Improving Vapor Compression System Efficiency through Advanced Vapor Compression Technologies

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• 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)

(TOTAL: 21.36 Quads/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
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Irreversibilities in a Vapor Compression Cycle

- Carnot Cycle vs Real Cycle with Irreversibilities

\[ T_H \quad 3 \quad q_H \quad 2 \]
\[ T_L \quad 4 \quad q_L \quad 1 \]
\[ S_3 = S_4 \quad S_1 = S_2 \]

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
Outline

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Suction-to-Liquid Line Heat Exchange
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Suction-to-Liquid Line Heat Exchange

\[ \dot{Q}_{\text{cond}} \]

\[ \dot{Q}_{\text{evap}} \]
Effect on cooling capacity?

1.) Increases superheat $\rightarrow$ increases specific volume at state 1
   $\rightarrow$ reduces mass flow rate $\rightarrow$ decreases cooling capacity
2.) Increases subcooling $\rightarrow$ decreases enthalpy at state 4
   $\rightarrow$ increases $\Delta h$ across evaporator $\rightarrow$ increases cooling capacity

$\Rightarrow$ net result depends on refrigerant characteristics
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Suction-to-Liquid Line Heat Exchange (cont’d)

- Effect on COP?
  1.) Increases superheat $\rightarrow$ increases $\Delta h$ across compressor
  2.) Increases subcooling $\rightarrow$ increases $\Delta h$ across evaporator
  $\Rightarrow$ net result depends on refrigerant characteristics

![Graphs showing comparison between R22 and R134a with different pressure characteristics](image-url)
Outline

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Multi-Stage Compression with Intercooling
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Multi-Stage Compression with Intercooling

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• 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)

• Example of two-stage hermetic rolling piston compressor with intercooling (Mathison et al., 2008)
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Multi-Stage Compression with Intercooling (cont’d)
In Search of Carnot Efficiency
Multi-Stage Compression with Intercooling (cont’d)

![Diagram of a refrigeration cycle with intercooling and multi-stage compression. The diagram includes symbols for evaporator, gas cooler & intercooler, expansion valve, and compressors. The enthalpy-pressure diagram for carbon dioxide is also shown, with isotherms and isentropes for various temperatures.]
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Vapor Injection with Economizing
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Vapor Injection with Economizing

\[ \dot{Q}_{\text{cond}} \]

\[ \dot{Q}_{\text{evap}} \]

\[ W_{c,1} \]

\[ W_{c,2} \]

Condenser
Economizer
Evaporator
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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
- $p_{\text{evap}} = 244.5$ kPa (−20 C), $p_{\text{cond}} = 1476.7$ kPa (43.3 C), $\Delta T_{sh} = 11.1$ K
- ECU for cooling application in cold climates (Bahman et al. 2018)
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Vapor Injection with Economizing (cont’d)

- Hermetic scroll compressor for cold-climate heat pump (Bell et al. 2013)
R-410A vapor compression cycle with three injection ports (Mathison 2008)
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Vapor Injection with Economizing (cont’d)

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

Cycle Schematic of Liquid Flooded Compression with Regeneration (Bell 2011)
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Liquid Flooding with Regeneration (cont’d)

Cycles in T-s Diagram

Modeling Results

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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
Cold-climate heat pump with oil-flooded compression (Sugirdhalakshmi et al. 2014)

- R-410A
- ISO 32 POE
- $T_{cd} = 43.3 \, ^\circ\text{C}$; varied $T_{ev}$
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Cylinder Cooling with Regeneration
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Cylinder Cooling with Regeneration

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Cylinder Cooling with Regeneration (cont’d)

Cycles in T-s Diagram

Cycles in p-h Diagram

Variation of intermediate pressure

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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
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Cylinder Cooling with Regeneration (cont’d)

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

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

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

LG Inc. patented and commercialized several versions of linear compressors

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

Wisemotion compressor technology was developed by Embraco

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

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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
• 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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