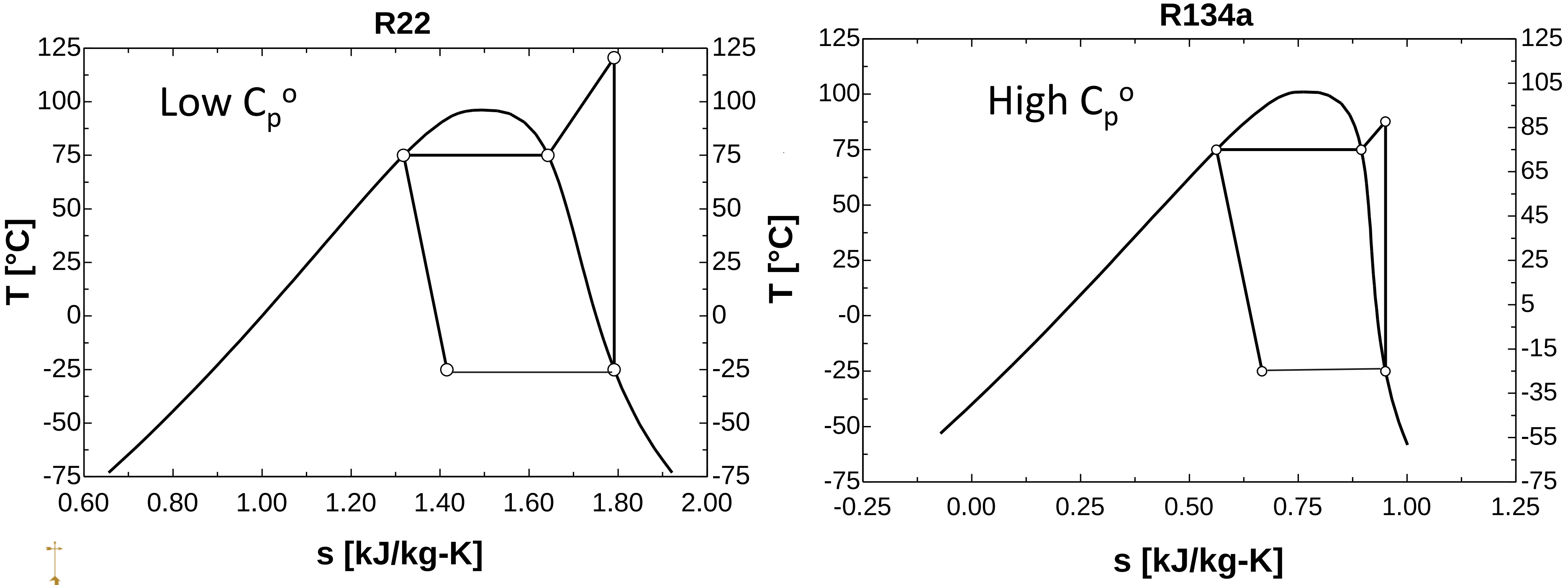
In Search of Carnot Efficiency
Suction-to-Liquid Line Heat Exchange (cont'd)

- Effect on COP?

1.) Increases superheat → increases Δh across compressor

2.) Increases subcooling → increases Δh across evaporator

➔ net result depends on refrigerant characteristics

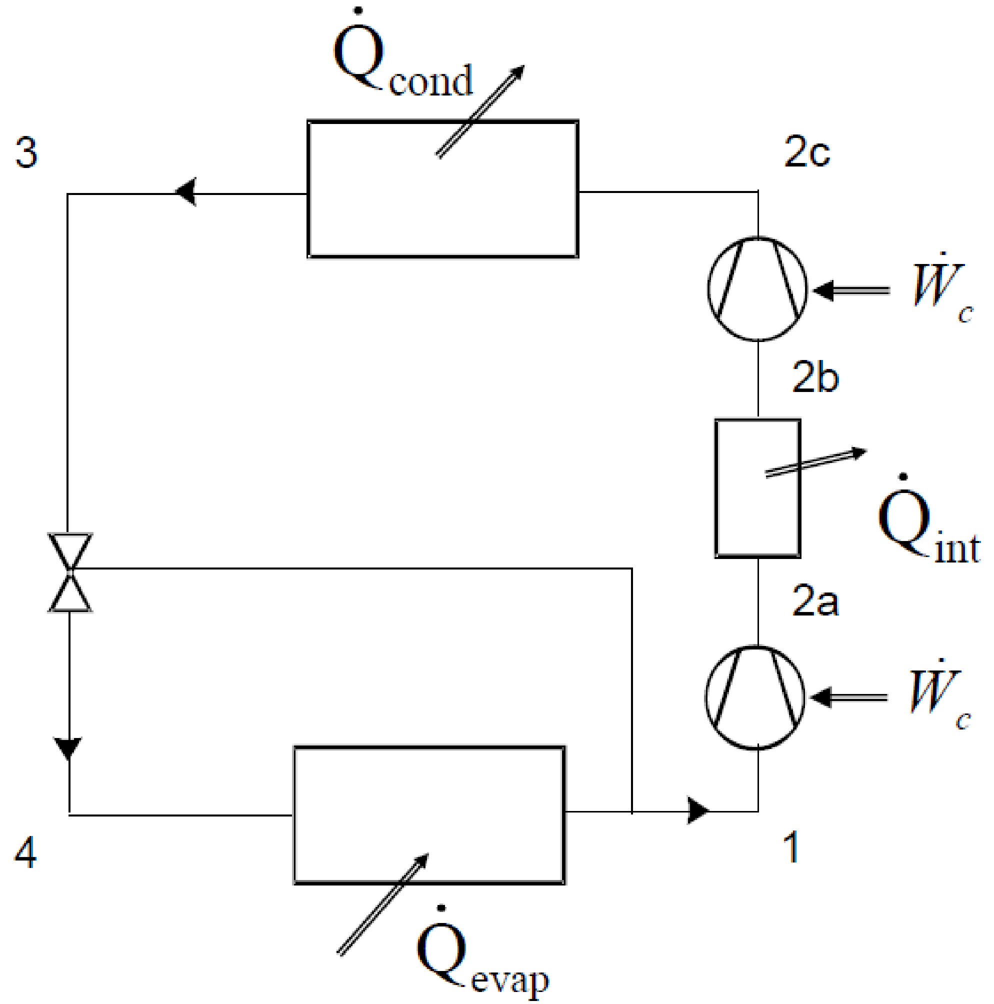


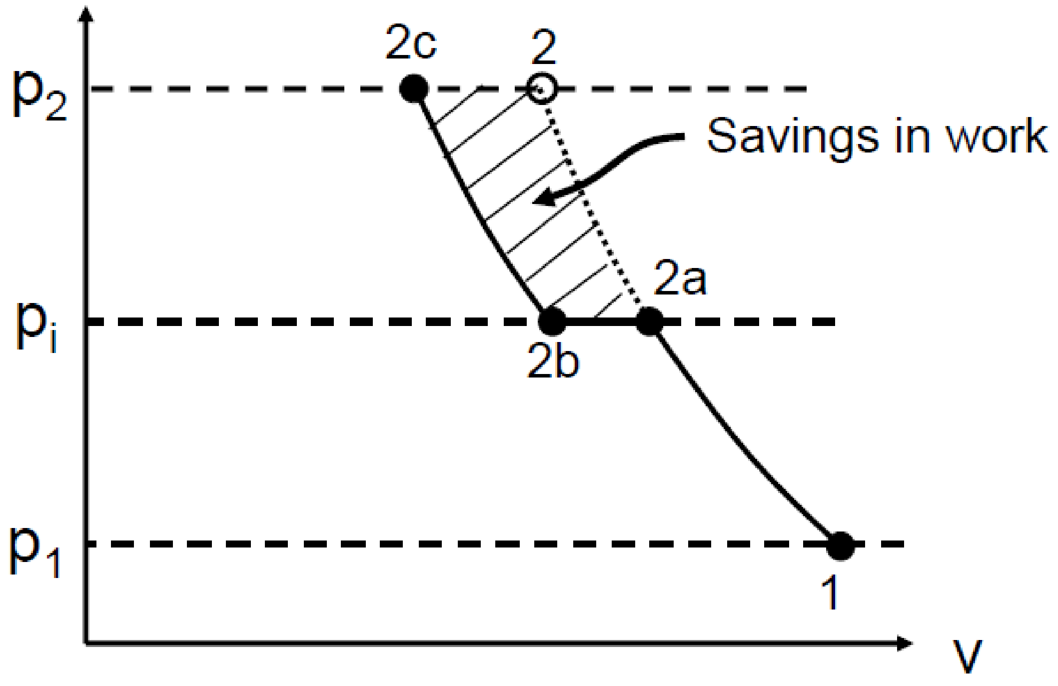
In Search of Carnot Efficiency

Multi-Stage Compression with Intercooling

In Search of Carnot Efficiency

Multi-Stage Compression with Intercooling





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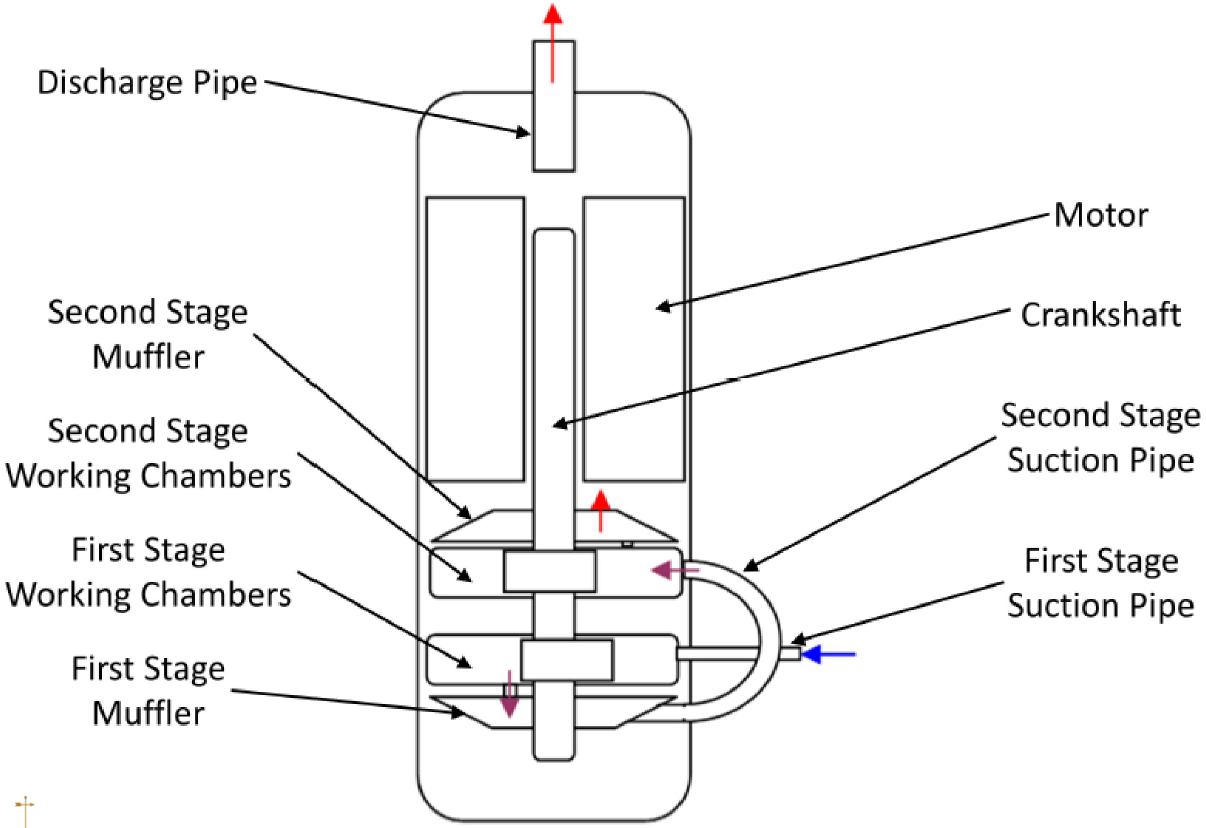
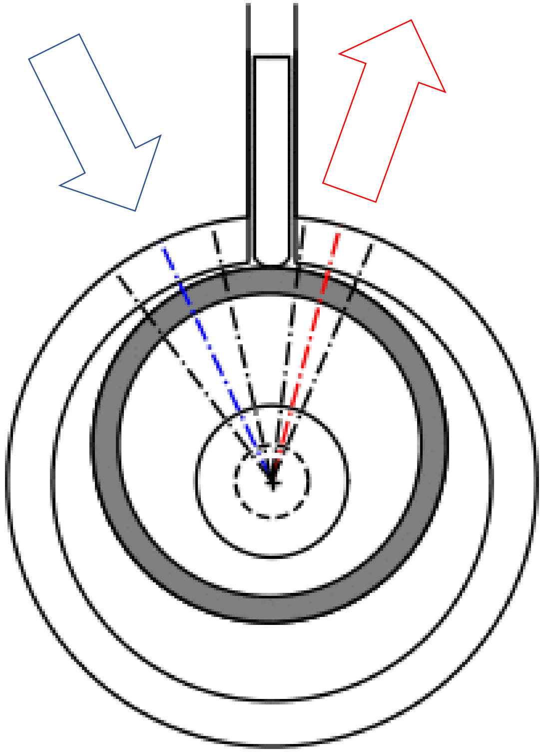
Multi-Stage Compression with Intercooling (cont'd)

- Example of two-stage hermetic rolling piston compressor with intercooling (Mathison et al., 2008)





In Search of Carnot Efficiency
Multi-Stage Compression with Intercooling (cont'd)

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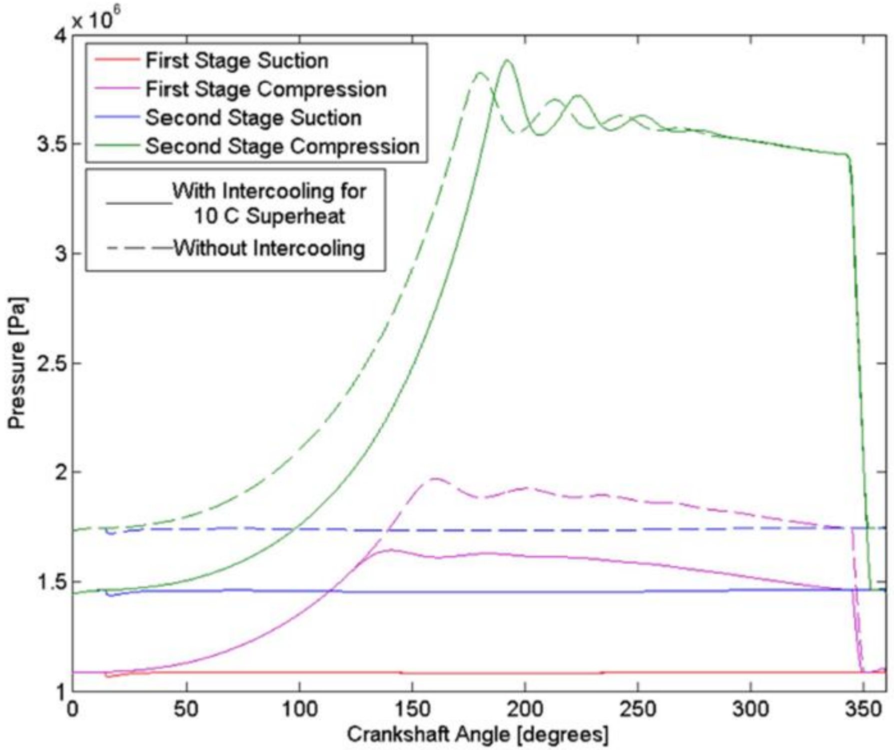
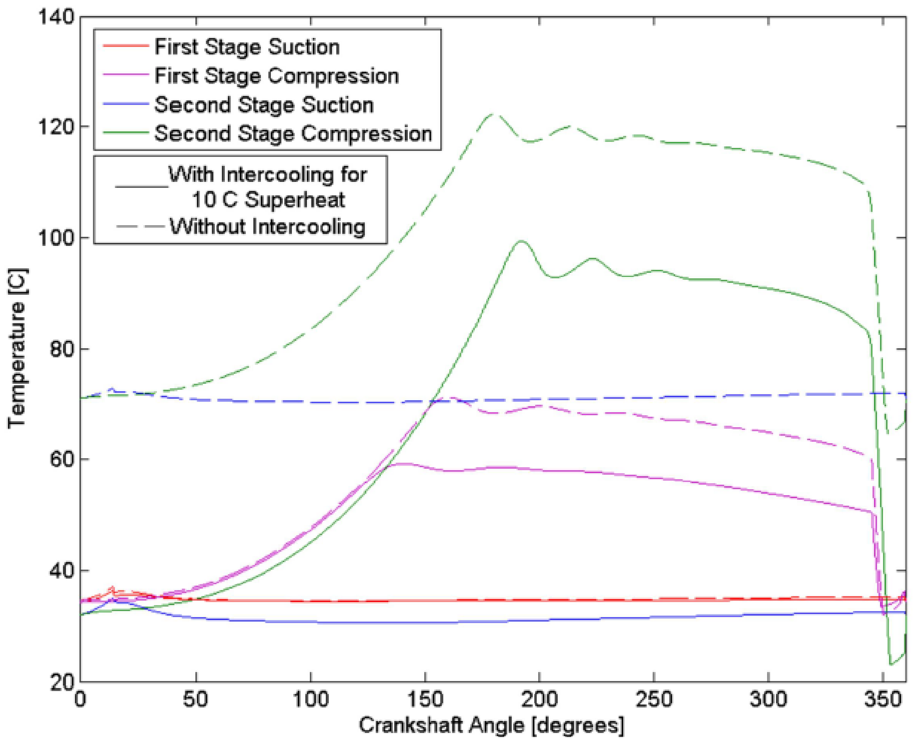
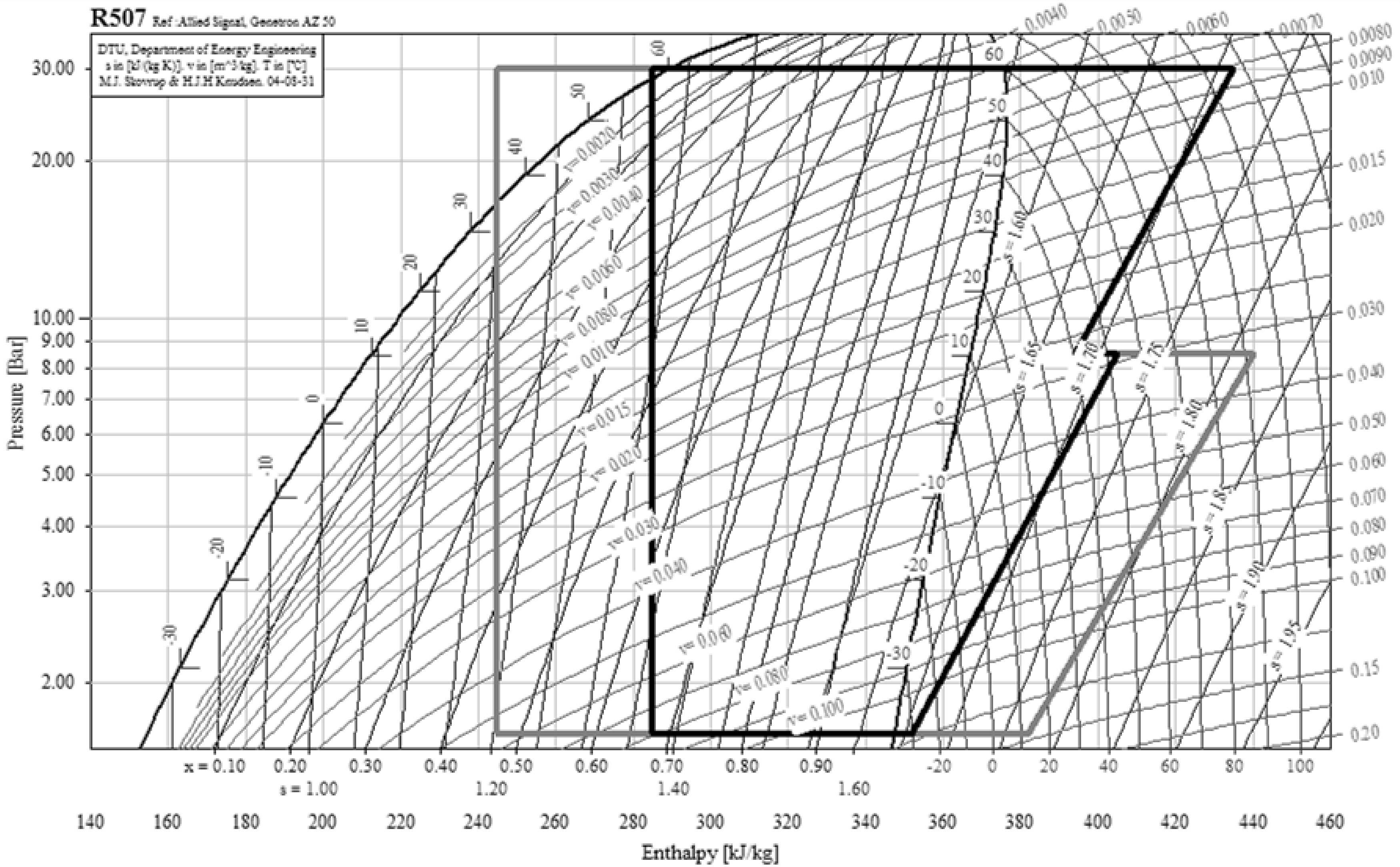




In Search of Carnot Efficiency

Multi-Stage Compression with Intercooling (cont'd)



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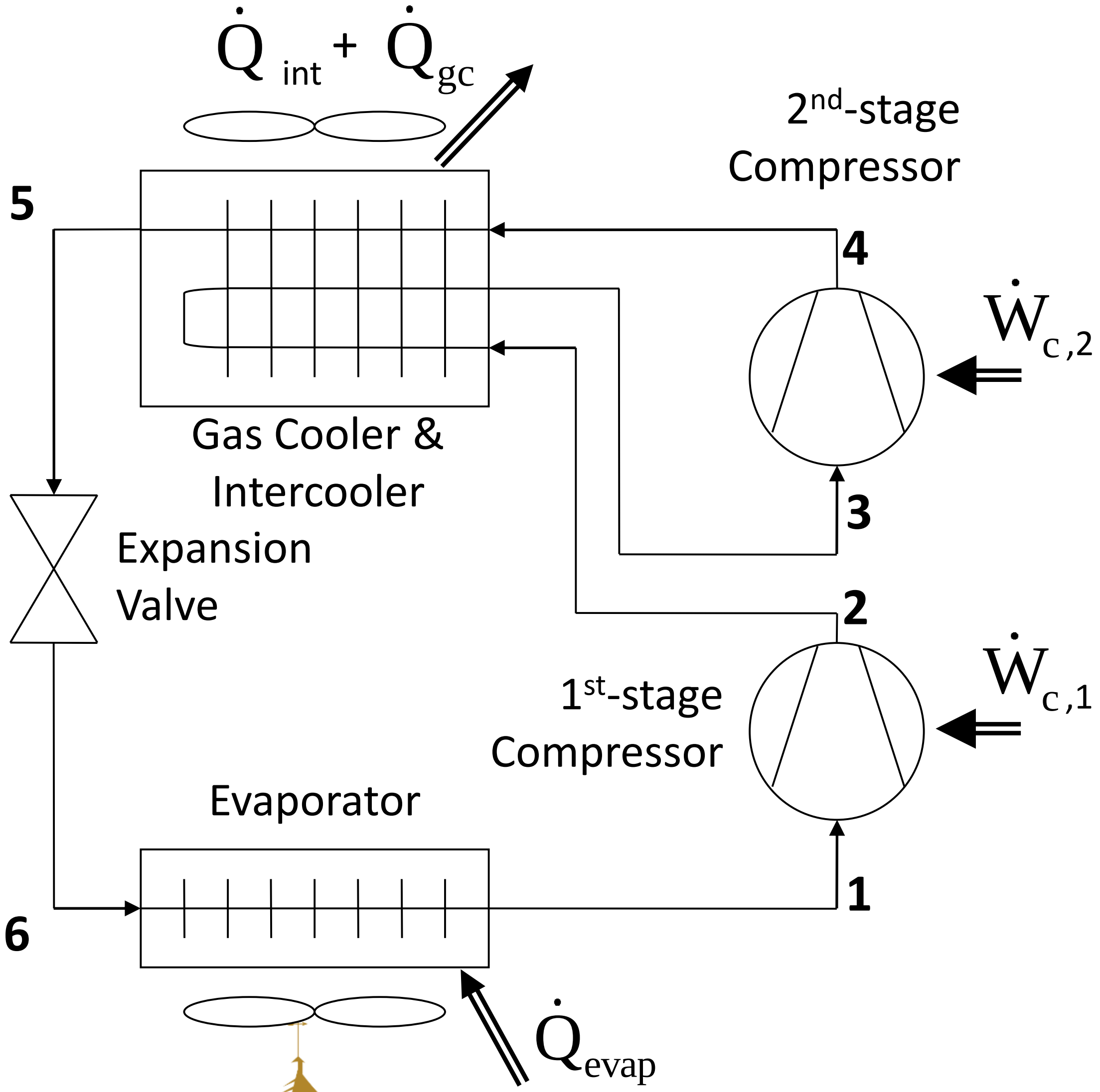
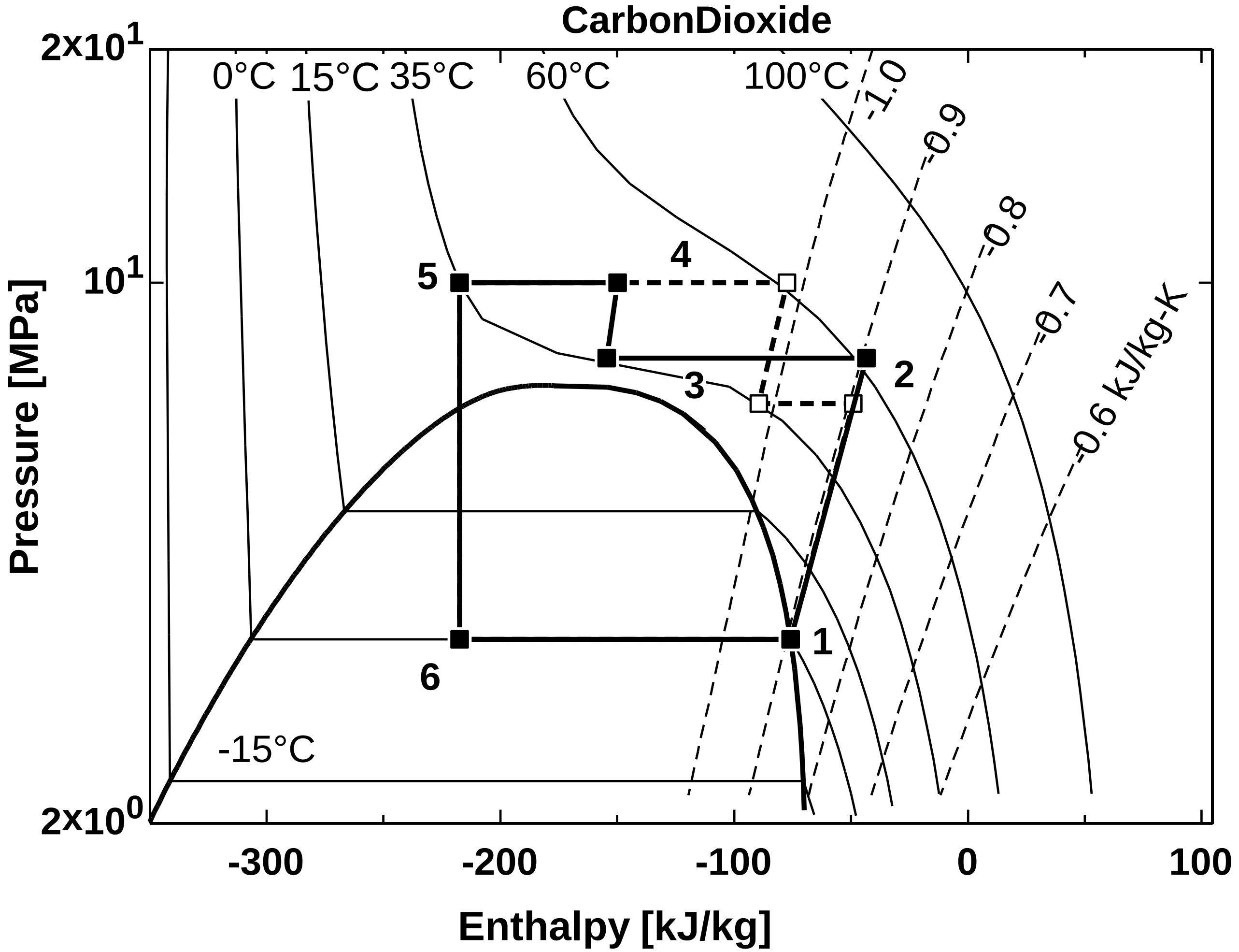
In Search of Carnot Efficiency

Multi-Stage Compression with Intercooling (cont'd)





In Search of Carnot Efficiency

Vapor Injection with Economizing

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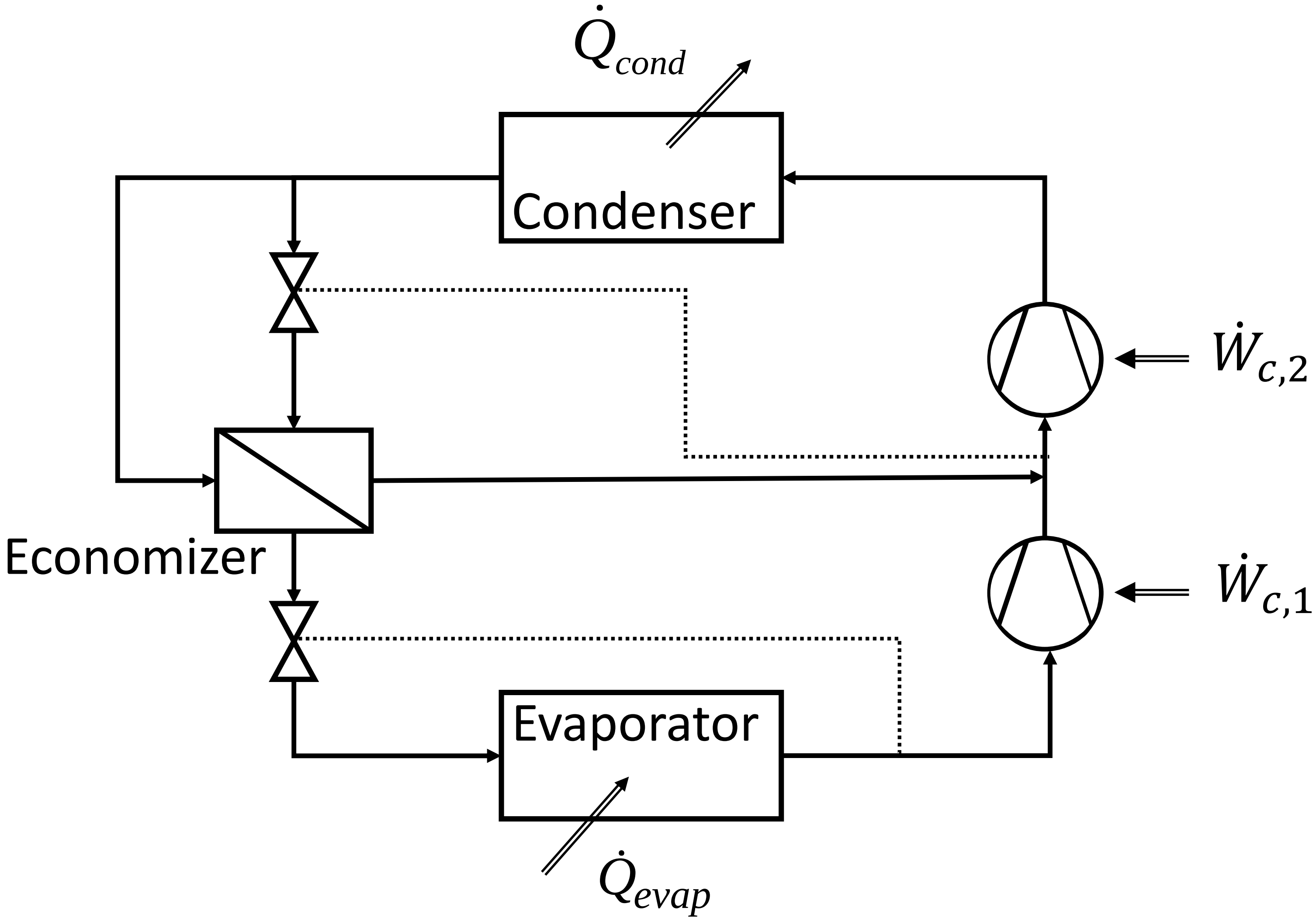
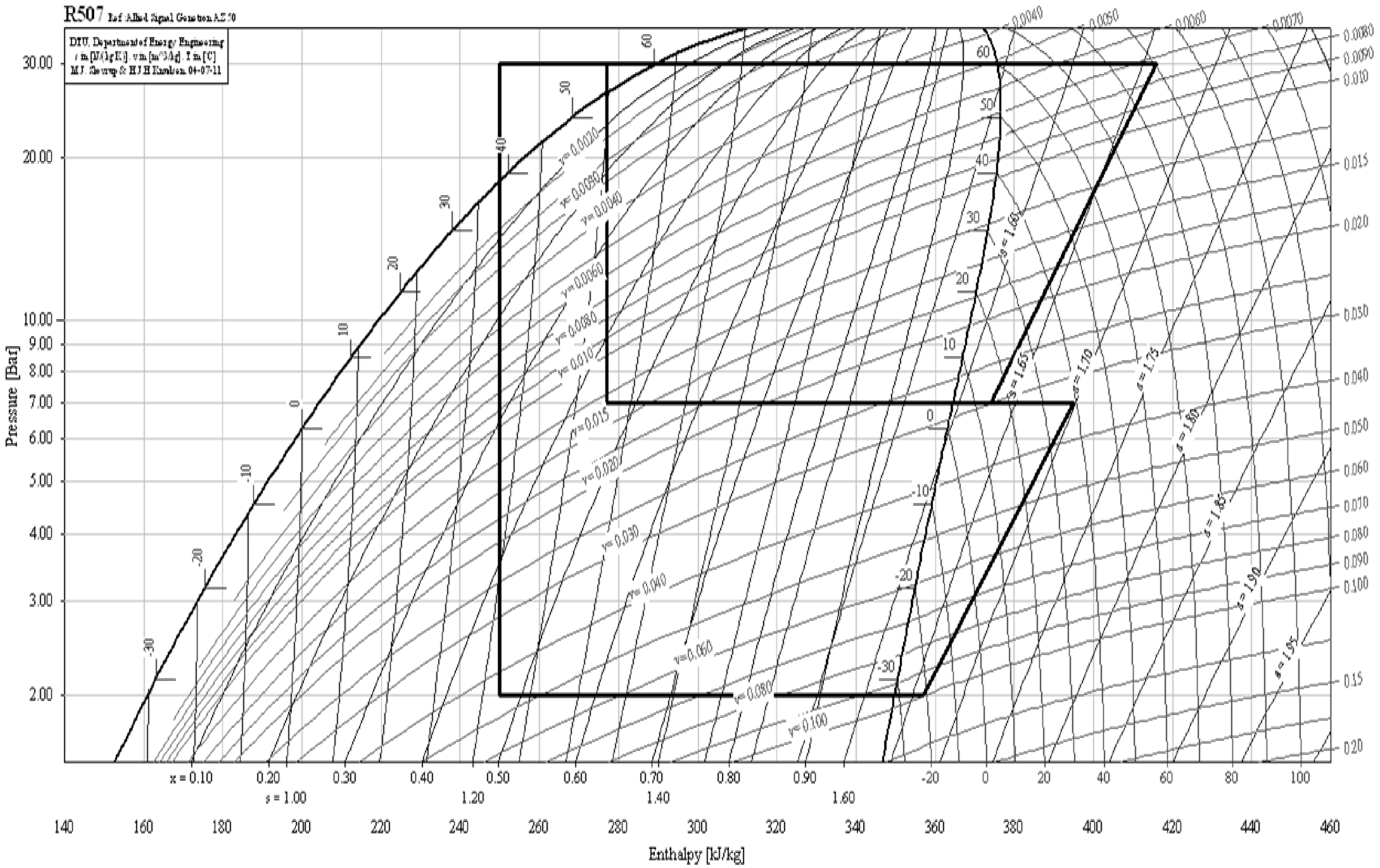
Vapor Injection with Economizing



In Search of Carnot Efficiency
Vapor Injection with Economizing (cont'd)



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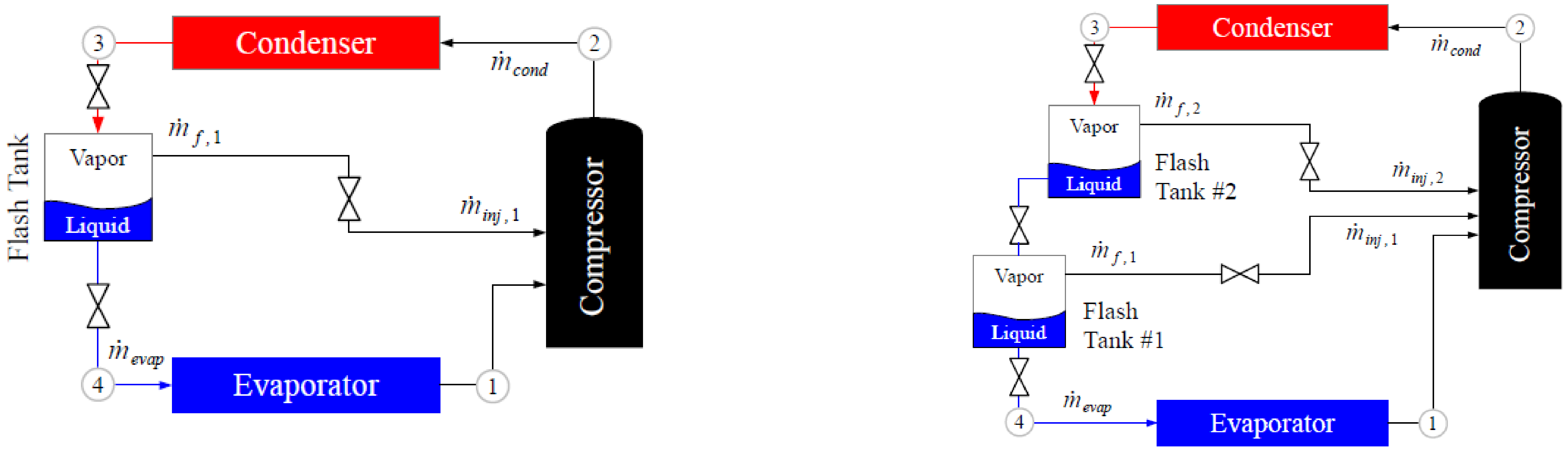
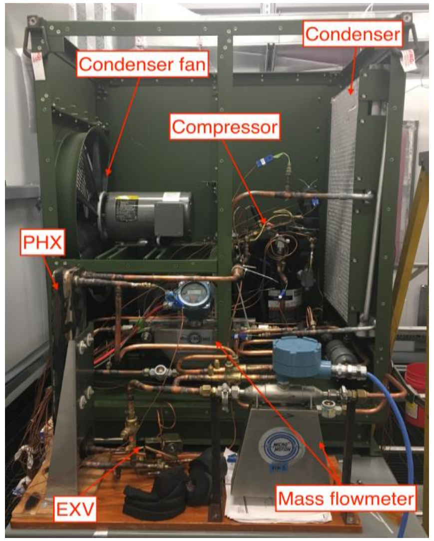
Vapor Injection with Economizing (cont'd)

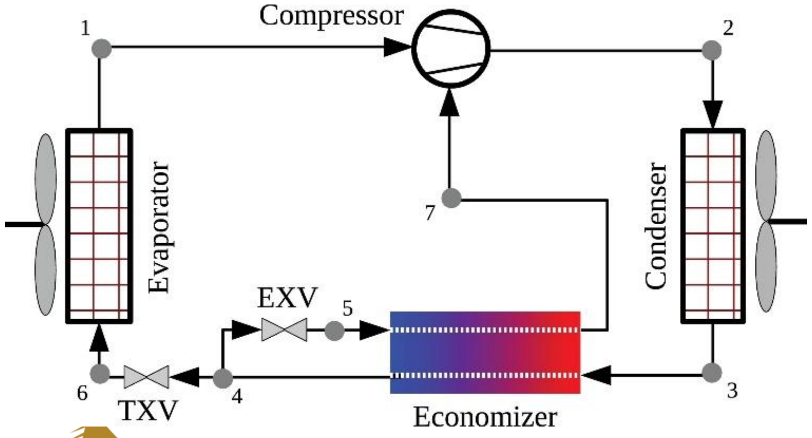
- Hermetic scroll compressor for cold-climate heat pump (Bell et al. 2013)
  - Symmetric scroll wraps with constant wall thickness
  - Single- and double-injection points
  - R-290; Volume ratio 3
  - $p_{\text{evap}} = 244.5\text{ kPa }(-20\text{ C})\,, p_{\text{cond}} = 1476.7\text{ kPa }(43.3\text{ C}), \Delta T_{\text{sh}} = 11.1\text{ K}$

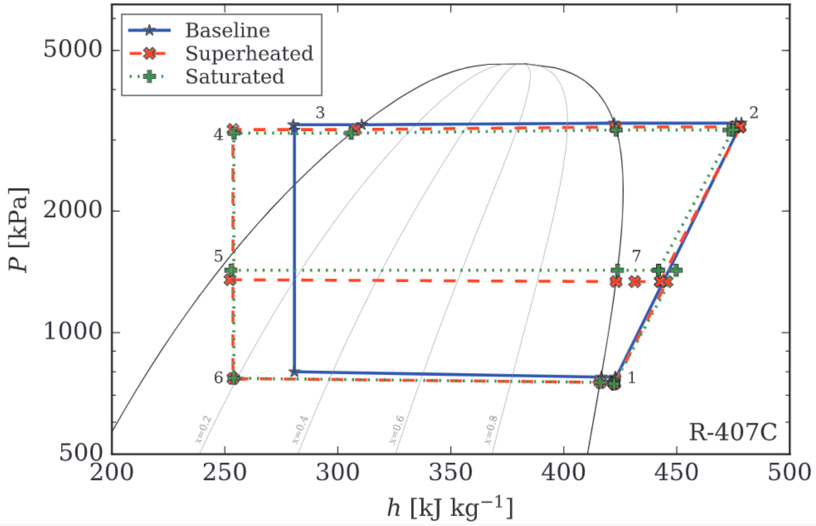


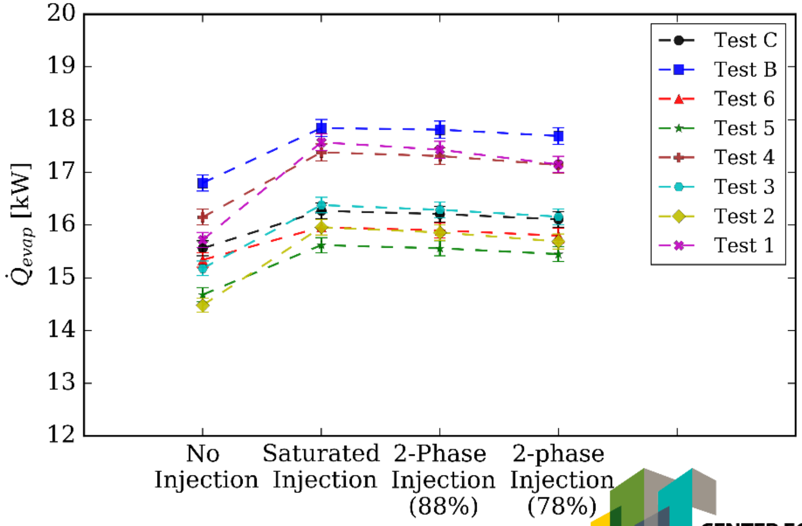
In Search of Carnot Efficiency
Vapor Injection with Economizing (cont'd)

- ECU for cooling application in cold climates (Bahman et al. 2018)









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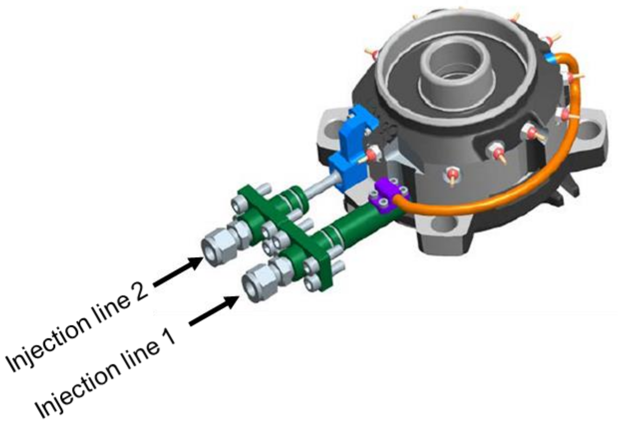
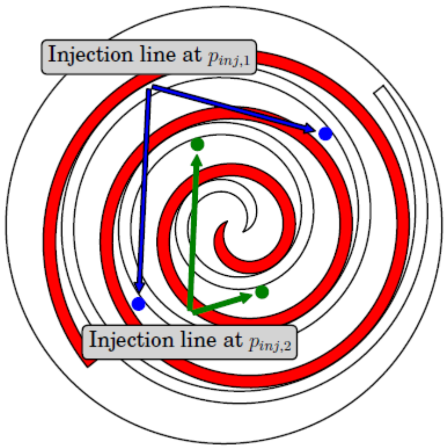
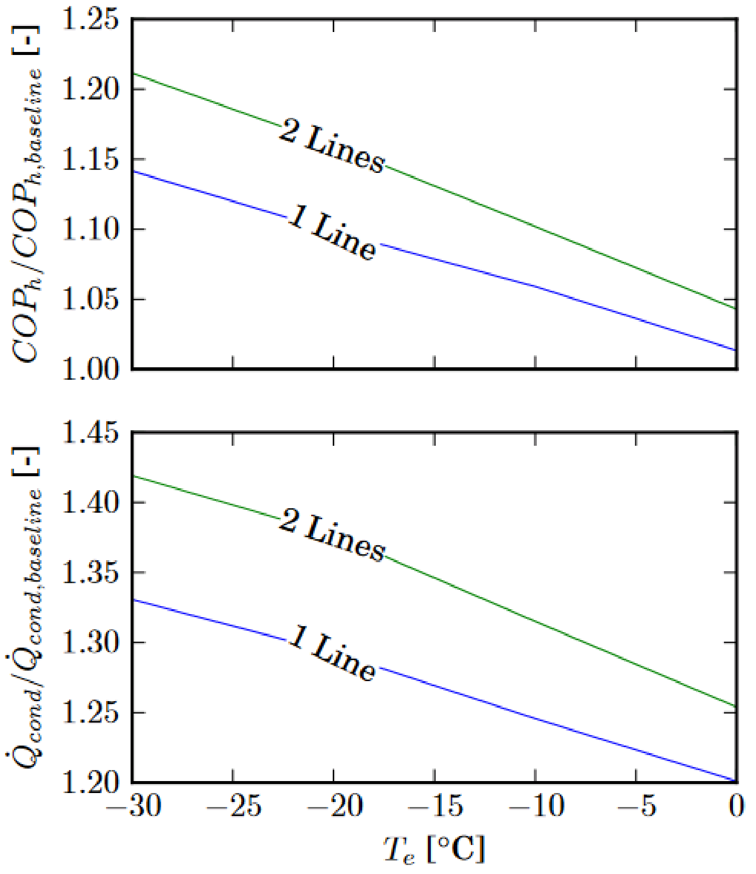
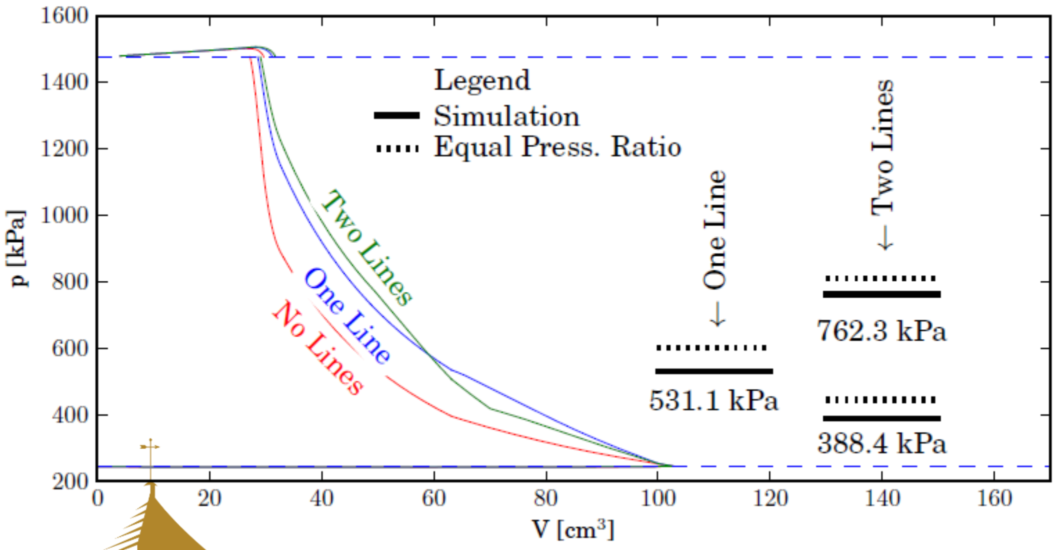
In Search of Carnot Efficiency
Vapor Injection with Economizing (cont'd)

- Hermetic scroll compressor for cold-climate heat pump (Bell et al. 2013)









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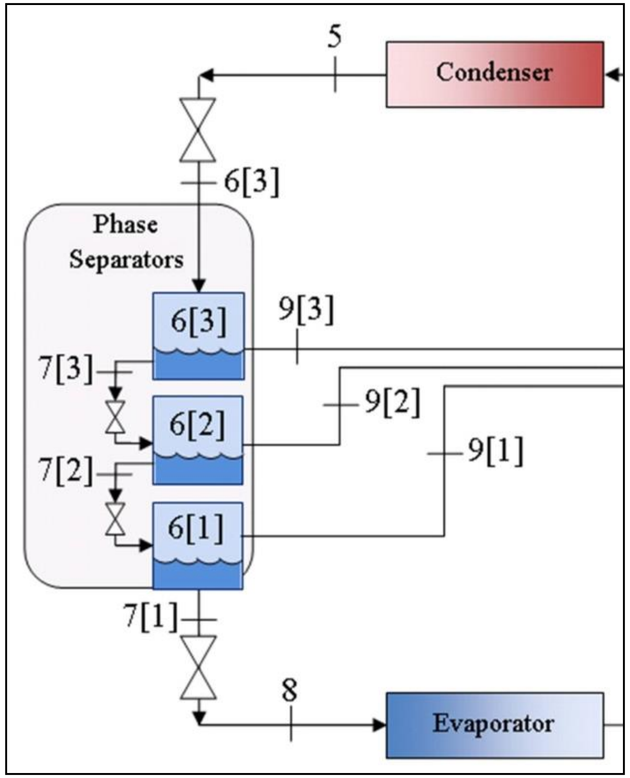
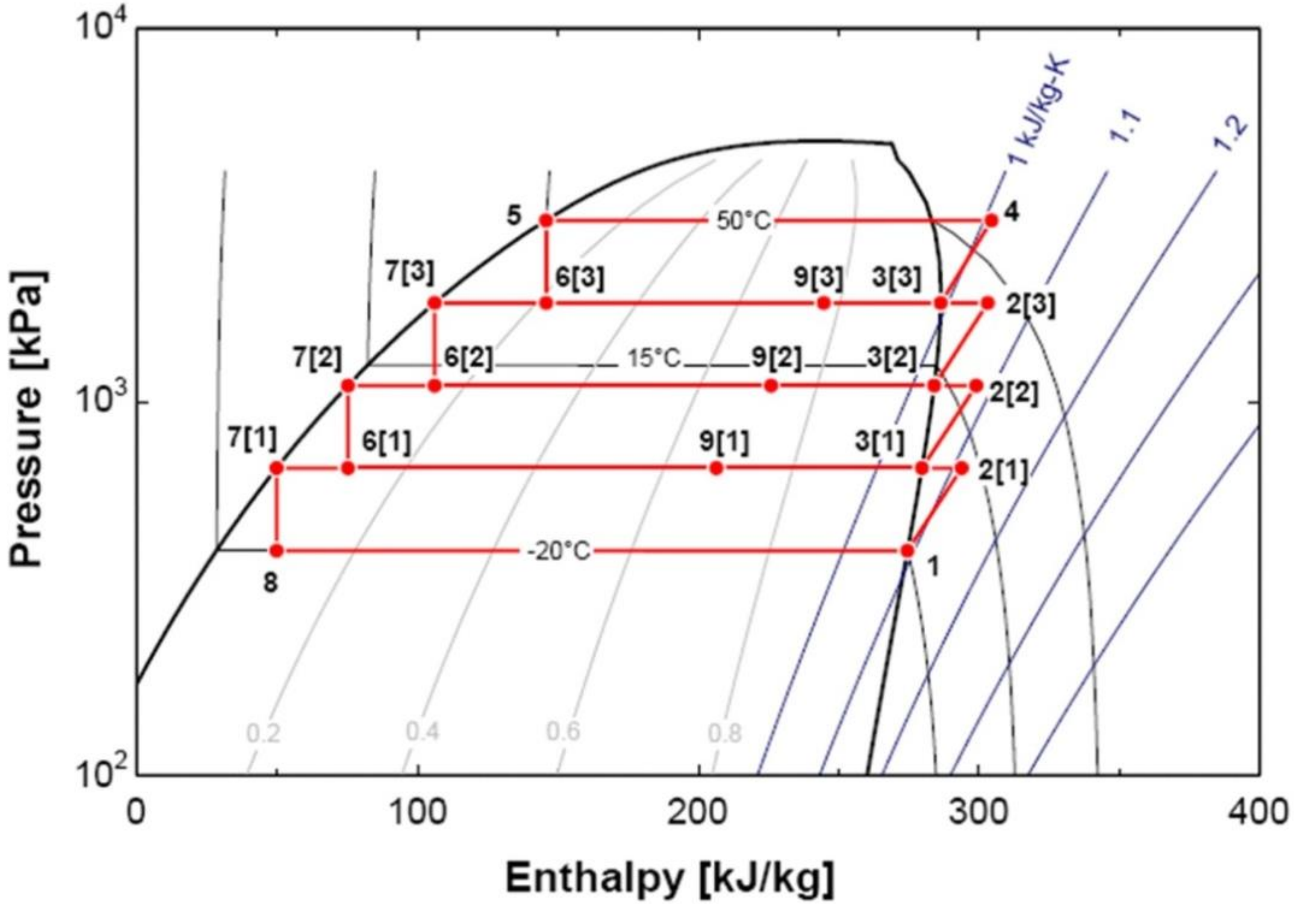
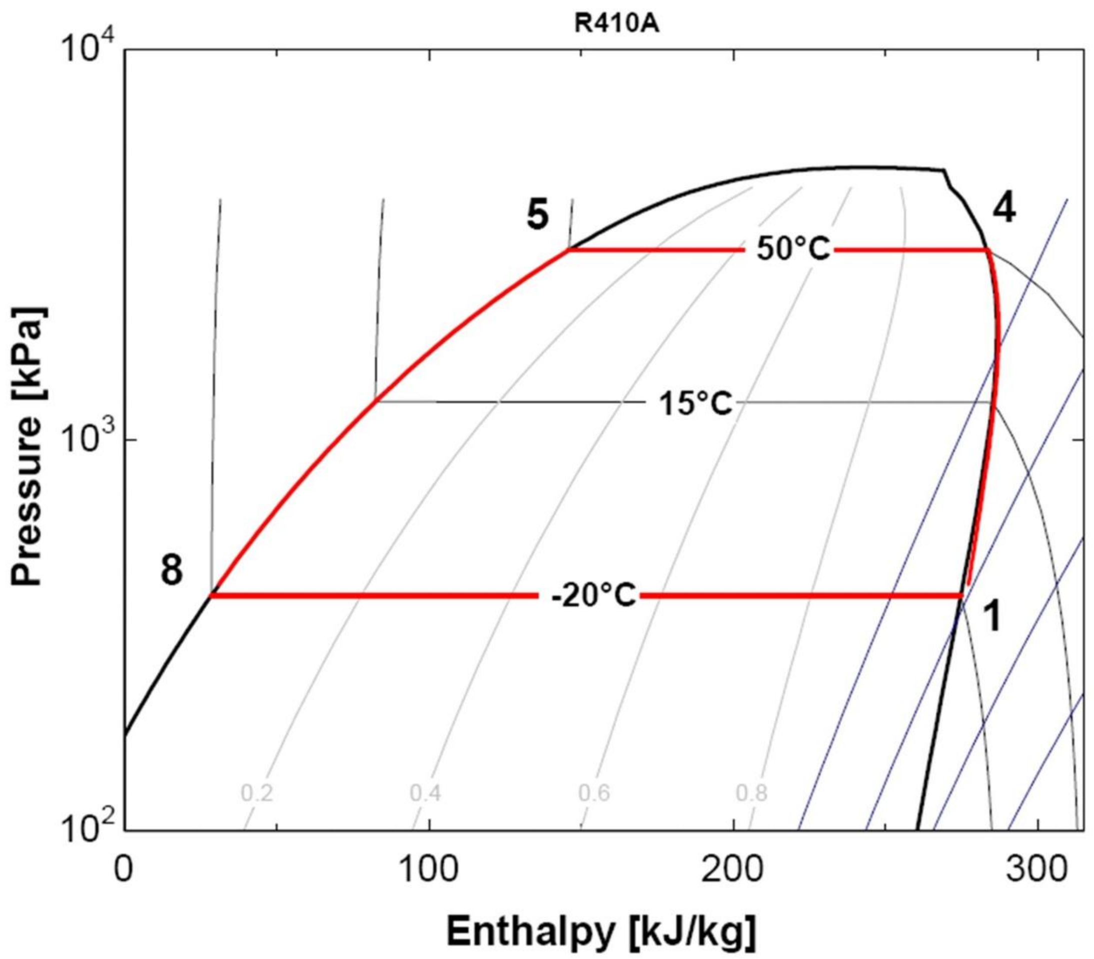
Vapor Injection with Economizing (cont'd)





R-410A vapor compression cycle with three injection ports (Mathison 2008)

In Search of Carnot Efficiency
Vapor Injection with Economizing (cont'd)



R-410A vapor compression cycle with continuous injection (Mathison 2008)

Outline

In Search of Carnot Efficiency

Liquid Flooding with Regeneration

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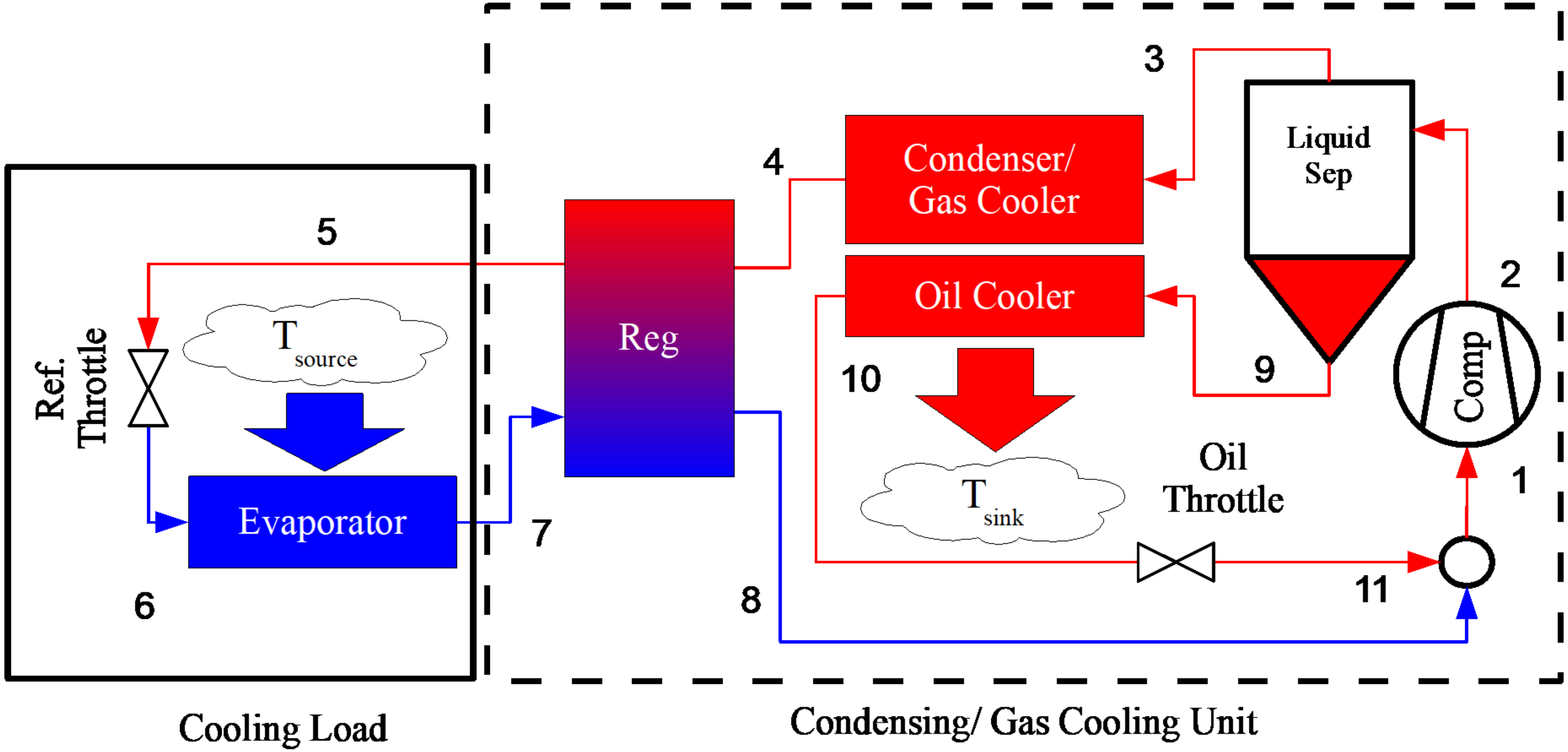
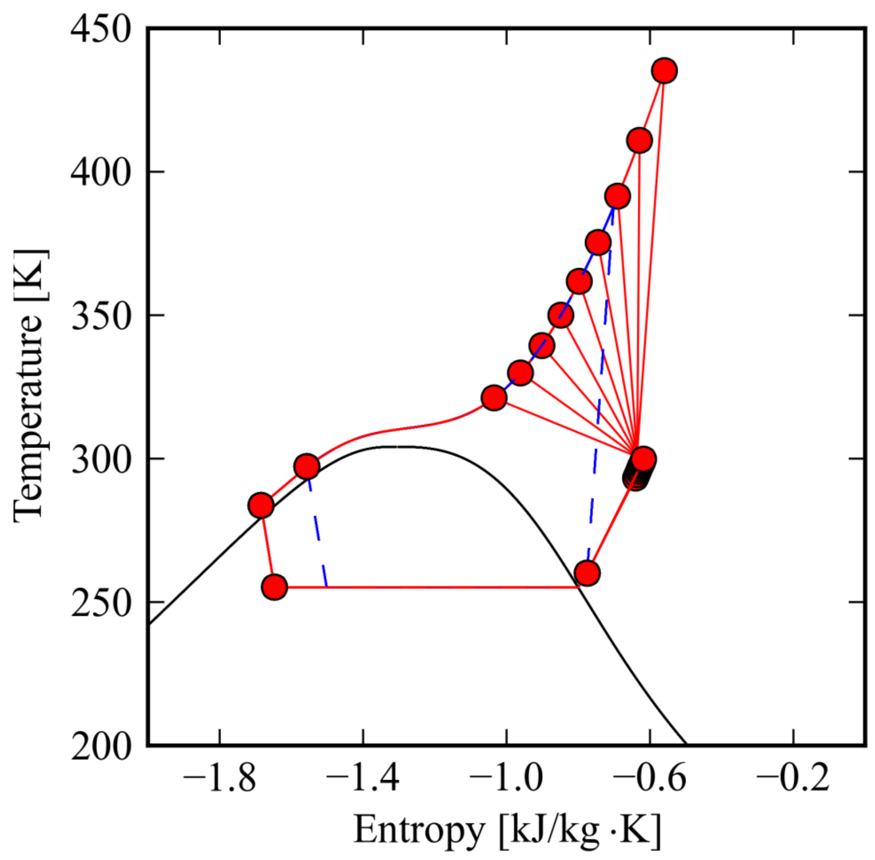
Liquid Flooding with Regeneration



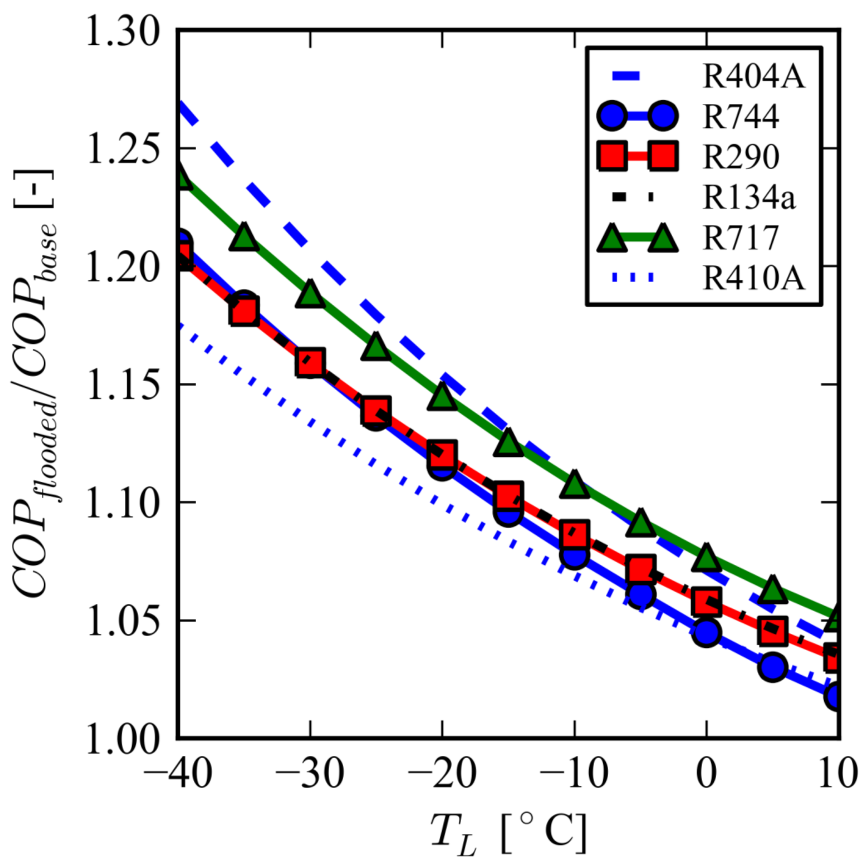
Cycle Schematic of Liquid Flooded Compression with Regeneration (Bell 2011)

In Search of Carnot Efficiency
Liquid Flooding with Regeneration (cont'd)

Cycles in T-s Diagram



Modeling Results



Bell, I.H., Groll, E.A., and Braun, J.E., "Performance of Vapor Compression Systems with Compressor Oil Flooding and Regeneration," Int'l J. Refrigeration, Vol. 34, No. 1, 2011, pp. 225-233.

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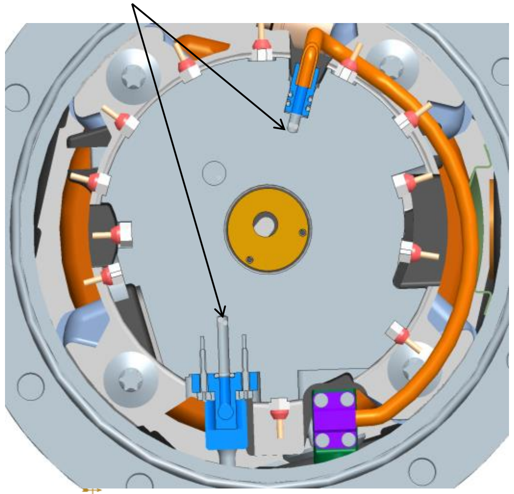
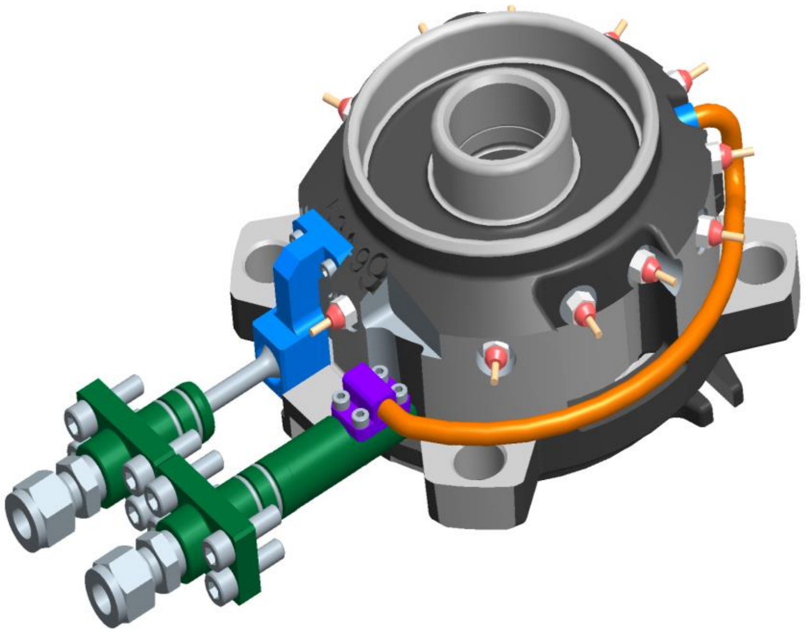
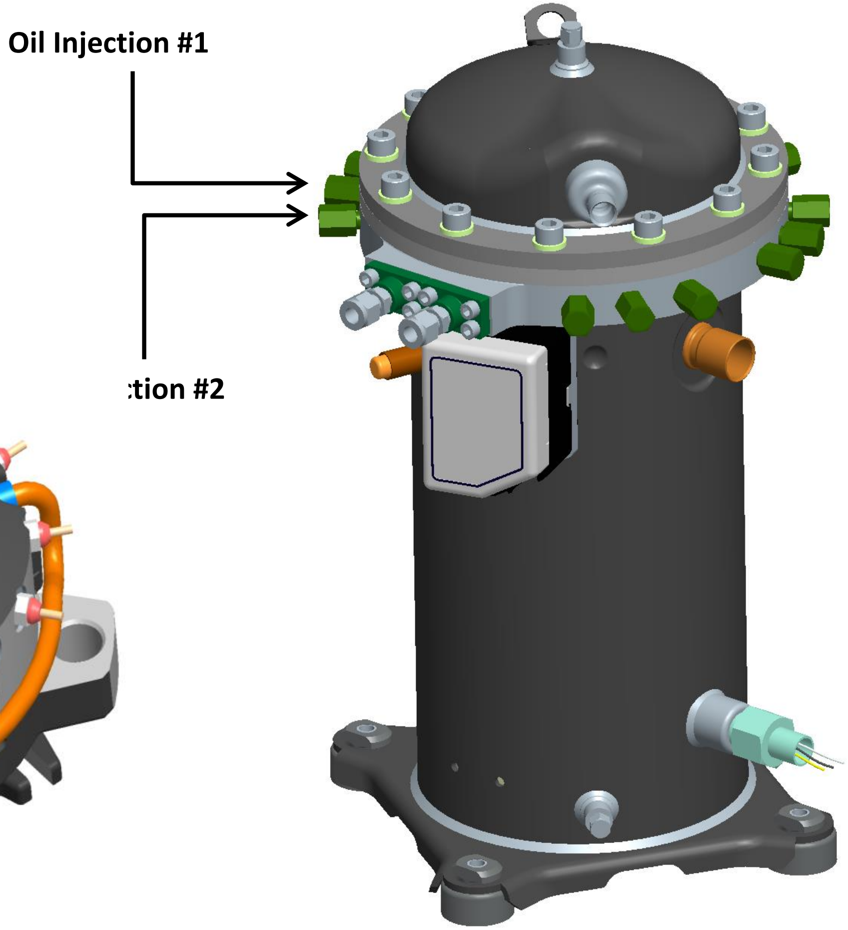
Liquid Flooding with Regeneration (cont'd)

- Oil Flooded R410A Scroll Compressor
  - Running gear modifications for R410A and flooding
  - Shaft and rotor modifications for better compressor balance
  - 4 inch^3 suction volume
  - 3.29 volume ratio

Location of Oil Injection Ports







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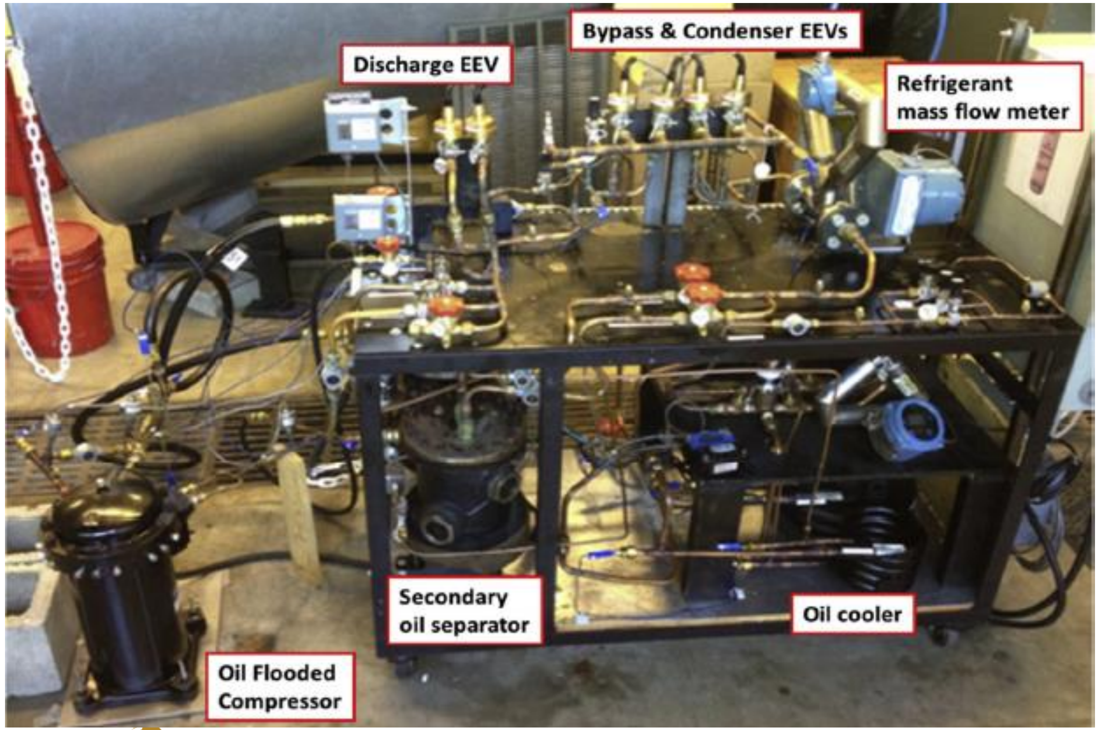
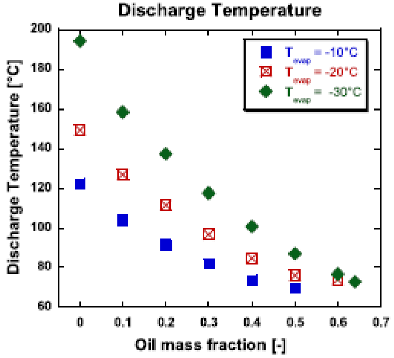
In Search of Carnot Efficiency

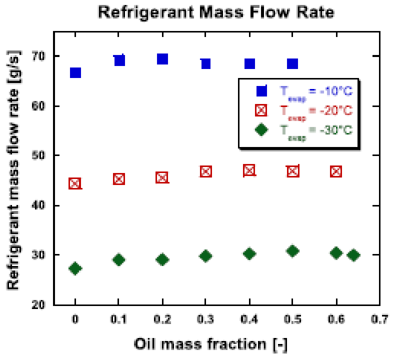
Liquid Flooding with Regeneration (cont'd)

- Cold-climate heat pump with oil-flooded compression (Sugirdhalakshmi et al. 2014)
  - R-410A
  - ISO 32 POE
  - T_{cd} = 43.3 °C; varied T_{ev}

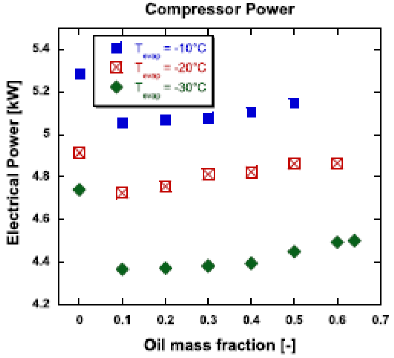




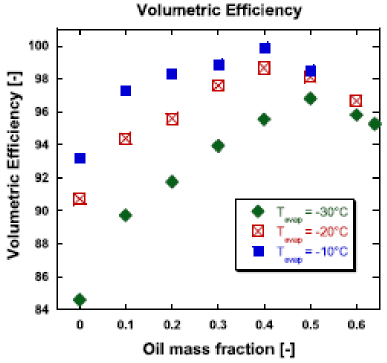
(a) Effect of oil injection on discharge temperature.



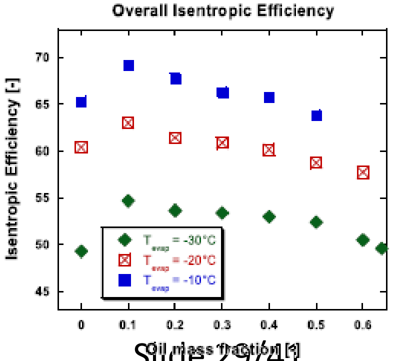
(b) Effect of oil injection on refrigerant mass flow rate.



(c) Effect of oil injection on electrical power consumption.



(d) Effect of oil injection on volumetric efficiency.



(e) Effect of oil injection on isentropic efficiency.

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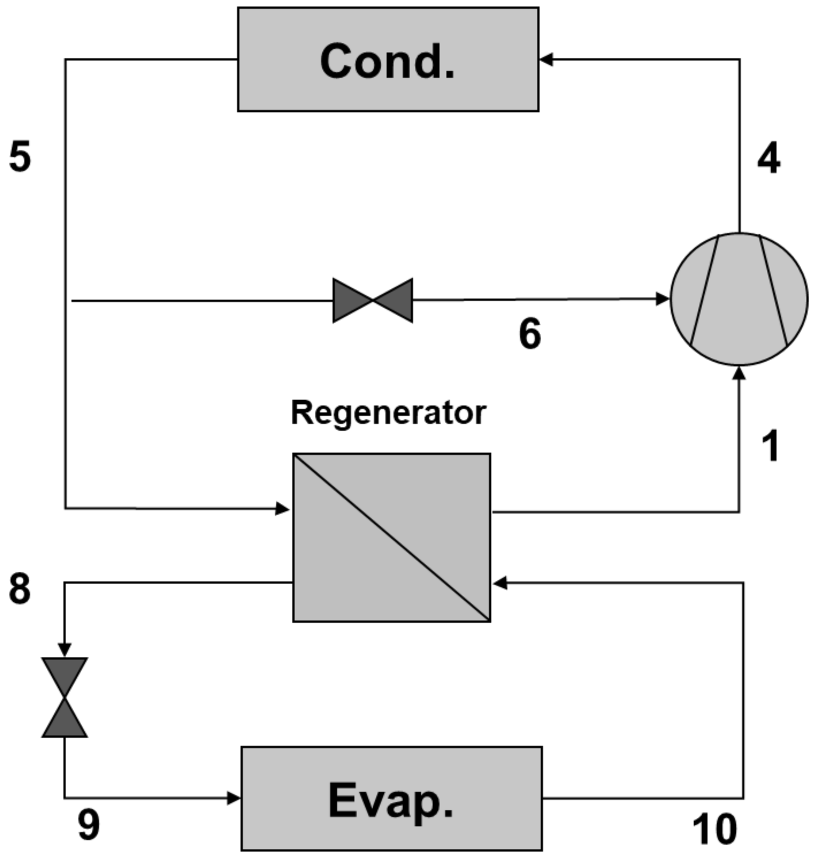
Outline

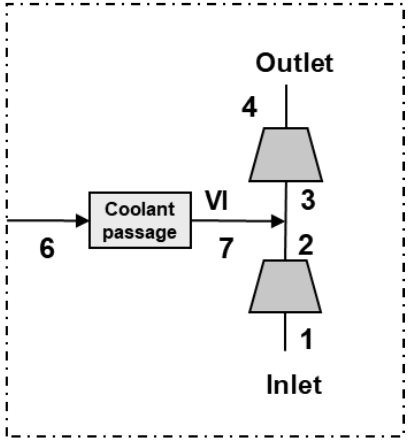
In Search of Carnot Efficiency

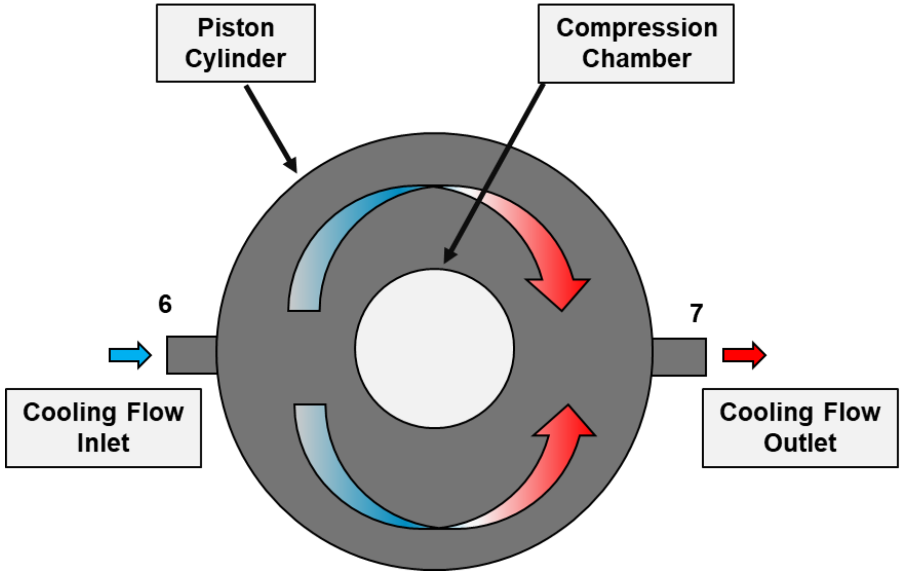
Cylinder Cooling with Regeneration

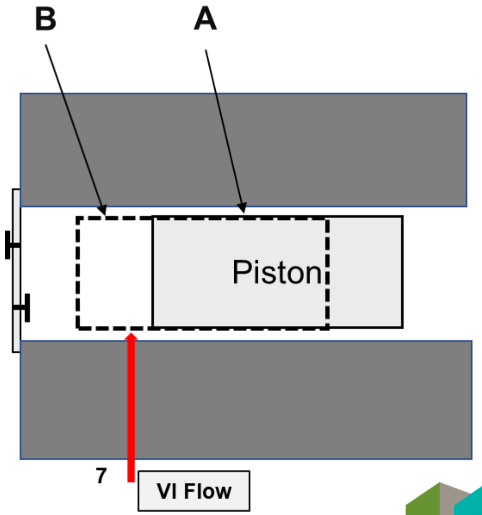
In Search of Carnot Efficiency

Cylinder Cooling with Regeneration



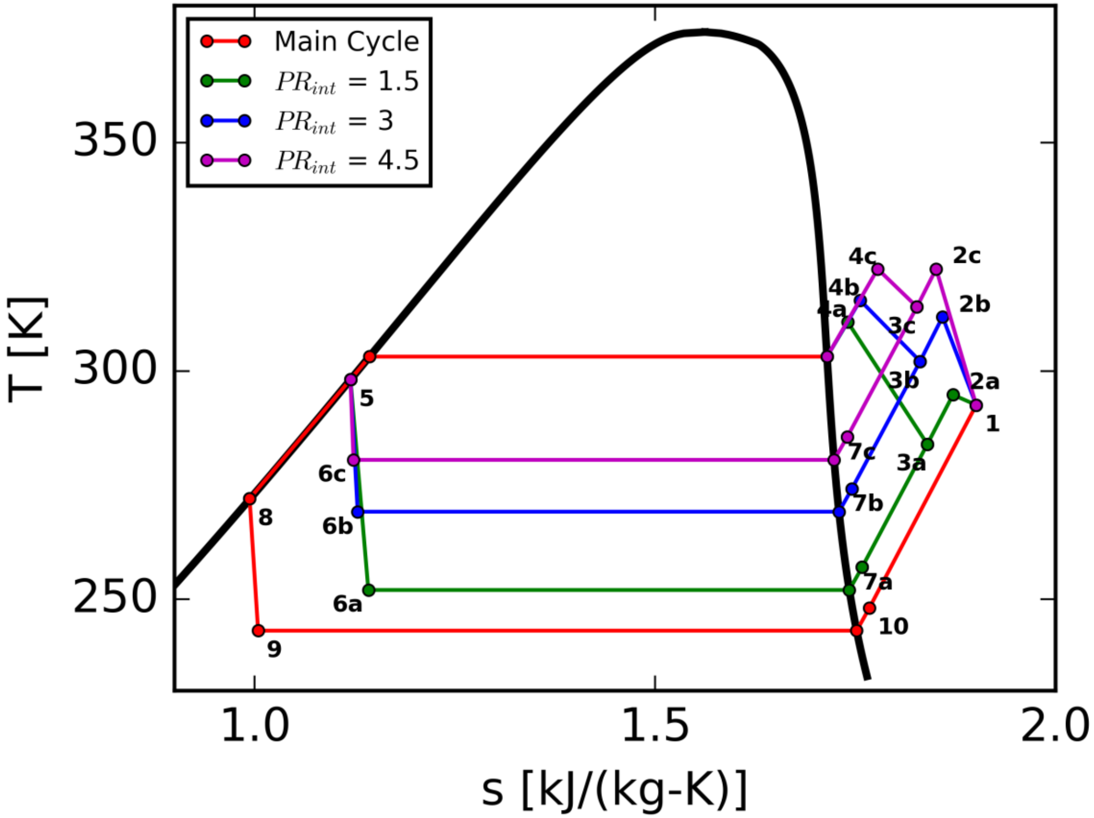




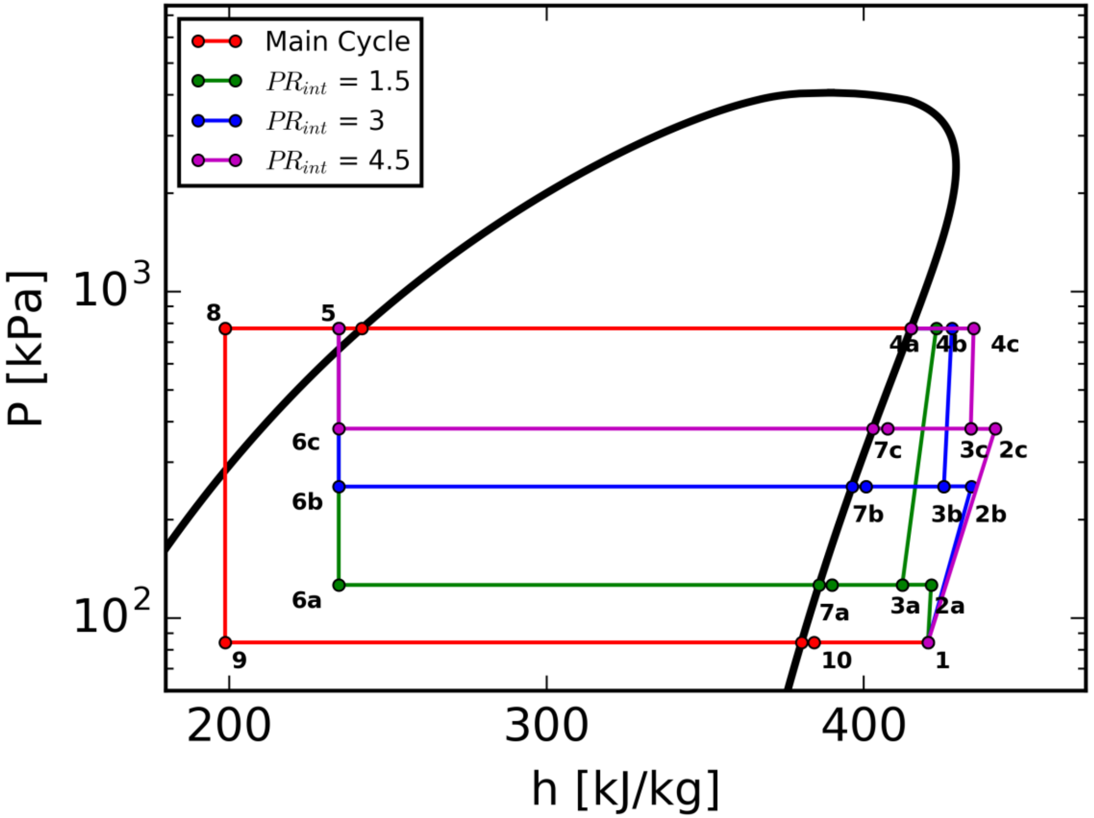


In Search of Carnot Efficiency
Cylinder Cooling with Regeneration (cont'd)

Cycles in T-s Diagram



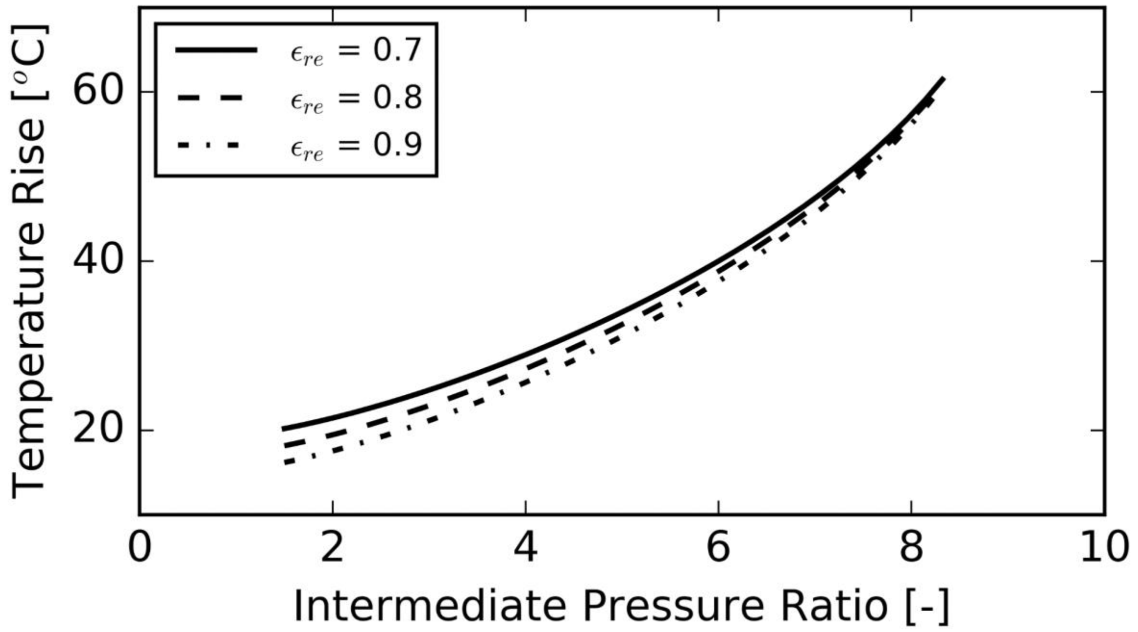
Cycles in p-h Diagram



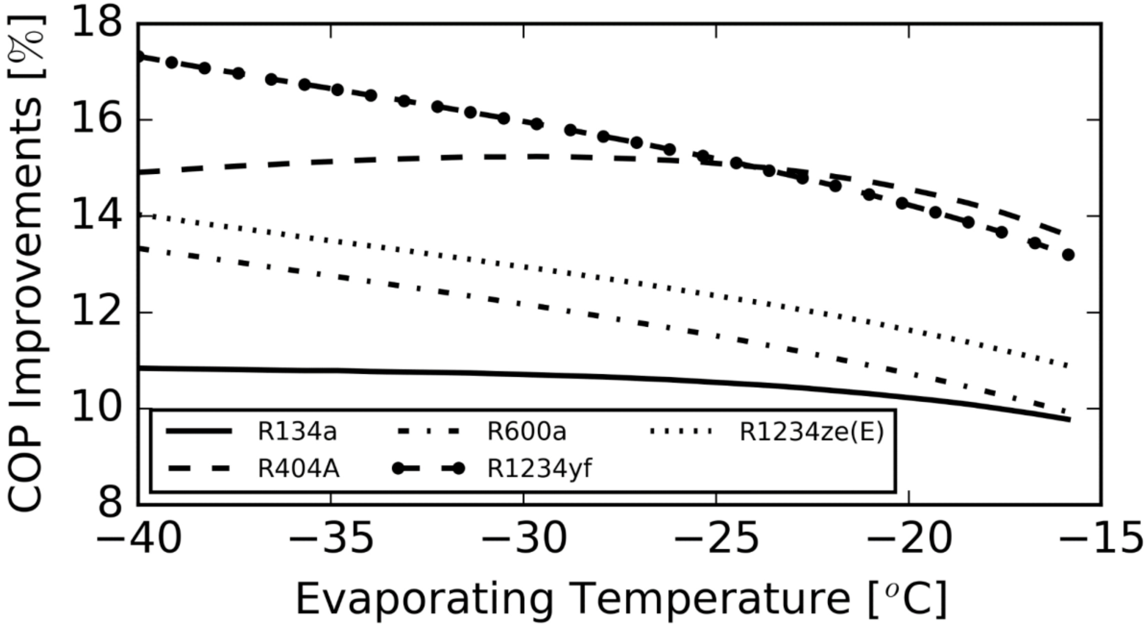
Variation of intermediate pressure

In Search of Carnot Efficiency
Cylinder Cooling with Regeneration (cont'd)

Compressor temperature rise
versus intermediate pressure ratio
for different regenerator efficiencies



COP improvements compared to
conventional vapor compression cycle
as a function of evaporating temperature

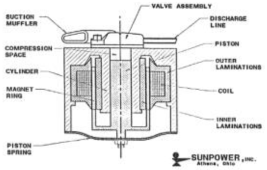


In Search of Carnot Efficiency

Cylinder Cooling with Regeneration (cont'd)

1950

Linear compressor was invented in Europe and Japan. (Dolz,1954)

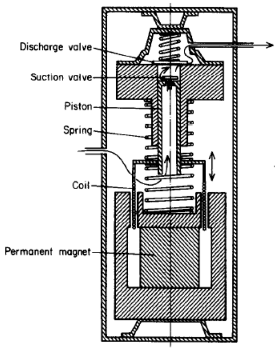


1980

First mathematical model of a linear compressor. (Pollak et al. 1979)

1992 – **2000**

Simulation model and several prototypes were developed by SunPower Inc. (Van at al. 1998)



2002

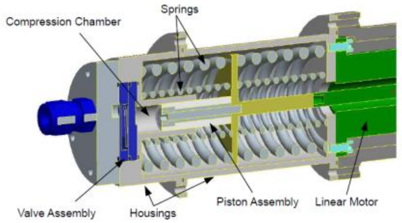
LG Inc. patented and commercialized several versions of linear compressors

2008

Wisemotion compressor technology was developed by Embraco

2012

Bradshaw built a prototype linear compressor and developed a simulation model. (Bradshaw, 2012)



2013

The university of Oxford built one linear compressor with new magnetic motor. (Liang at al. 2013)

2019

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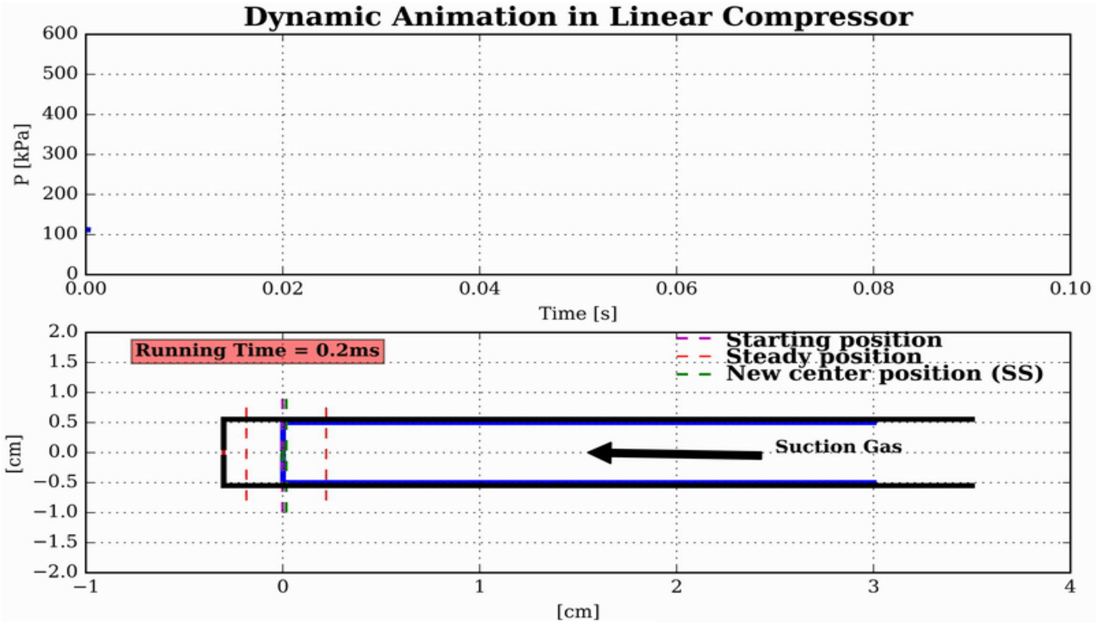
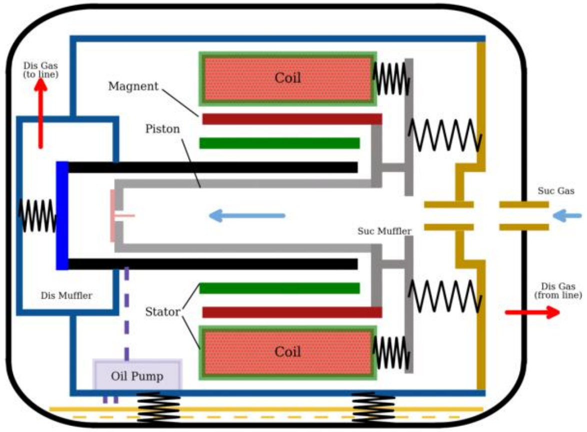
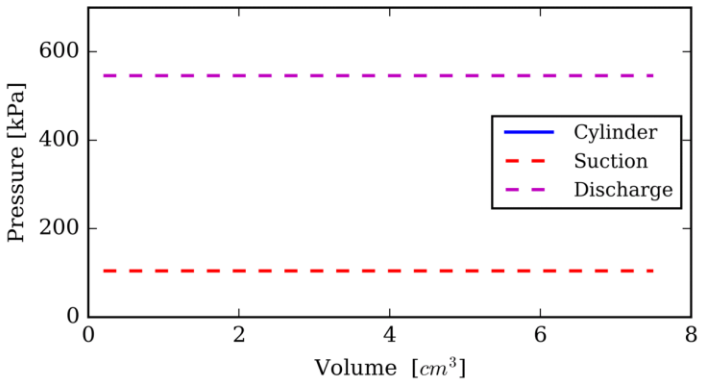
In Search of Carnot Efficiency
Cylinder Cooling with Regeneration (cont'd)

Transient



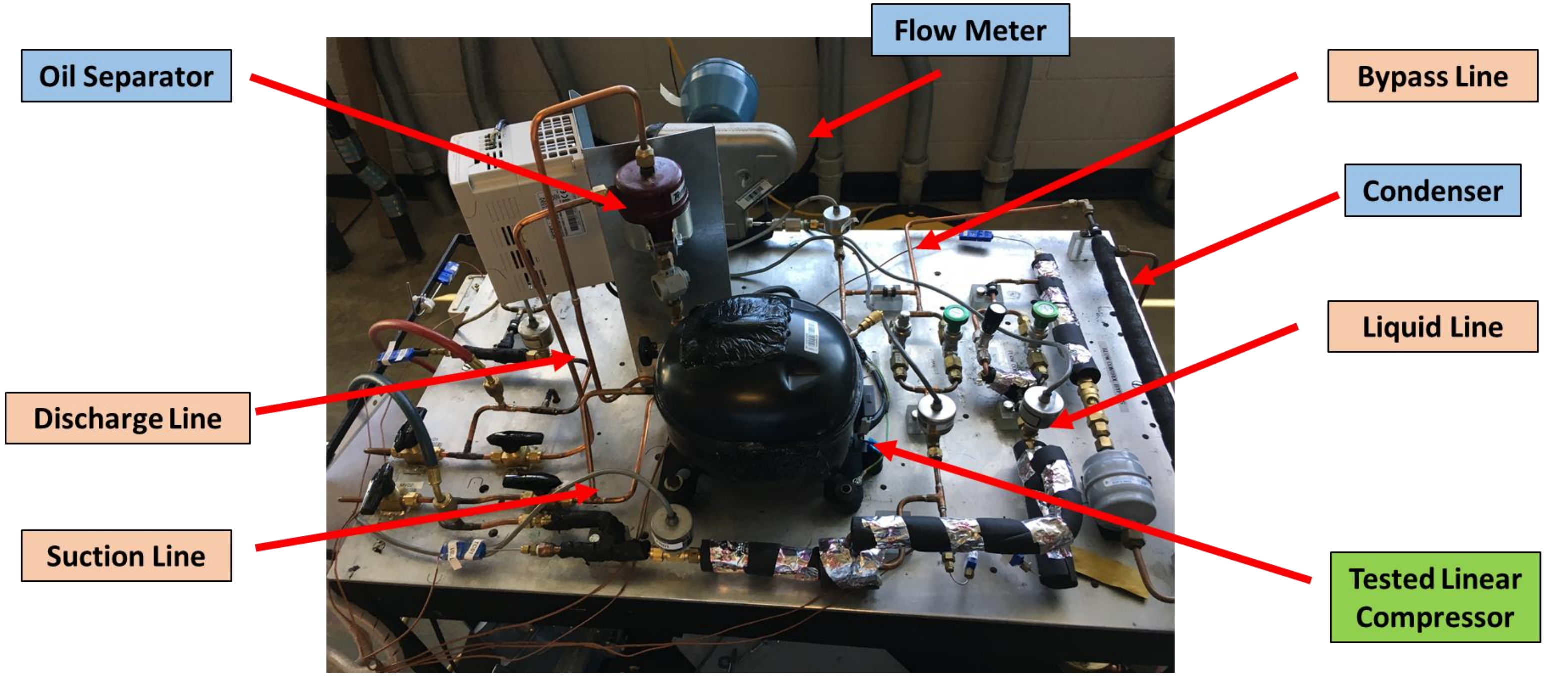
Periodic steady-state

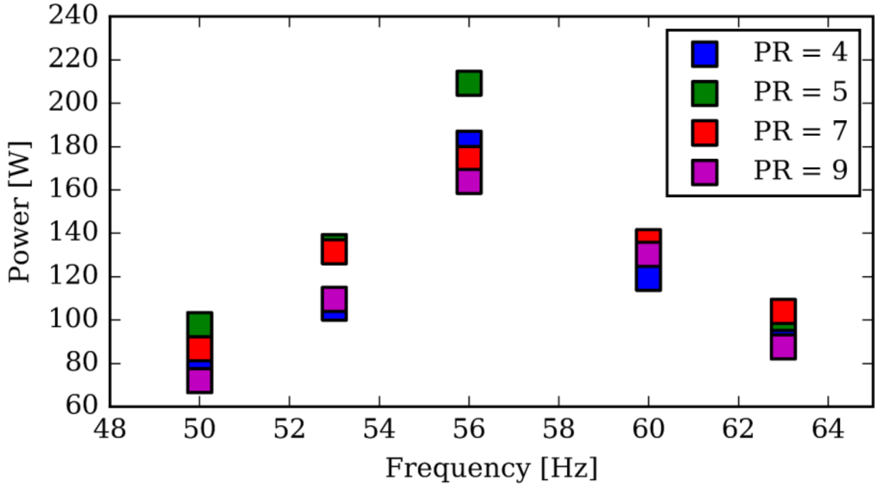


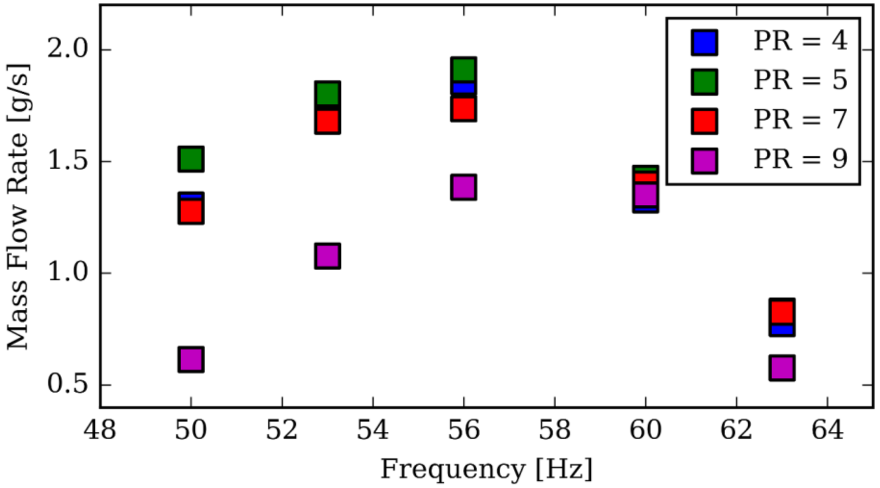


In Search of Carnot Efficiency
Cylinder Cooling with Regeneration (cont'd)

- Conducted testing of two commercially available linear compressors:
  - Refrigerator-freezer applications (cooling capacity ~200 W)
  - Embraco and LG
  - Refrigerant R134a

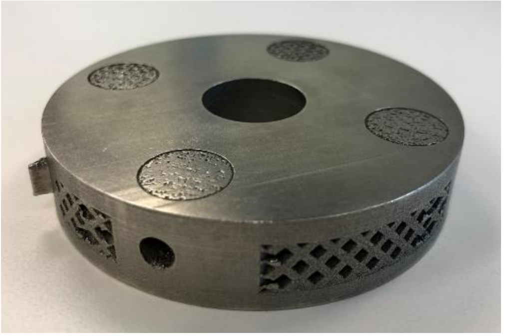


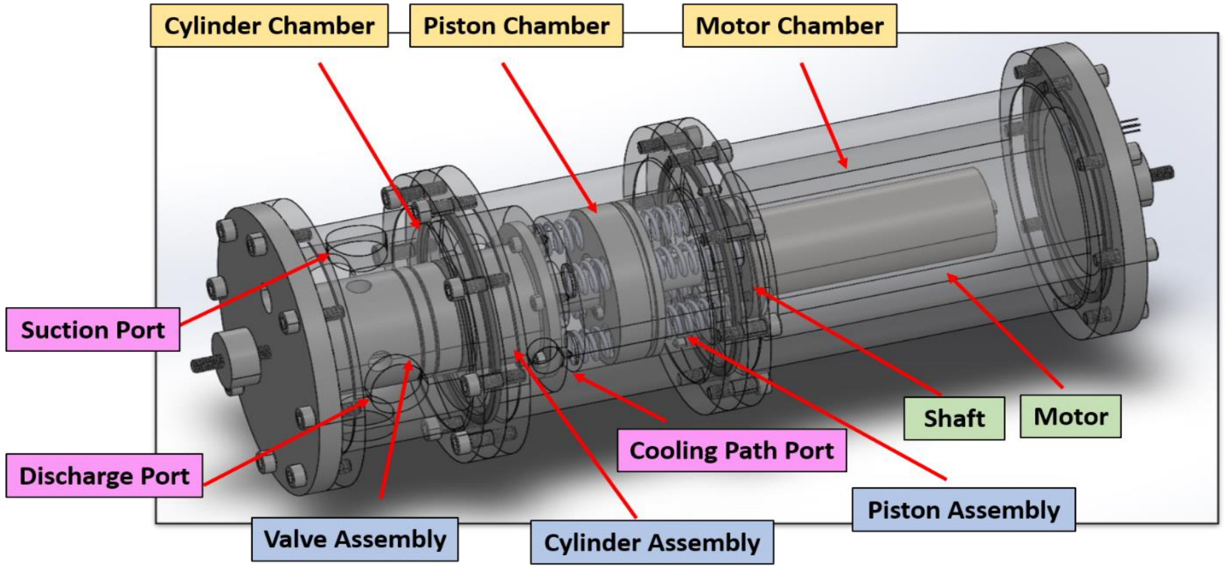




In Search of Carnot Efficiency
Cylinder Cooling with Regeneration (cont'd)

- Linear compressor research focuses on
  - Scaling to larger capacities
  - Using 3D metal printing capabilities to include internal cooling channels





- The same concept is being investigated for twin-screw compressors by 3D metal printing of the rotors and housing

Summary and Perspectives

- Research efforts related to vapor compression systems for the HVAC&R industry has rapidly increased over the last years
  - Phase-out and down of refrigerant
  - Recent advances in compressor and other vapor compression component technologies and control strategies
- An overview of several research topics concerning novel compression concepts and unique cycle integration have been introduced
  - The aim is to move system performance closer to Carnot efficiency
- Novel manufacturing techniques and computational resources will enable next generation of vapor compression cycles
  - Scientific breakthroughs could lead to non-vapor compression technologies

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December 16, 2019	Abstract Submission Deadline
January 27, 2020	Abstract Acceptance Notification
April 6, 2020	Manuscript Submission Deadline
May 4, 2020	Manuscript Acceptance Notification
May 25, 2020	Pre-Registration ends; Final Papers must be uploaded to Conftool

Visit **www.conftool.com/Purdue2020** to learn more about the submission process and requirements.

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Thank you!
Any Questions?