Cold Climate Heat Pump Research at the Ray W. Herrick Labs

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Cold Climate Heat Pump

April 1, 2010 – March 30, 2012

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RAs: Stephen Caskey and Derek Kultgen

Sponsor:	Department of Defense ESTCP
Subcontractor:	Prof. Stefan Bertsch, NTB Buchs, Switzerland
Partners:	Emerson Climate Technologies
	Ingersoll Rand – The Trane Company
	Danfoss

Outline

- Introduction
- System Design
- Modeling
- Simulation Results
- Conclusions

Introduction

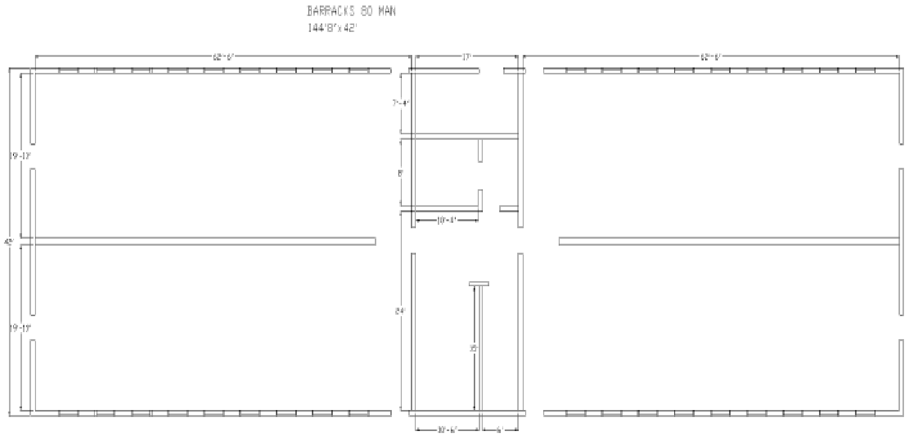
- Motivation
  - » Buildings consume 40% of the primary energy used in the U.S. [1]
  - » Energy Security Initiatives 2010 [2]
    - – Department of Defense mandate for all installations reducing energy consumption 3% per year through 2015
  - » Heat pumps for residences and small commercial buildings reach higher efficiencies
  - » Air-source heat pumps offer lower costs when compared to ground-source heat pumps

Introduction

- Objectives
  - » Demonstrate new air-source heat pump optimized for colder climates
    - – Compare alongside forced-air natural gas furnace and split air conditioning system
  - » Reduce primary energy use by 25%
  - » Reduce CO_2 emissions by 15%
  - » Current HVAC technicians able to install and operate system
    - – Incorporates off-the-shelf components

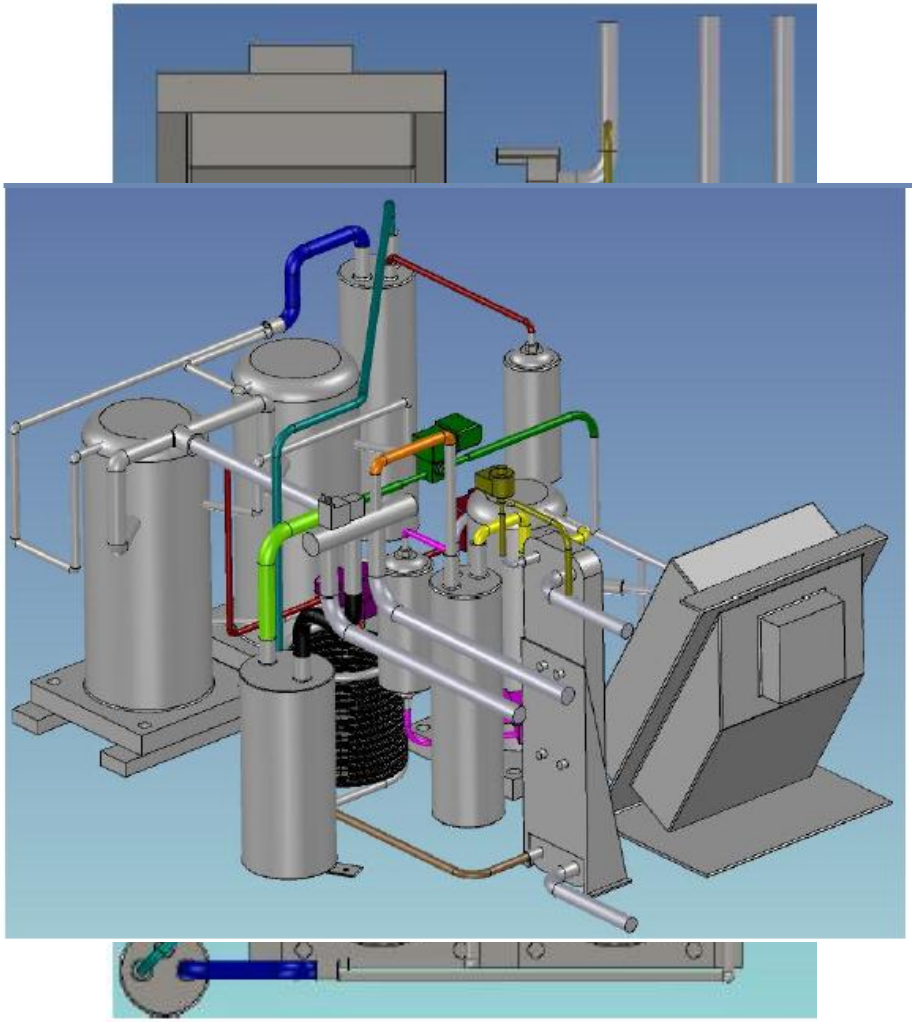
Introduction

- Field Demonstration
  - » Camp Atterbury, Indiana
  - » Staging ground for troop mobilization
  - » Two Military Barracks Buildings
  - » One HVAC systems per half: 244 m^2 (2,626 ft^2)
  - » ~80 person per building
  - » Two identical heat pumps
  - » One heating season

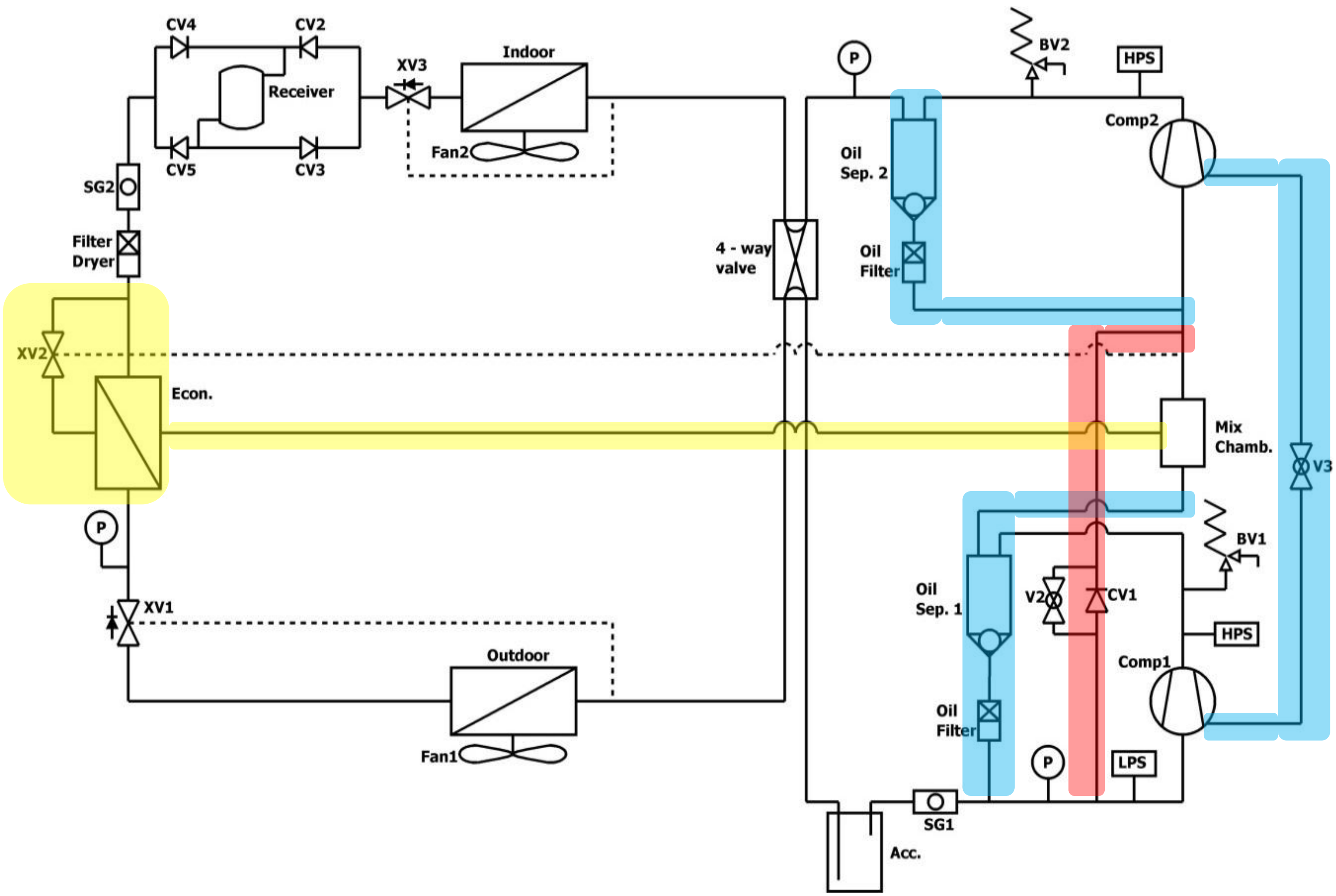


System Design

- Air-source heat pump
  - » R-410A refrigerant
  - » Two-stage compression
  - » Economizing
  - » Low-side compressor bypass
  - » Oil management system



System Design



System Design

- Oil management system
  - » Required due to series compressor operation
  - » Oil separators located after each compressor
    - – Allow for active oil return during two-phase mode
    - – Ensures adequate oil levels
  - » Equalization line
    - – Valve opens during shutdown connecting oil sumps of both compressors
    - – Compressors must be placed at equal vertical position
  - » Need to be robust due to demonstration conditions
    - – Remote site

System Design

- Outdoor expansion valve
  - » Danfoss EcoFlow expansion valve
  - » Distributor integrated
  - » Actively regulates and changes flow rate of each circuit
  - » One superheat sensor
  - » Silent defrost
    - – Cycles through each circuit
    - – Increase overall system performance

System Design

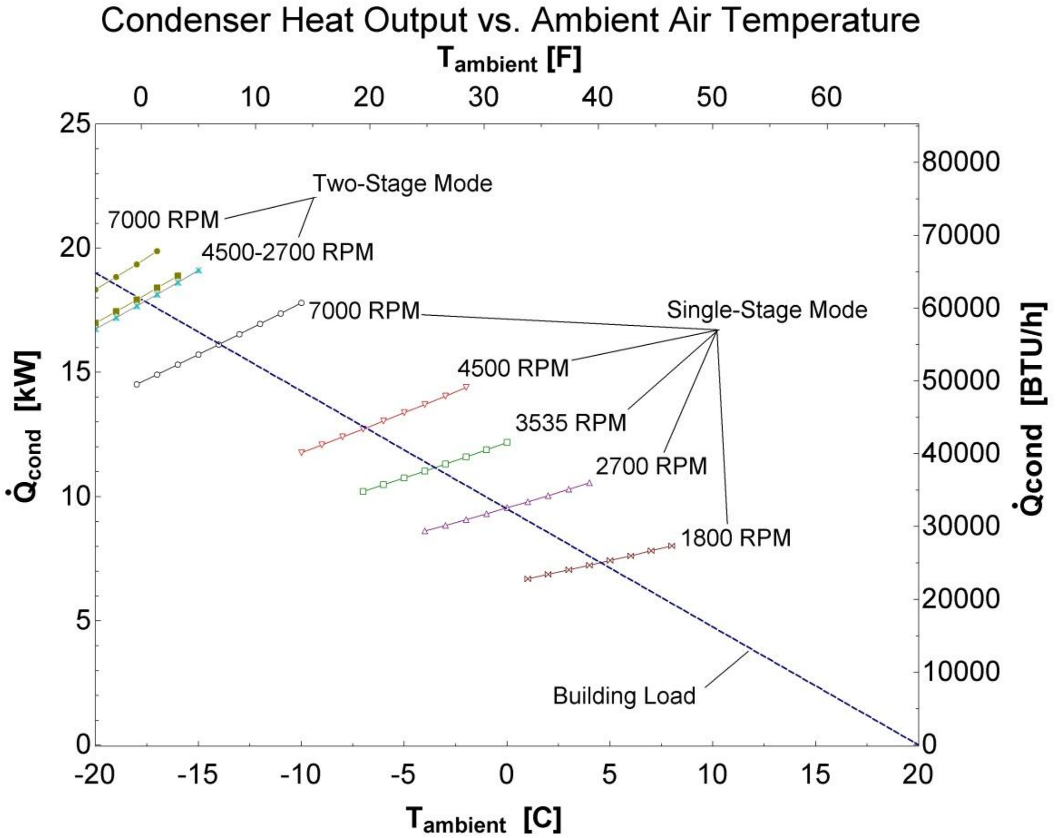
- eQUEST model
  - Provide maximum heating load
  - Heating set point 20 ^{0}C (68 ^{0}F)
  - 19 kW (64.8 kBTU/hr) at -20 ^{0}C (-4 ^{0}F)
- Compressor Configuration
  - Low side – Tandem Scroll Compressor
    - Rated displacement:102.3 cm^3/rev (6.24 in^3/rev)
  - High side – Variable Speed, Scroll Compressor
    - Estimated displacement: 36 cm^3/rev (2.2 in^3/rev)
    - 1800 RPM – 7000 RPM
- 17.5 kW (5 ton) packaged heat pump unit

Modeling

- Conventional HVAC System
  - » Natural gas furnace – 85% AFUE rating
  - » Yearly electric consumption – 200 kWh
- Electricity production from natural gas
  - » 1 kWh of electricity from 2.627 kWh natural gas
- Energy rates
  - » $0.1151/kWh – electricity
  - » $10.42/1000 ft^3 – natural gas

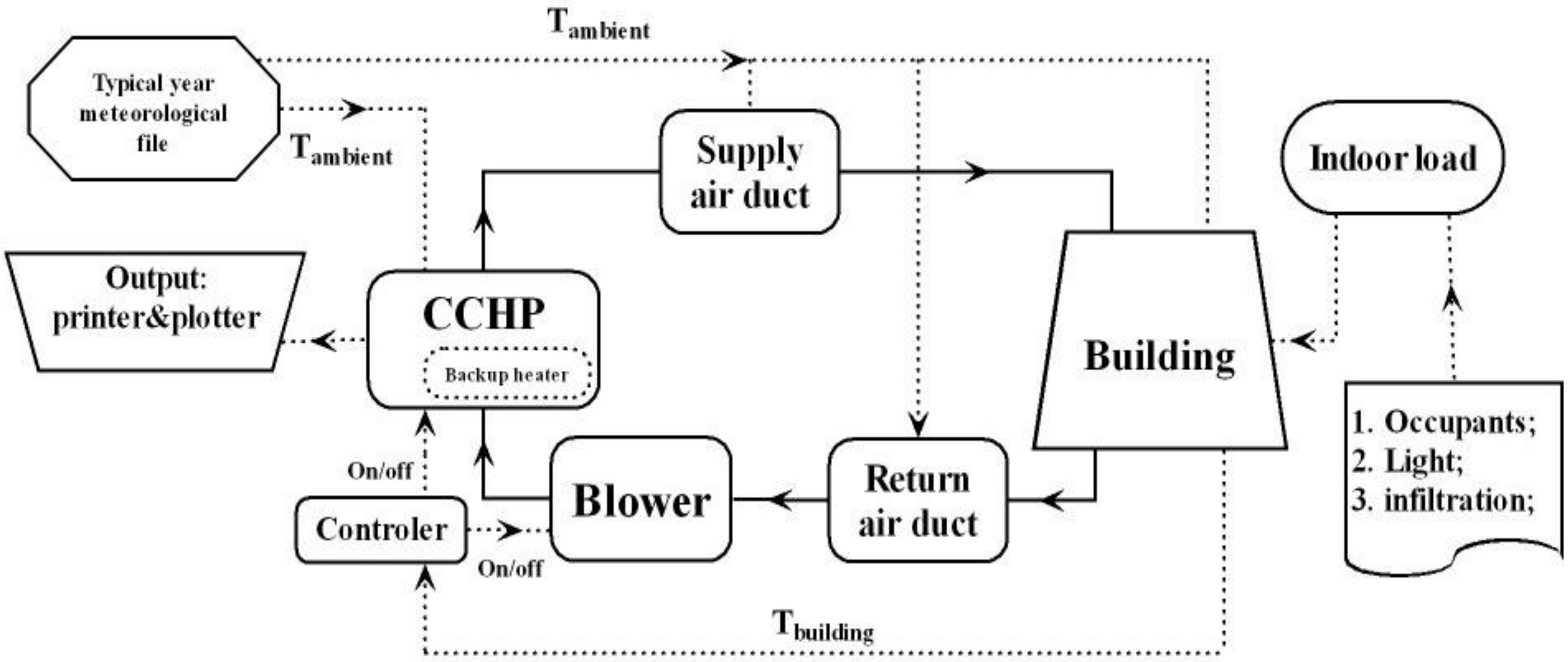
Modeling

- Variable speed compressor
  - » 5 compressor maps
  - » Need heat output at other speeds
  - » Linear interpolation
  - » Better prediction of real operation



Modeling

TRNSYS Model



Modeling

- Lighting
  - » 16 fluorescent lights
  - » 2.15 W/m^2 (0.68243 BTU/hr – ft^2)
- Infiltration and Occupants
  - » eQUEST
  - » Schedule assuming space as hotel use
  - » Four different cases
  - » Infiltration rate 0.4426 m^3/hr-m^2 (0.0242 CFM/ft^2)
  - » 40 persons

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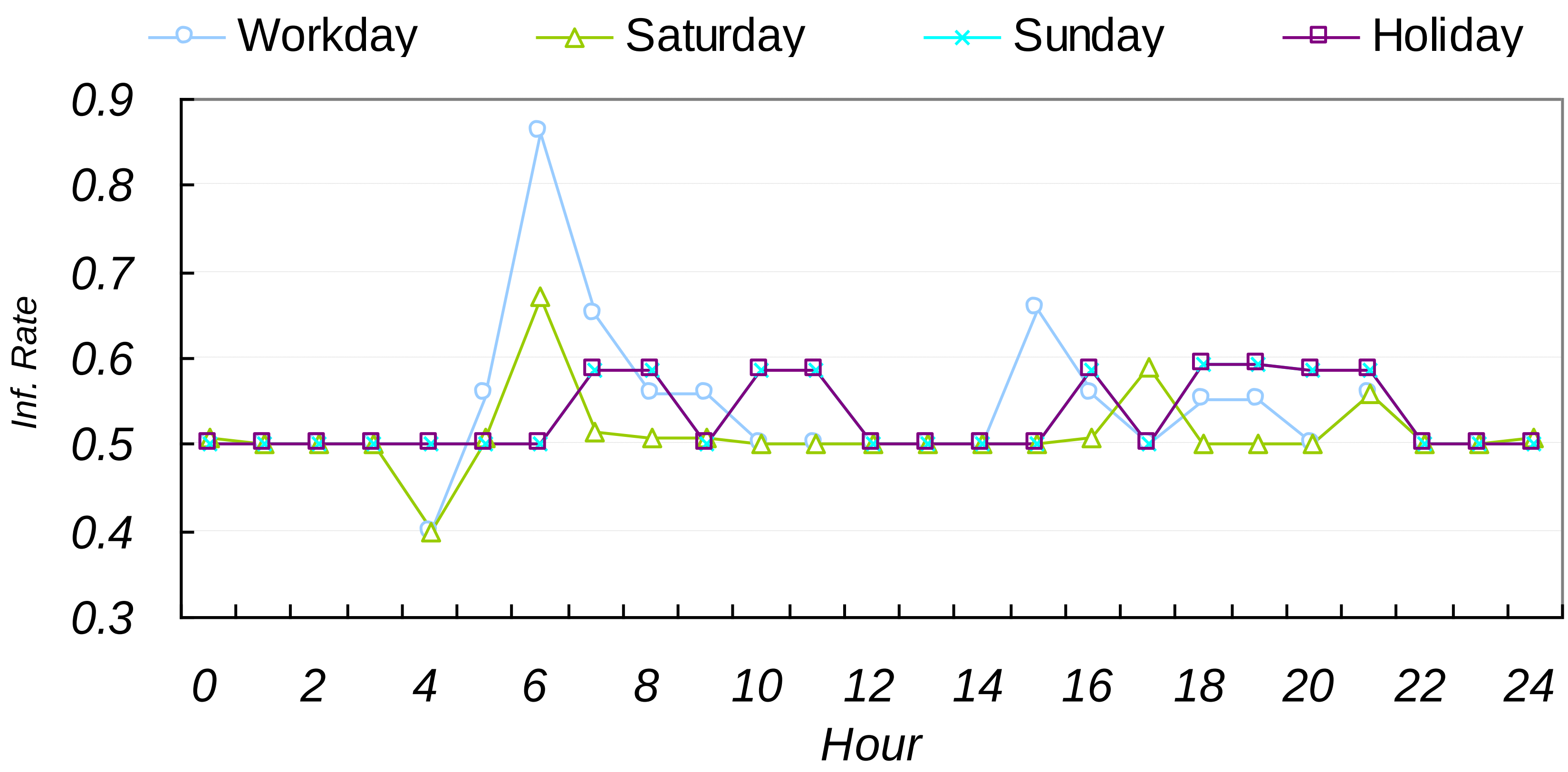
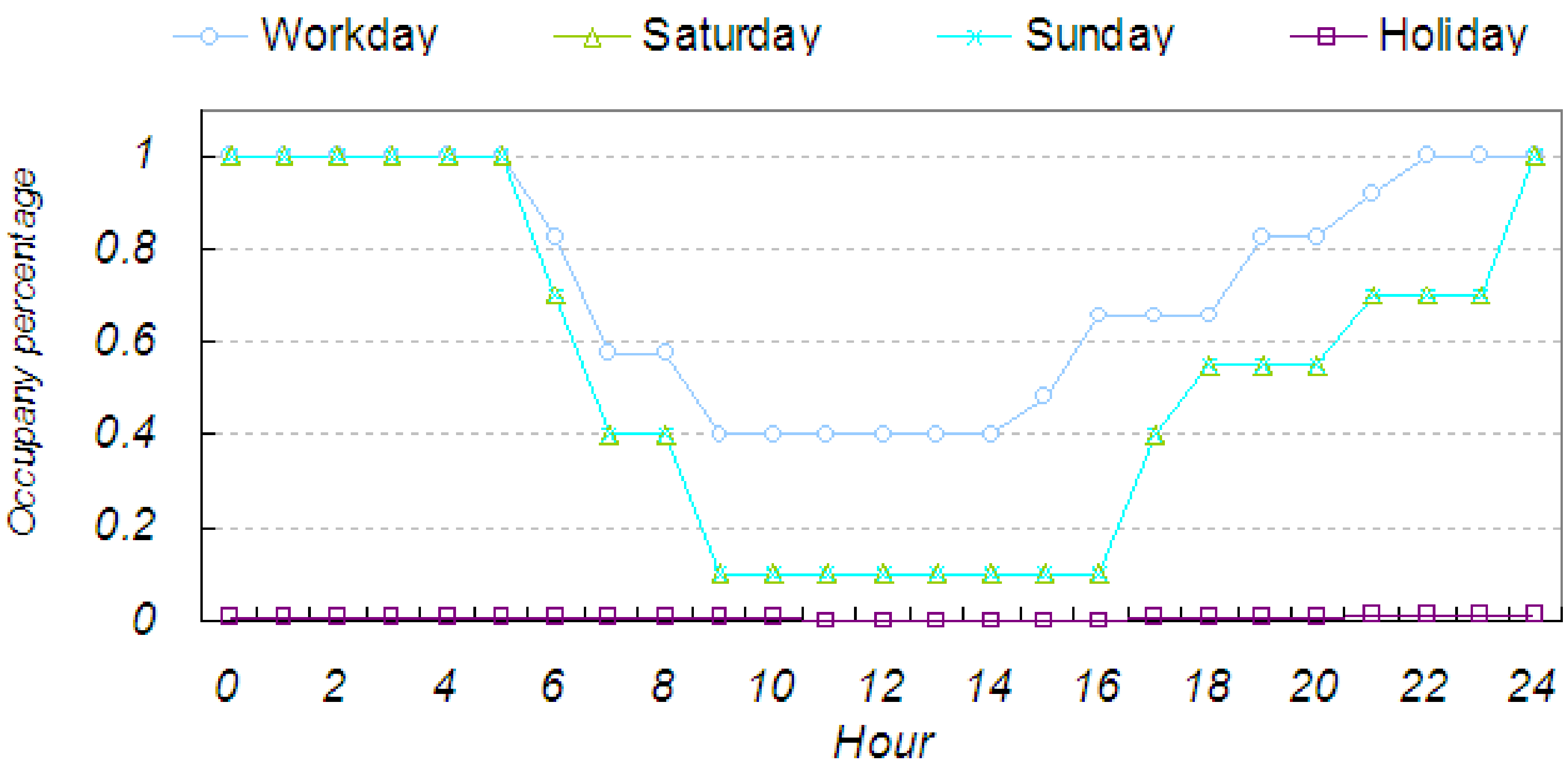
Model

Infiltration schedule

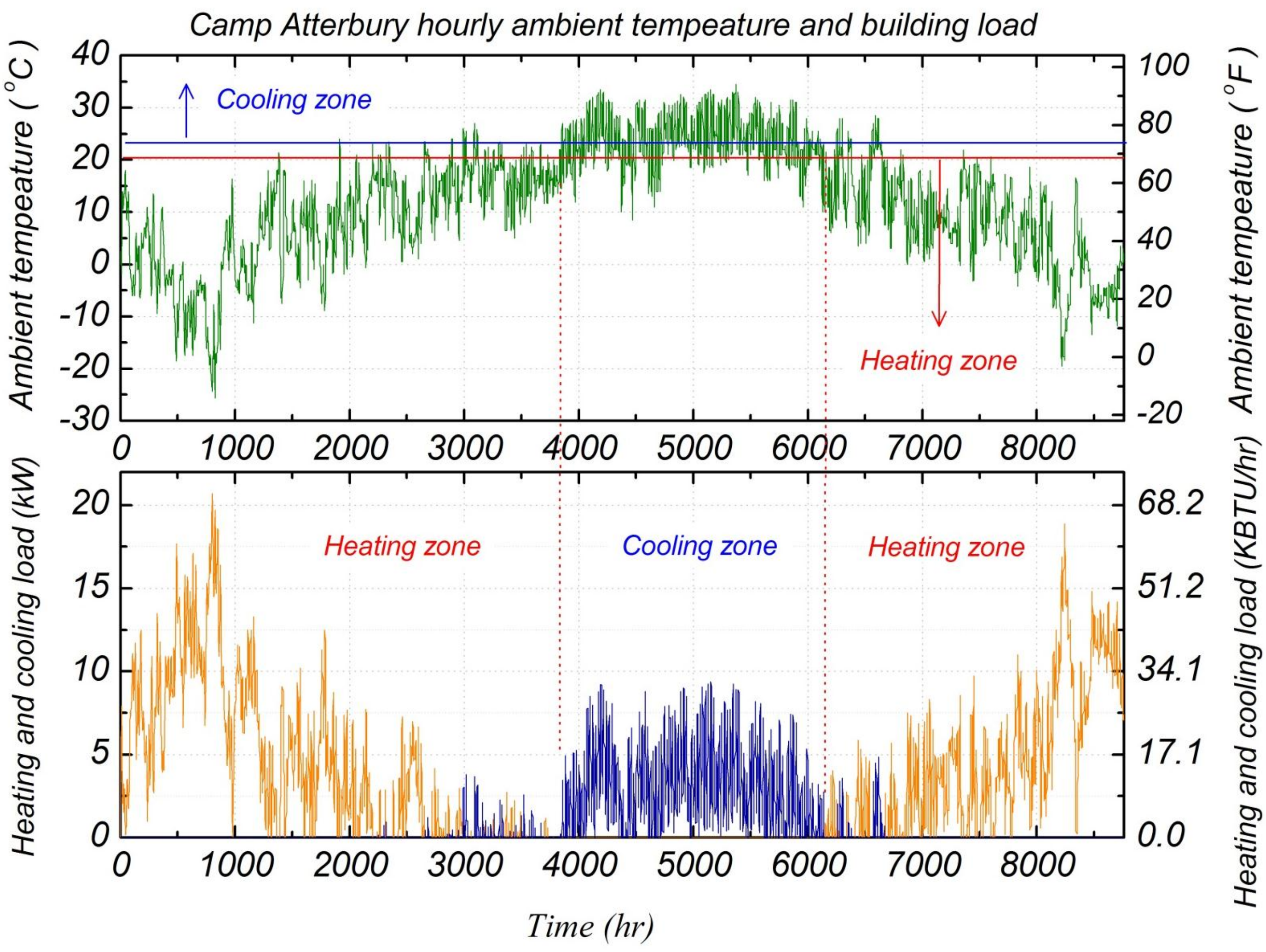


Model

Occupant schedule



Simulation Results



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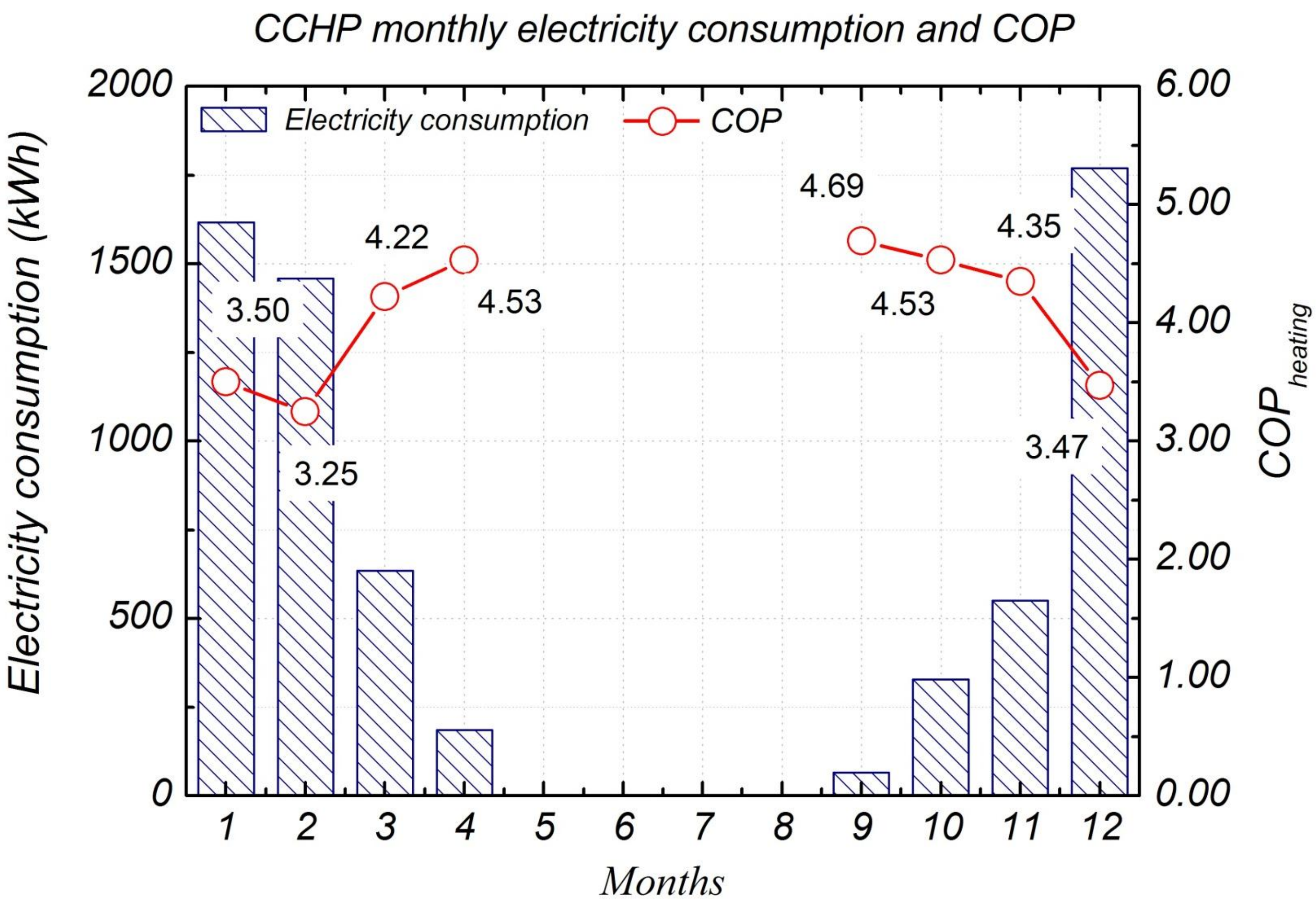

Simulation Results

Percent savings comparing heat pump to natural gas furnace

	COP or η	Thermal energy demand for heating (kWh)	Electricity consumption for heating (kWh)	Thermal energy supply for heating (kWh)	Natural gas supply for heating (kWh)	Cost ($)	CO_2 emission (ton)
CCHP	3.67	24232	6606	--	24630	760.35	3.52
Furnace	0.85	24232	200	28508	29092	1018	5.31
Percent Savings	--	--	--	--	15.34%	25%	33.7%

Conclusion

- Predicted COPs show good heat pump performance in cold climates
- Heat pump capacity can provide at least 95% of the expected heating load
- Significant benefits when compared to conventional HVAC system
- Field Tests Currently Ongoing
  - » Two systems are installed
  - » Data collection until April 2013

Development of a High Performance Cold Climate Heat Pump

August 1, 2010 – July 31, 2013

PIs: James E. Braun, Eckhard A. Groll, W. Travis Horton

RAs: Christian Bach, Sugirdhalakshmi Ramaraj, Yuanpei Song

Sponsor:	Sponsor: Department of Energy
Partners:	Emerson Climate Technologies
	UT Carrier Corporation

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- Liquid Flooded Compression with Regeneration
- Multiport Refrigerant Injection with Economizing
- Heat Pump Analysis for Cold Climate
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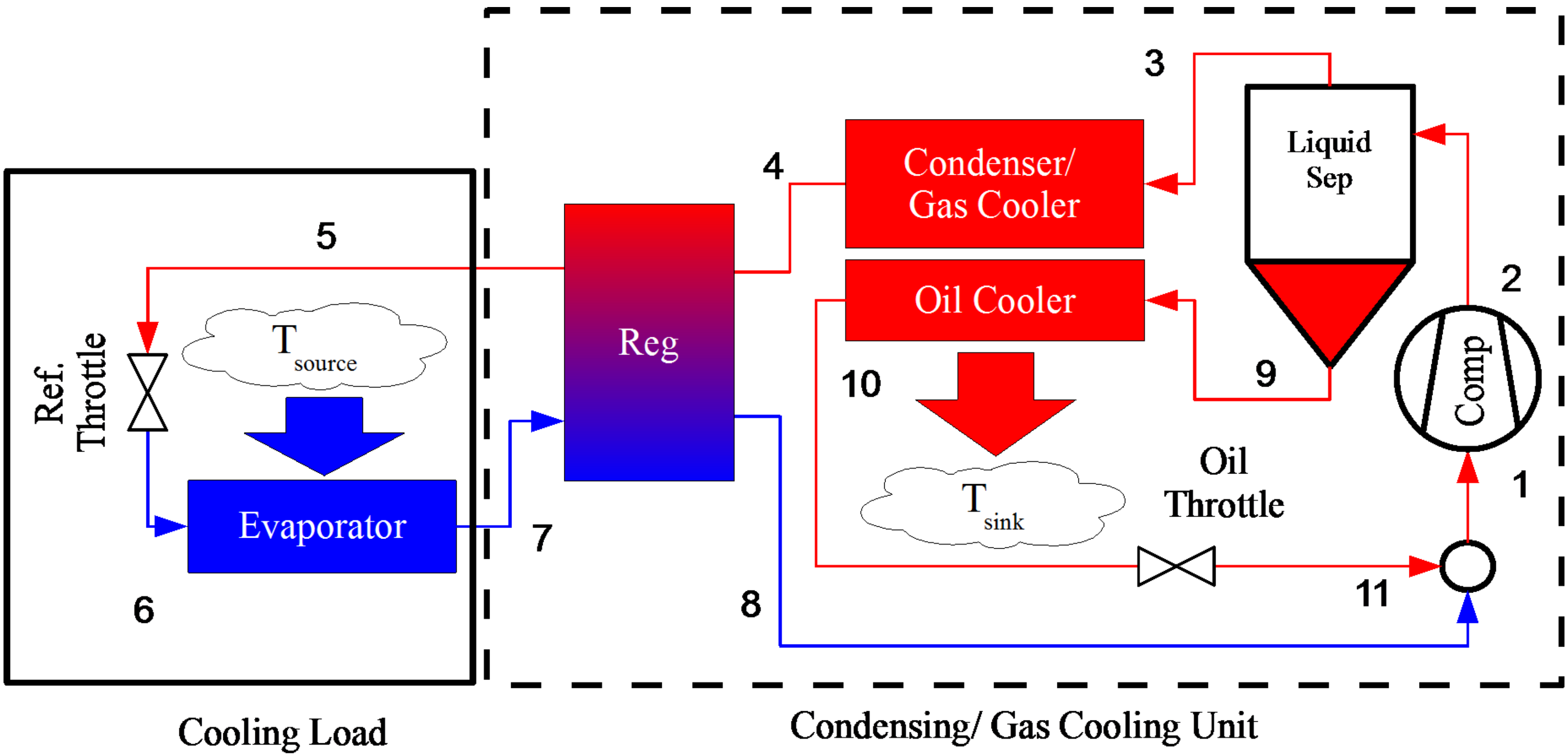
Introduction

- Heat pump heating COPs decrease with cold source temperatures
- Conventional approaches to overcome this problem, e.g. two stage compression, are expensive
- Production cost for efficient low temperature HPs have to be reduced while maintaining sufficient efficiency
- This might be possible to achieve by employing integrated concepts at compressor

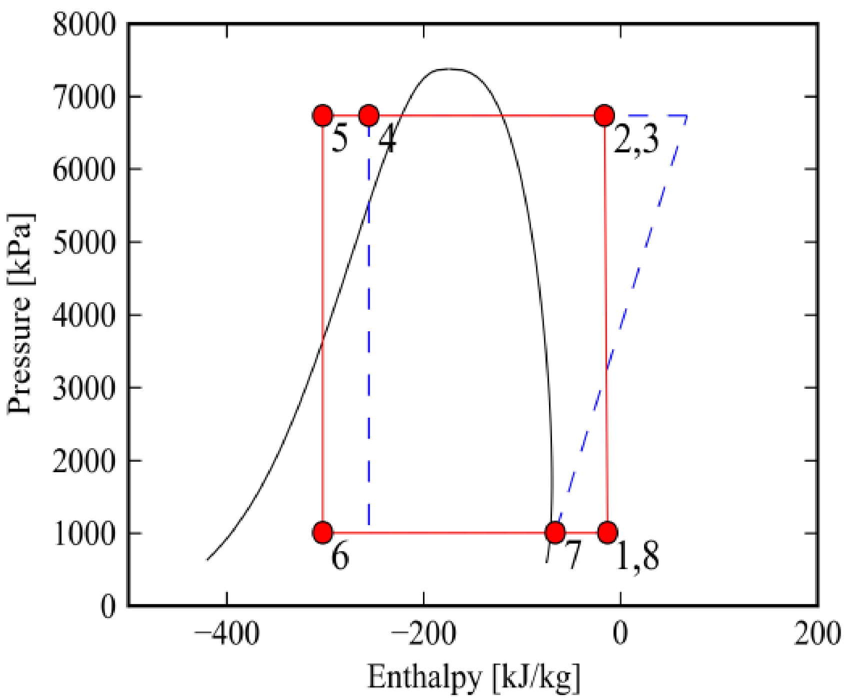
Liquid Flooded Compression with Regeneration

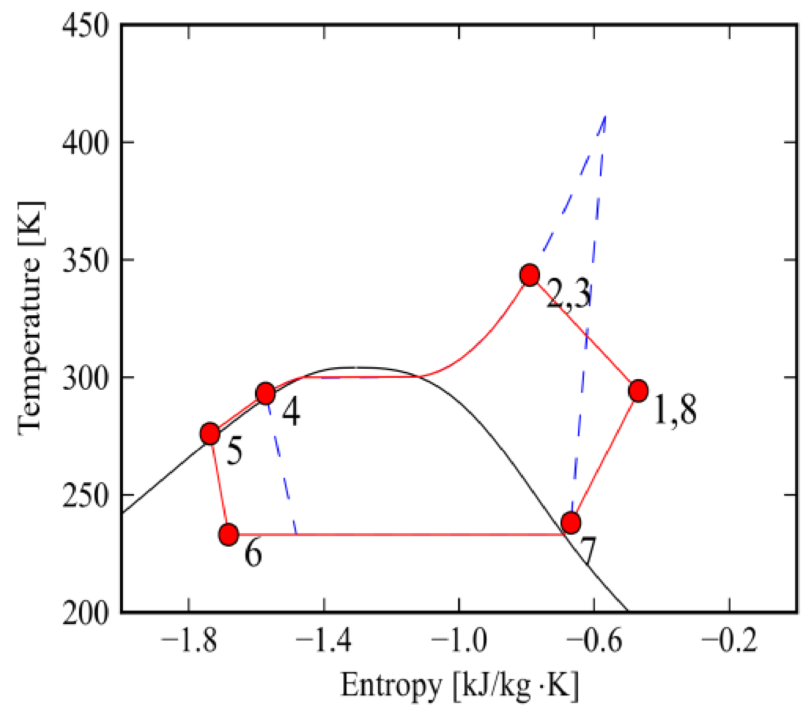
- Non-volatile liquid/oil is mixed into the stream of refrigerant entering the compressor to achieve isothermal compression and decrease discharge temperature
- Flooded Compression
  - » Improves volumetric efficiency by the improved sealing of compressor leakage gaps
  - » Reduces thermodynamic losses associated with the desuperheating of refrigerant in the condenser
- Addition of Regeneration
  - » Improves the system efficiency by reducing the losses due to throttling of two-phase refrigerant in the expansion device
- Improves energy efficiency and maintains high heating capacity for vapor compression heat pumps, particularly at low ambient temperatures

Flooded Compression with Regeneration



Thermodynamic Plots for Liquid Flooded Compression with Regeneration

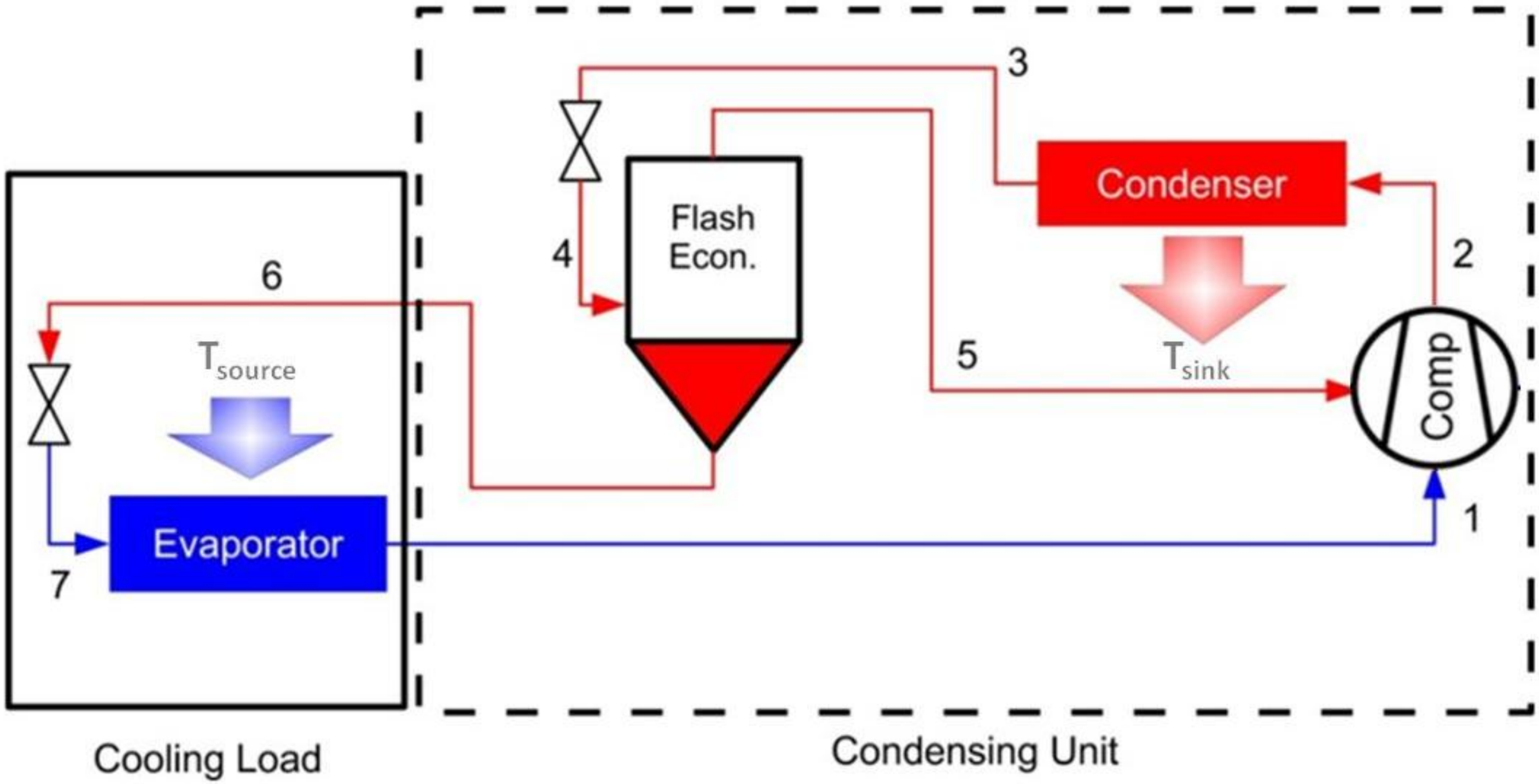




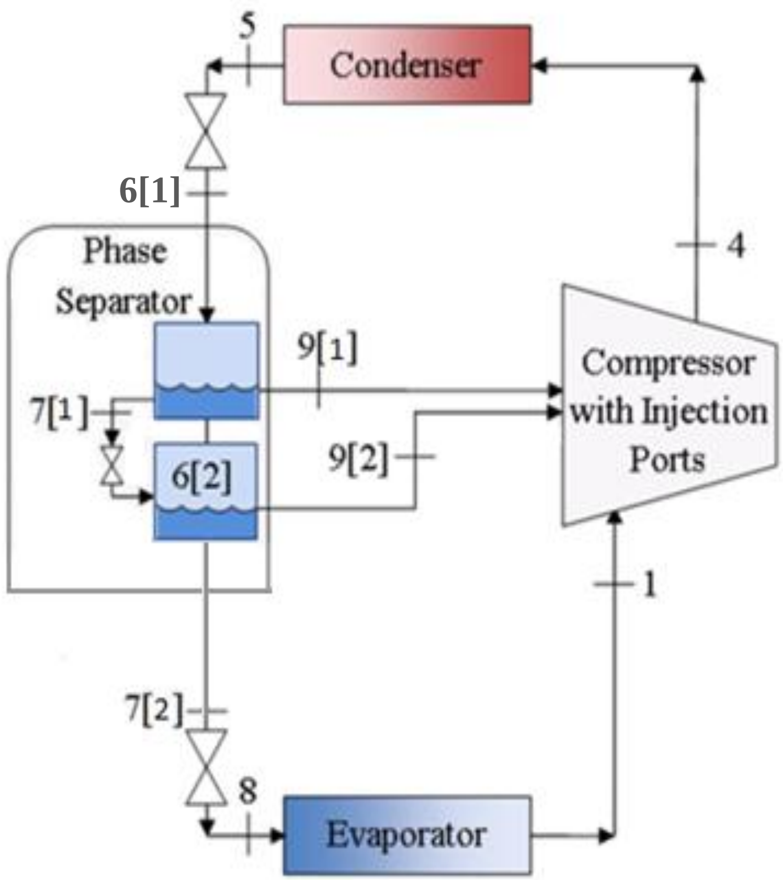
Multiport Refrigerant Injection with Economizing

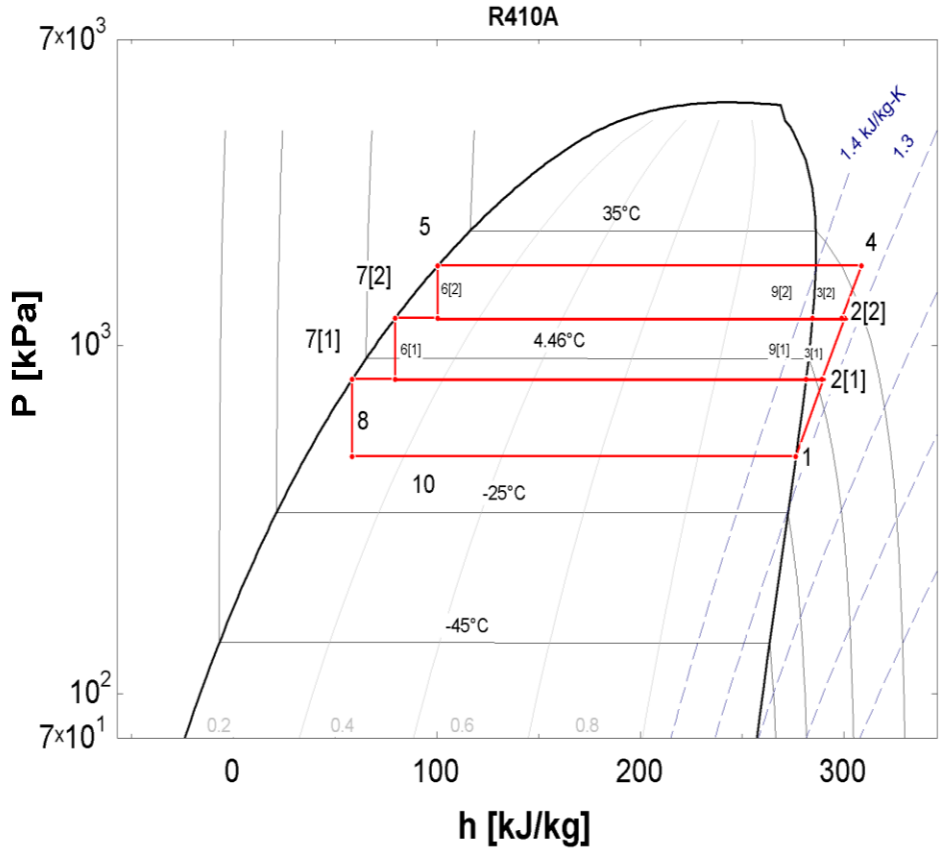
- Economized refrigerant is injected between compressor stages to provide cooling during compression and thus decreases compression work
  - » Similar to multi-stage compression in providing cooling and higher-density refrigerant between compressor stages
  - » Multi-port refrigerant injection within a single compressor eliminates the need for multiple compressors and thereby lowers the cost significantly
- Significant improvements in both heating capacity and COP, particularly at low ambient conditions

Multiport Refrigerant Injection with Economizing



Multiport Refrigerant Injection with Economizing





Heat Pump Analysis for Cold Climate

- Out of the 51 largest cities in United States, **Minneapolis, Minnesota** has the coldest winter weather, based on normal daily temperatures. The annual average temperature is 7.33°C
- The concatenated hourly records of the dry bulb temperature for 12 typical meteorological months (January through December) was binned from TMY3 data for every 5°C difference between the highest and the lowest ambient temperatures of the city
- This data was used to estimate seasonable performance comparisons for the enhanced and conventional vapor compression cycles.

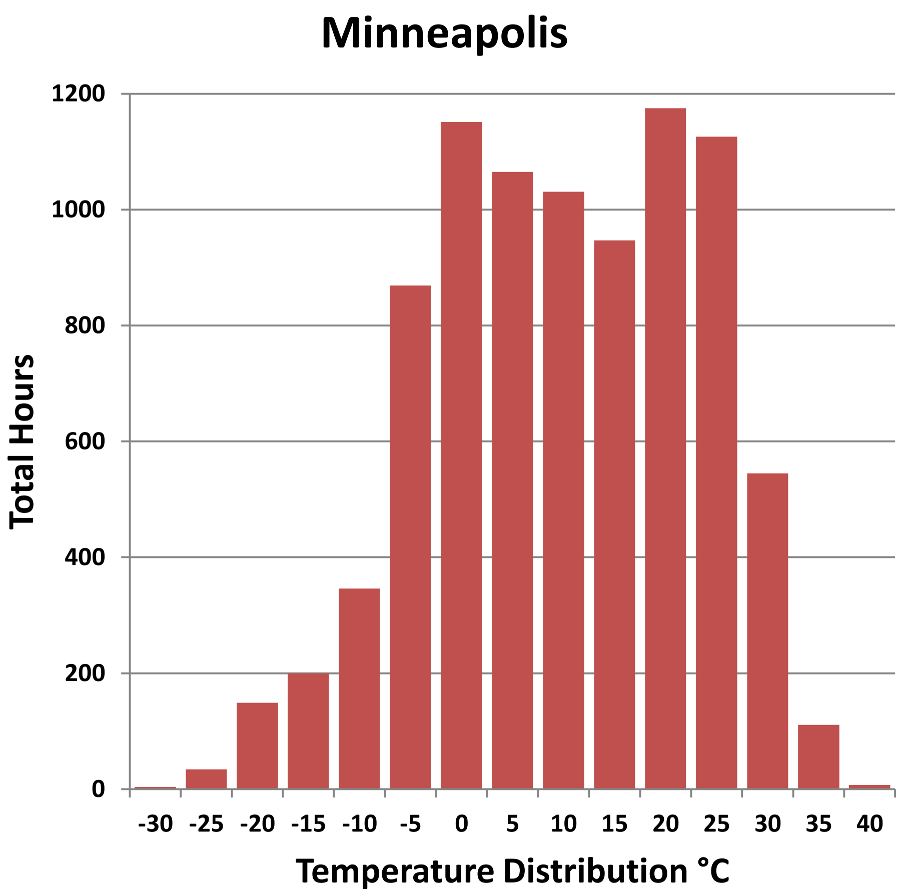


Fig. Hourly Temperature Distribution of Minneapolis based on TMY data

Heat Pump Analysis for Cold Climate

- Design conditions for the heat pump:
  - Heating capacity of 17.6 kW (60,000 Btu/h) at an ambient temperature of -10 °C (14 °F)
  - At 18.33°C (65°F), ideally no heating or cooling is required and thus, the heating/cooling capacity is assumed to be 0 kW at that outdoor temperature
  - Cooling capacity of 11.7 kW (40,000 Btu/h) at standard DOE A rating conditions of 35°C (95°F) ambient temperature
- The heating and cooling load at various ambient temperatures for Minneapolis is calculated by interpolating and extrapolating the data from the design conditions

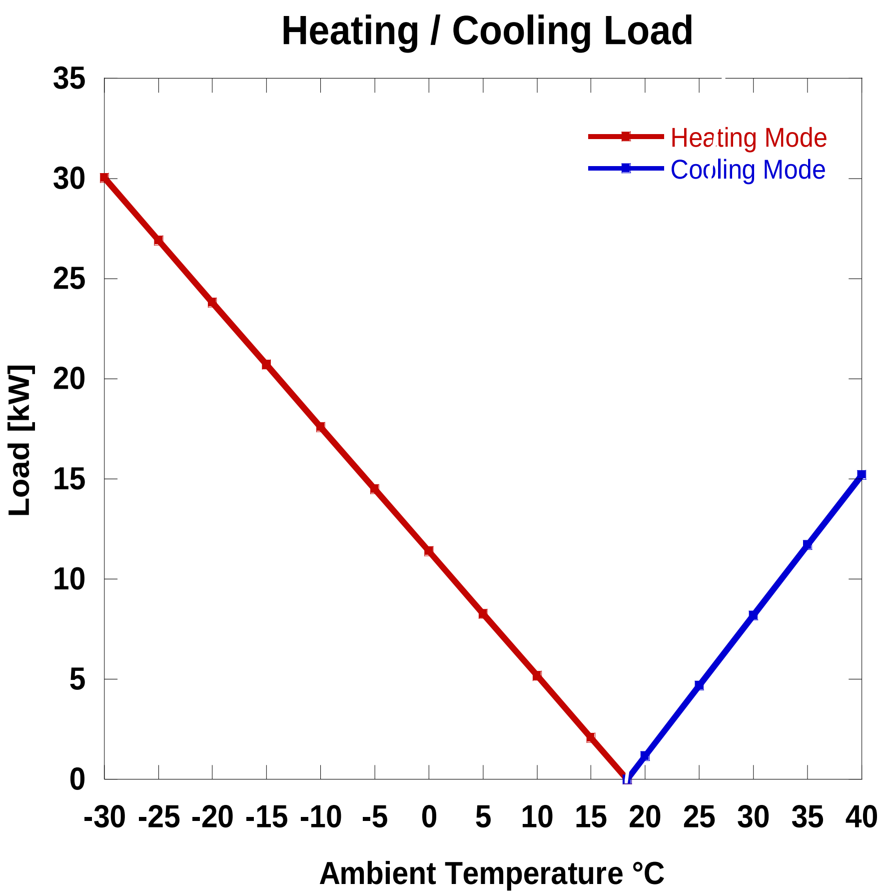
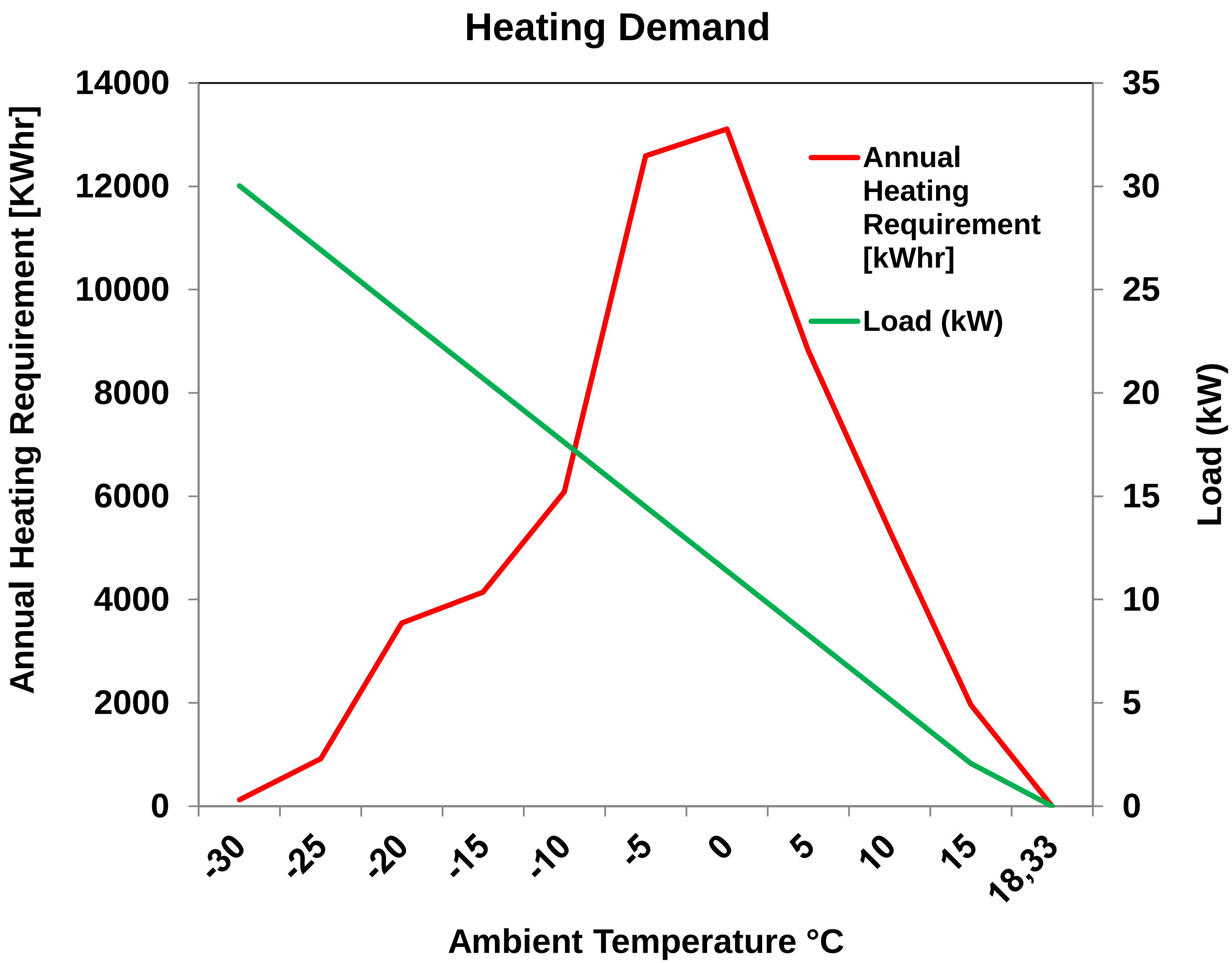


Fig. Heating and Cooling Load at various ambient temperatures for Minneapolis

Heat Pump Analysis for Cold Climate



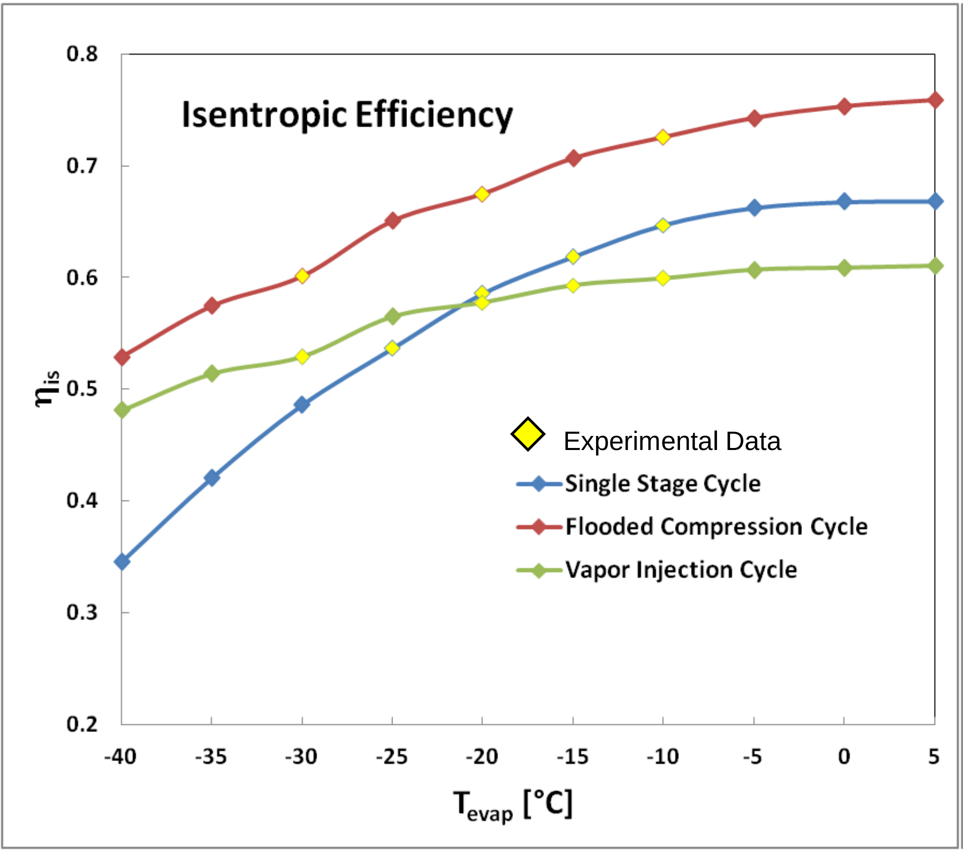
Heat Pump Analysis for Cold Climate

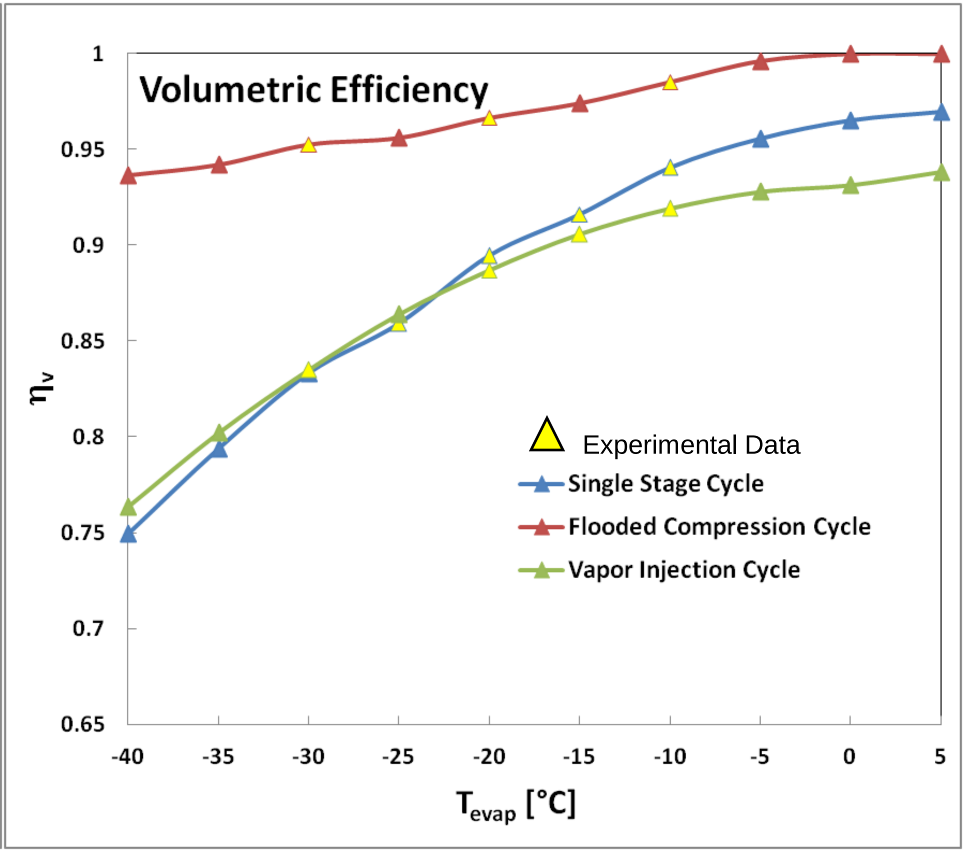
- Working fluid: R410A
- Fixed ΔT_{pinch}= 5°C, $\Delta T_{superheat}$=5°C, $\Delta T_{subcool}$=7°C between the outlet of heat exchangers and their respective thermal reservoirs
- For HP mode, the source temperature (T_L) is the ambient temperature ranging between -30°C to 15°C and the sink temperature (T_H) is kept as a constant 31.33°C
- Throttling device operates adiabatically for both the models and pressure drops in the heat exchangers are neglected
- Flooding agent for liquid flooded compression - POE Oil . At each point, the optimal oil mass flow fraction was found which optimizes the system heating COP
- 2 ports saturated vapor injection with equal pressure ratios across injection lines

Heat Pump Analysis for Cold Climate

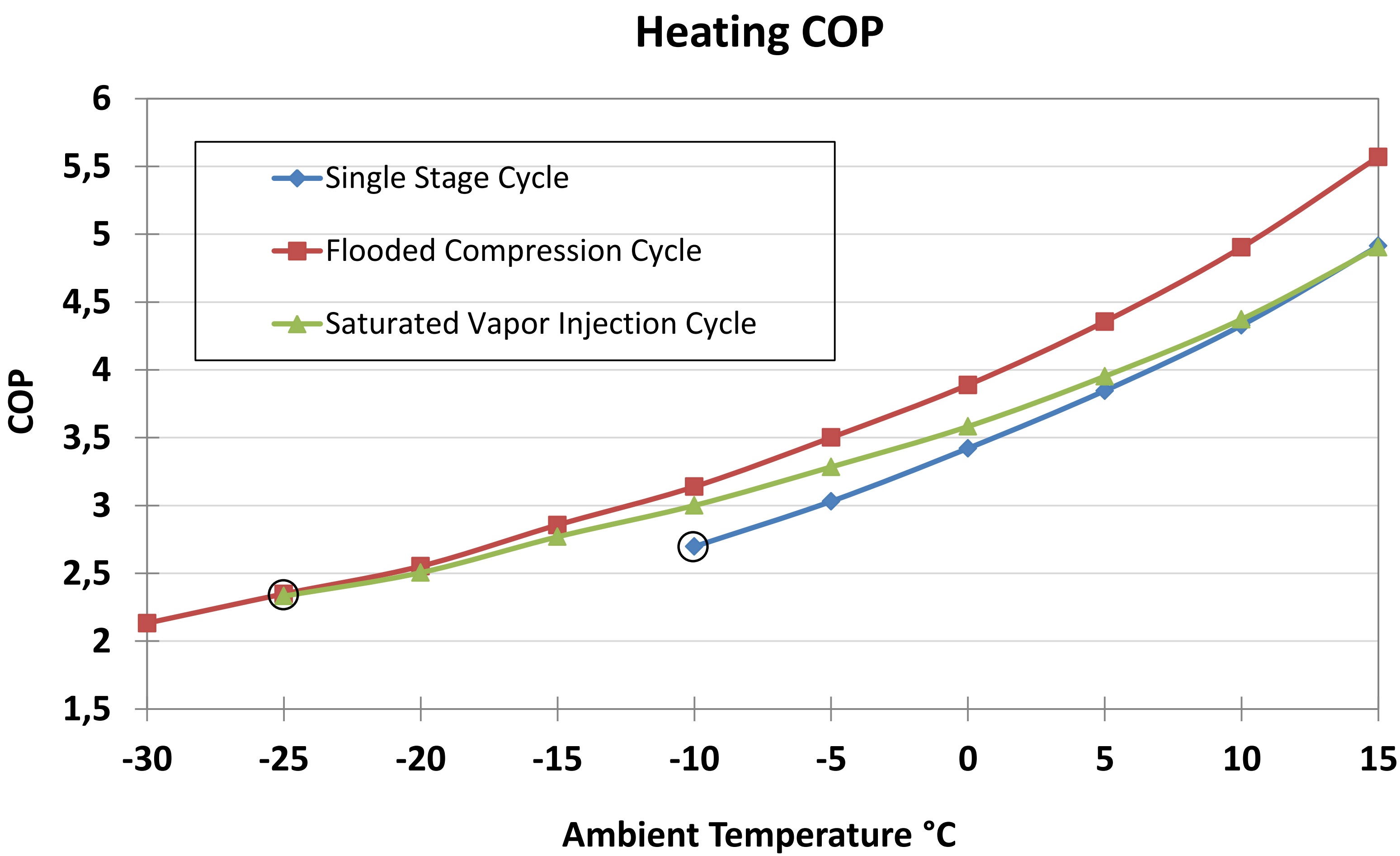
- The maximum allowed discharge temperature inside the scroll compressor is 130°C
- Compressor displacement for the each cycle is adjusted to give the same heating capacity of 17.6 kW at -10 °C and same cooling capacity of 11.7 kW at 35 °C
- The speed of the compressor is varied to yield the necessary capacity for each temperature bin
- Use of experimentally measured compressor performance

Efficiency from Experimental Data





Modeling Results



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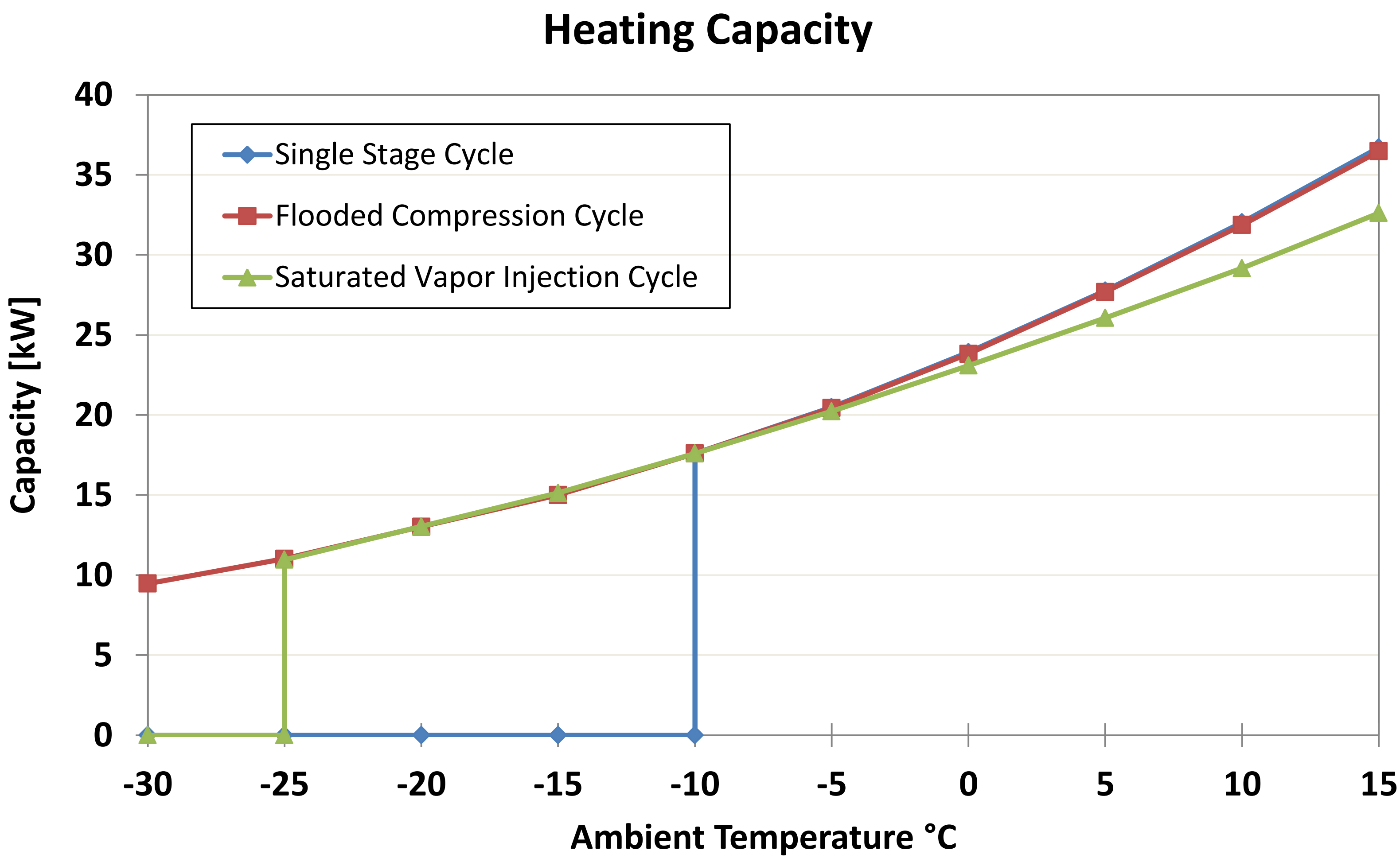
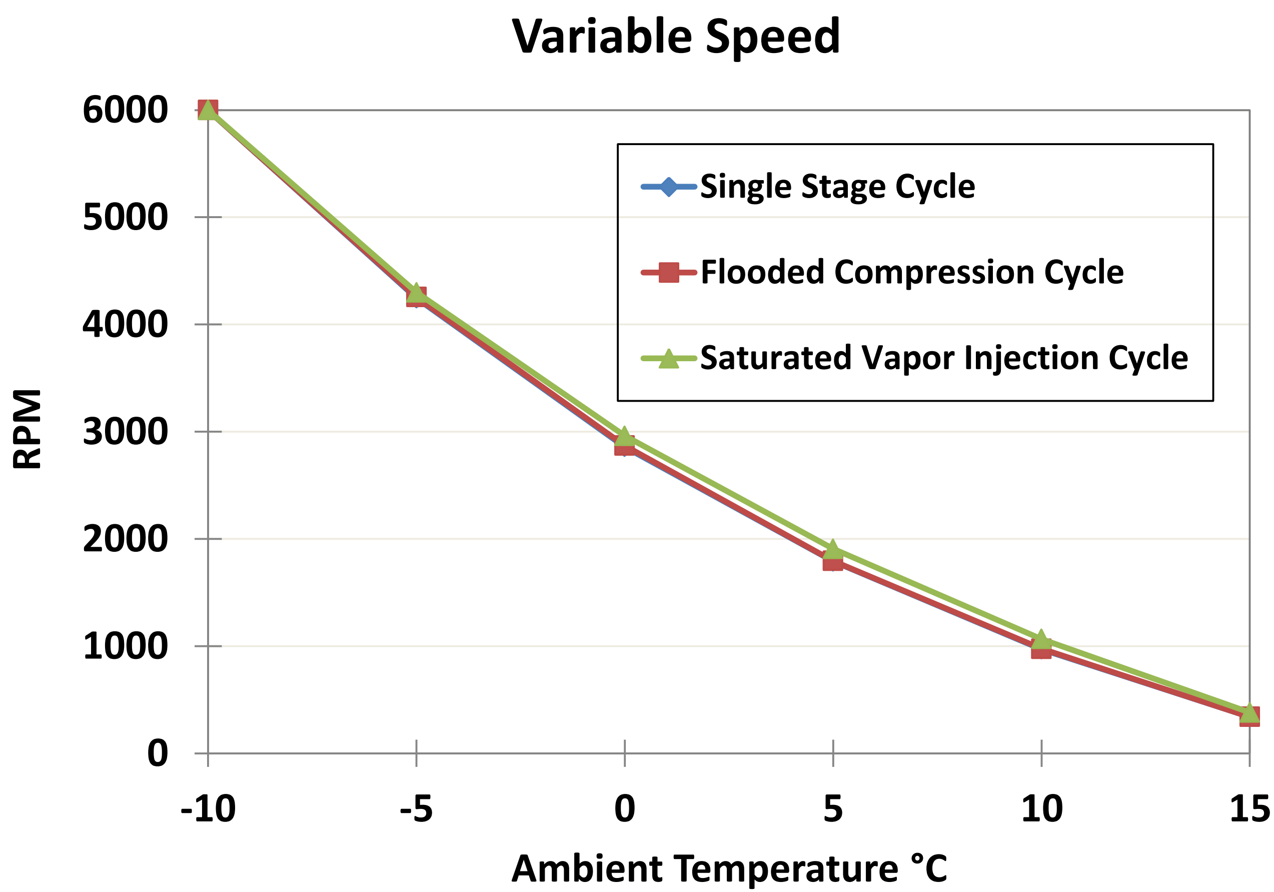
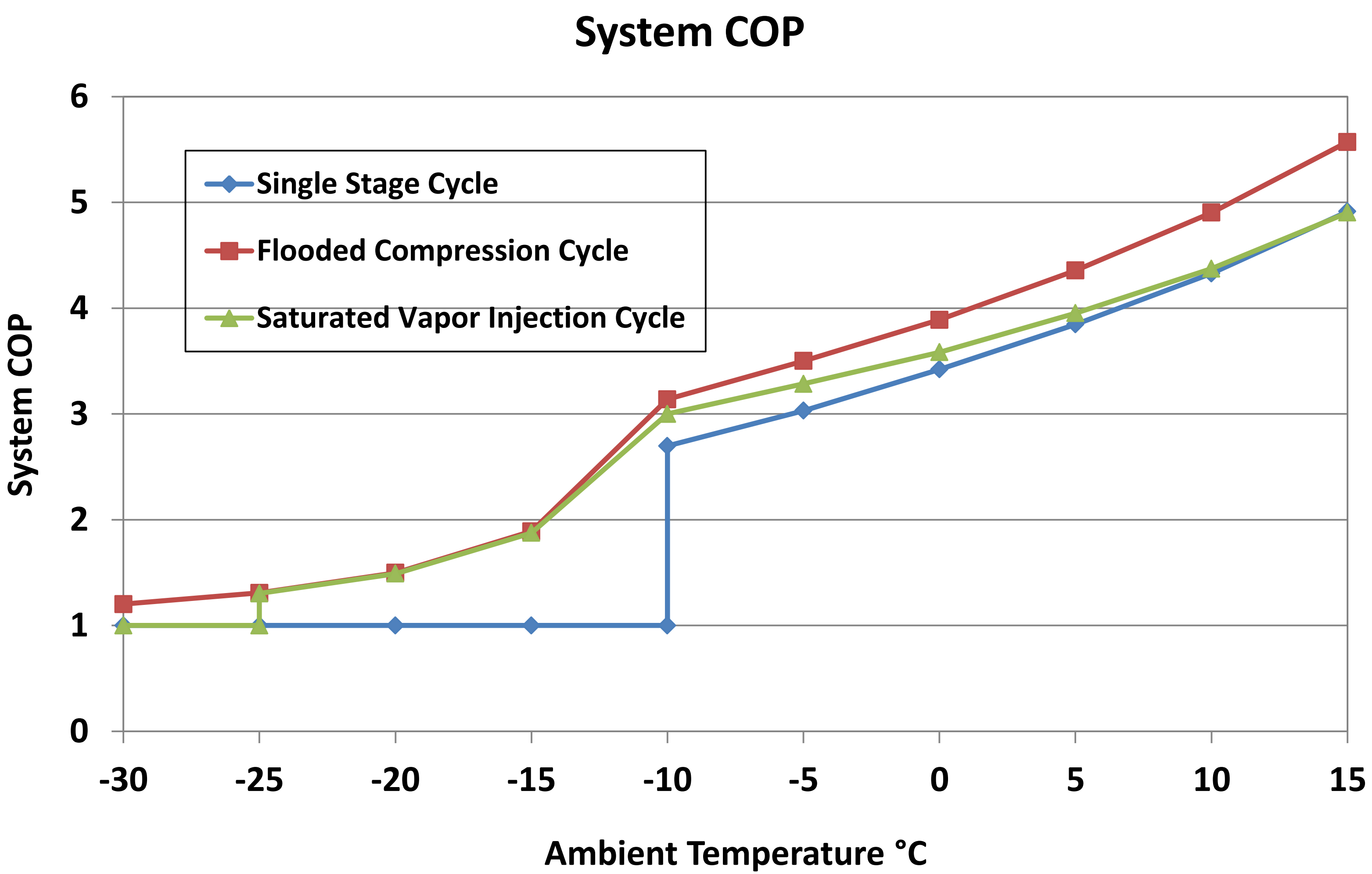


Modeling Results

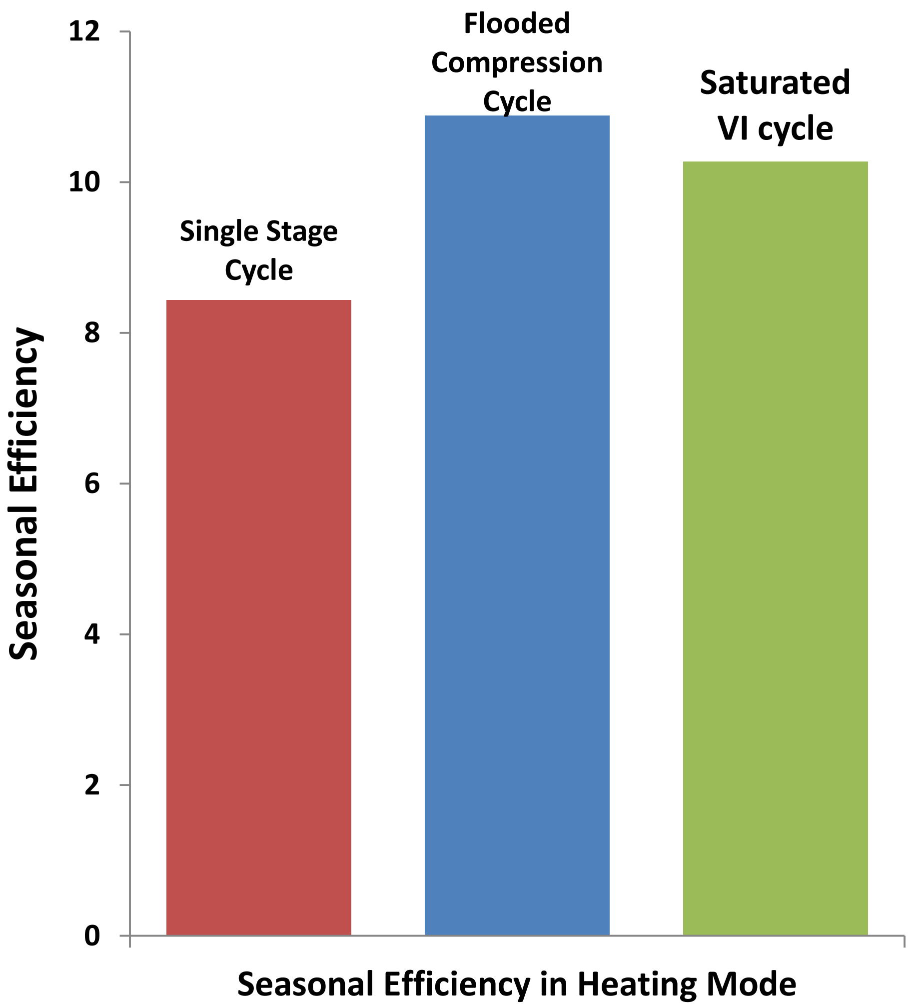


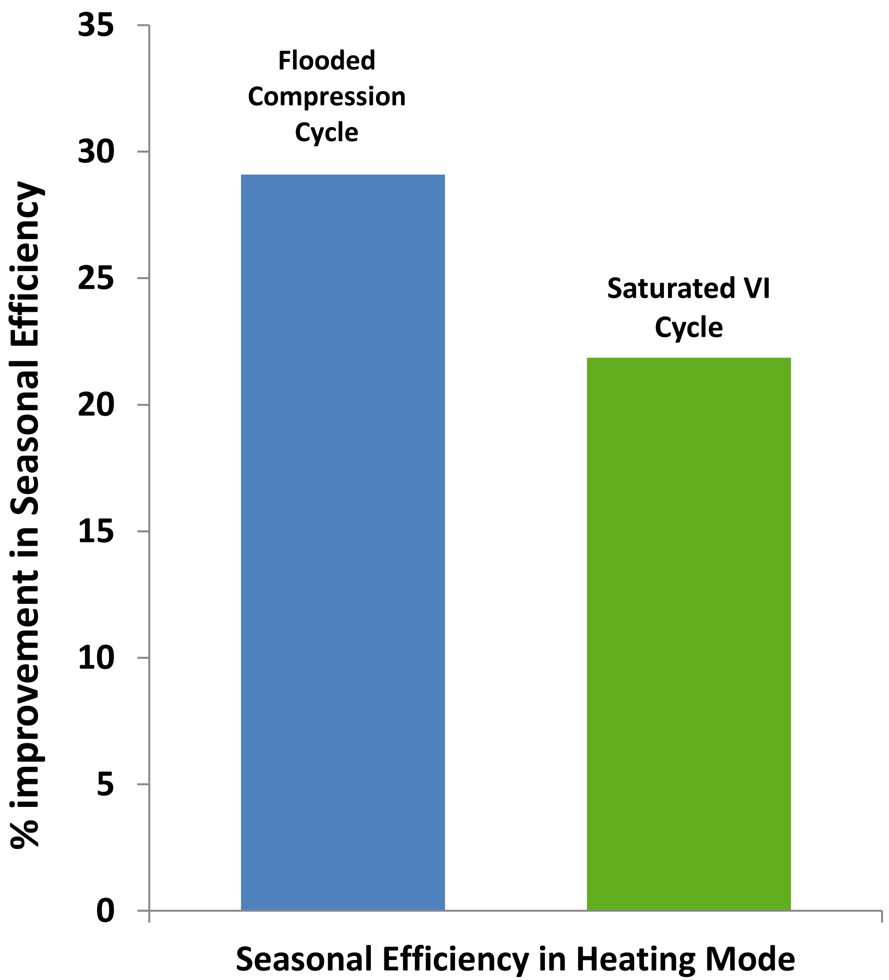
Speed Range : 30-100 Hz

Modeling Results



Seasonal Efficiency (Heating)





Conclusions

- Both technologies address thermodynamic inefficiencies inherent within conventional vapor compression cycle
- At -10°C ambient temperature, heating COP of flooded compression cycle is 16% higher while that of vapor injection cycle is 11% higher than conventional vapor compression cycle
- Seasonal heating COP of flooded compression cycle is 29% higher while that of vapor injection cycle is 22% higher than conventional vapor compression cycle
- Also suitable for high temperature lift applications
- Ongoing
  - » Constructing and testing pre-manufactured heat pump systems
  - » Quantify benefits and identify best applications for each technology