Future of the HVAC&R Industry: High Efficiency & Environmentally Friendly

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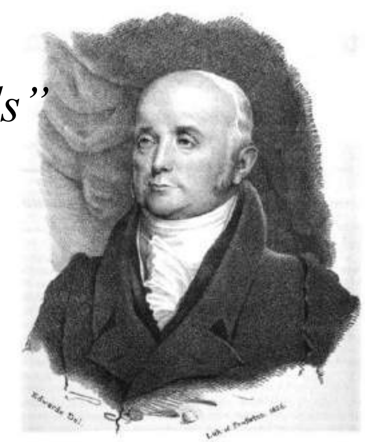
Presentation Highlights

- Vapor compression refrigeration system technology and current trends
- Not-in-kind cooling technology review and comparison
- New refrigerants for future HVAC&R applications
- Vapor compression cycle system enhancements to improve efficiency
- Automated fault detection and diagnosis

Vapor Compression Technology & Trends

- Origins of the vapor compression (VC) refrigeration system
  - William Cullen (1748) University of Glasgow
    - Demonstrated the first 'refrigerator'
    - Pulled a vacuum on a container of diethyl ether
  - Oliver Evans (1805)
    - Conceived the idea of VC refrigeration
    - Never constructed a refrigerator
  - Jacob Perkins (August 14, 1835)
    - Patented the first VC refrigeration system
    - *"Apparatus and means for producing ice, and in cooling fluids"*
  - John Gorrie (1851) & Alexander Twining (1853)
    - Patents for the first refrigeration appliances
    - Gorrie's focus was on comfort cooling to improve health
  - Fred Wolf (Ft. Wayne, Indiana, 1913)
    - Patented the first refrigerator for domestic household use



JACOB PERKINS.

Vapor Compression Technology & Trends

- Mechanical refrigeration technology
  - Research began over 250 years ago
    - Preserve perishable food items
    - Comfort cooling applications generally came later
  - Early refrigerants were naturally occurring "natural" substances
    - Ethyl ether
    - Ammonia
    - Sulfur dioxide
    - Carbon dioxide
- The basic cycle we use today is essentially unchanged
- However, we have made substantial improvements in many key areas…

Vapor Compression Technology & Trends

- Advances
  - Material sciences
  - Manufacturing
  - Refrigerants
  - Lubricants
  - Computers
- Results
  - Reliable components
  - Widespread application of vapor compression systems
    - Refrigeration, air conditioning, heating
  - Higher efficiency
  - Environmental impact

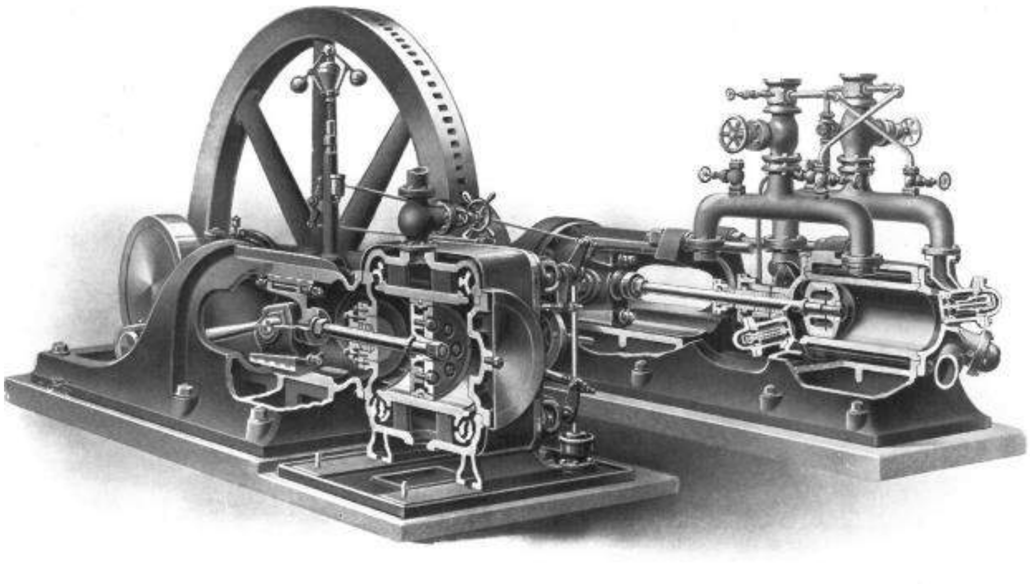




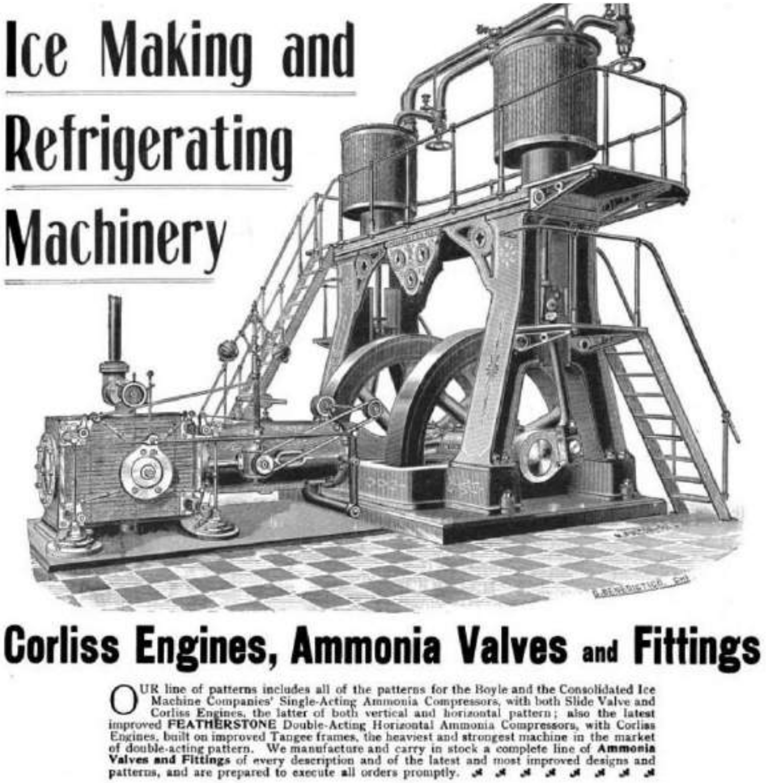


Vapor Compression Technology & Trends

- Refrigeration equipment around the turn of the 20th century
  - Large, expensive machinery
  - Only used at a commercial scale

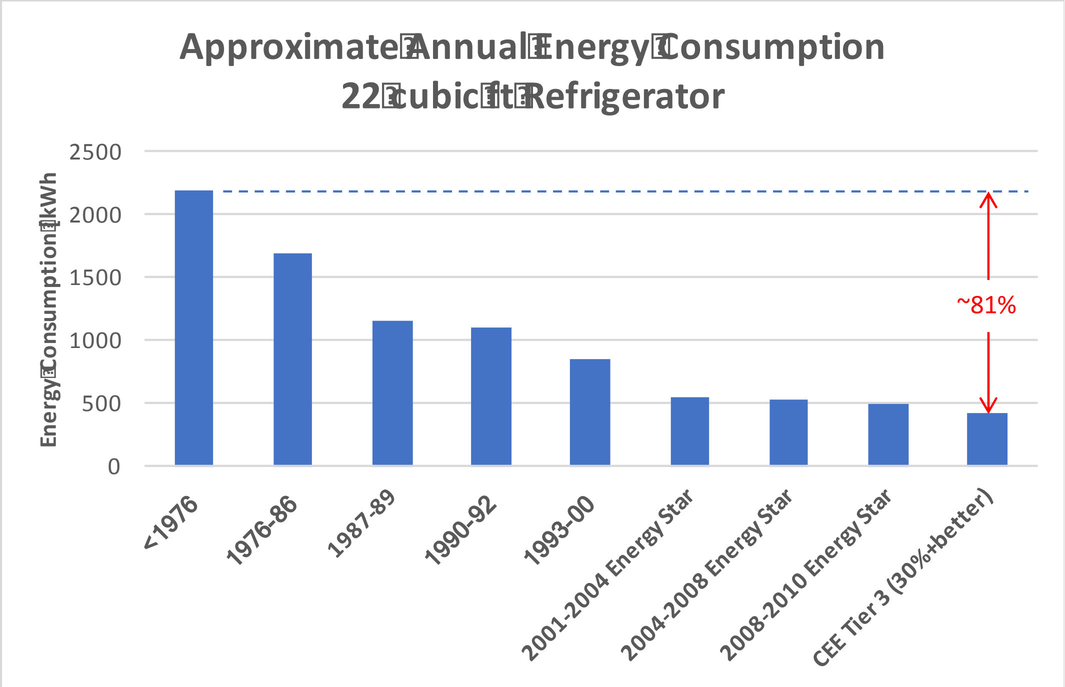


D83—Full Shaded Perspective Sectional View of Horizontal Double-Acting Refrigerating Machine



Vapor Compression Technology & Trends

- Today's VC refrigeration and heat pump technology
  - Multiple scales
    - Industrial
    - Commercial
    - Residential
    - (Individual?)
  - Improved efficiency
    - Not all improvements are attributable only to the VC system
    - Integrated system efficiency is improving
    - Variable speed technology to allow load matching
    - The burden to achieve high efficiency is shared by the vapor compression system (supply-side) and the integrated system (demand-side)



Vapor Compression Technology & Trends

- Environmental impact
  - Improved quality of life
    - Cold chain for perishable items
      - Dramatic reduction in food waste
      - Improved access in cities to fresh fruits/vegetables
      - Preservation of medications to control disease and improve health
    - Comfort cooling
      - Improved worker productivity
      - Fewer heat-related deaths and illnesses
      - Improved indoor air quality
  - Climate impacts
    - Ozone depletion (chlorinated refrigerants)
    - Global warming
      - Direct (refrigerant leakage)
      - Indirect (fossil fuel combustion for power production to provide cooling)

Vapor Compression Technology & Trends

- Current trends are towards minimizing size
  - Drive VC systems to the individual (or smaller) scale
    - Why do we cool an entire space in a building to accommodate a few individuals?
    - Targeted cooling systems will lead to dramatic reductions in power consumption for comfort cooling

Turbo-compressor with an impeller diameter <30mm

Vapor Compression Technology & Trends

- Future trends for compressors
  - Significant size reduction
  - Increased operating speed (~24,000 – 600,000 rpm)
  - Oil free technology
  - In-cylinder heat transfer (i.e. isothermal compression)
  - Multi-stage compression with intercooling
  - Integrated low cost, high performance plastics
  - ‘Smart’ compressors that can detect and diagnose their own state of health

Vapor Compression Technology & Trends

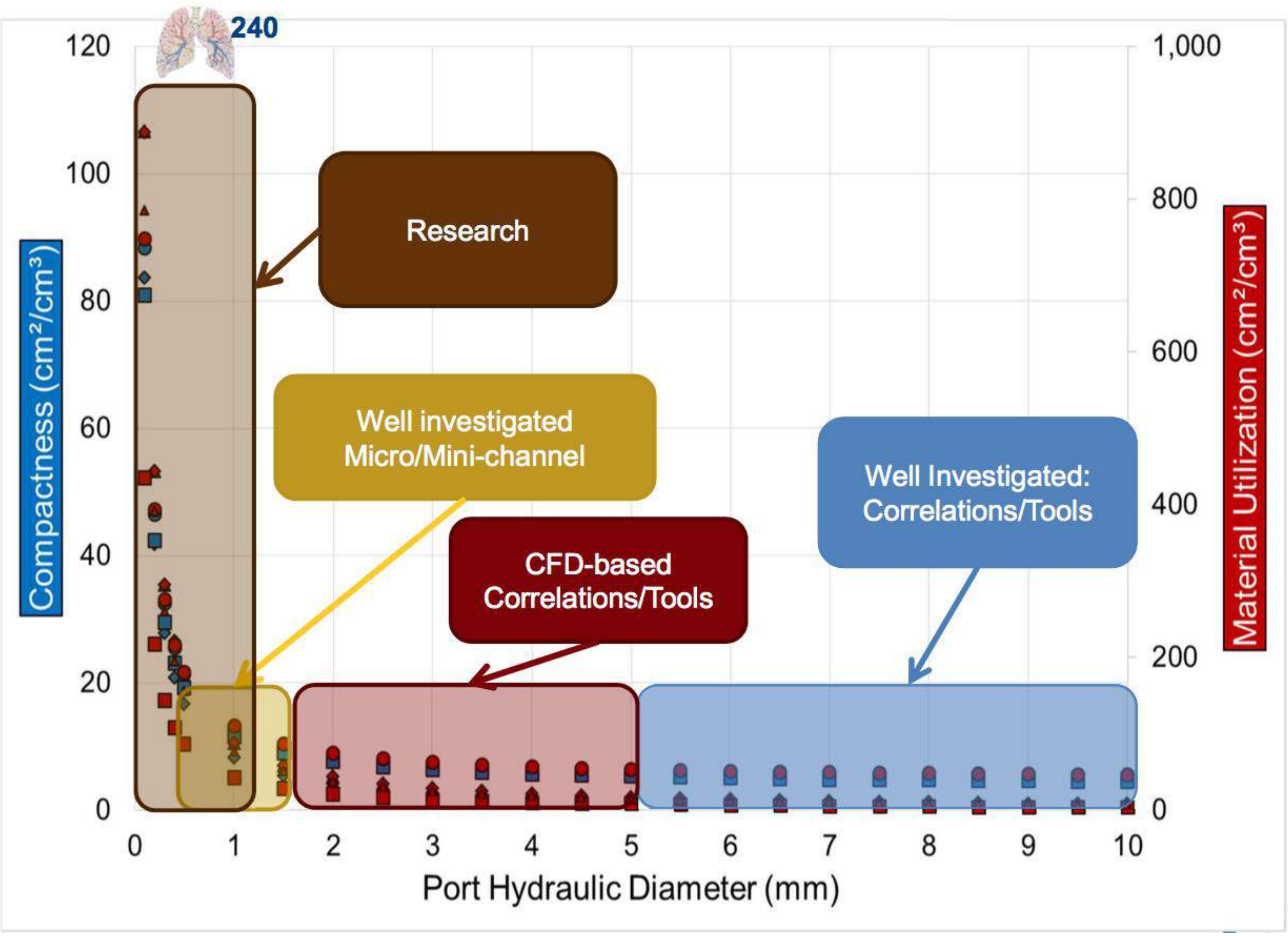
- Future trends for heat exchangers
  - Computer aided (mathematical) optimization
  - Consider a heat exchanger:
    - 10 discrete variables (tube ID, OD, horizontal/vertical tube spacing, material, …)
    - 6 continuous variables (length, width, height, fin pitch, …)
    - Total design space is > 10^{13} combinations
    - The only way to explore this design space is through computer aided optimization

"Mathematically rigorous optimization allows engineers to innovate:
Because, whatever the computer can simulate, the computer can optimize,
Freeing humans to do what humans do best: ***Create and Innovate!"***

Reinhard Radermacher – 2018 Purdue Compressor and Refrigeration Systems Engineering Conference

- Imagine an HVAC installer who arrives on a job-site and 3D prints a plastic heat exchanger that conforms to any custom shape and form

Heat Exchanger Road Map

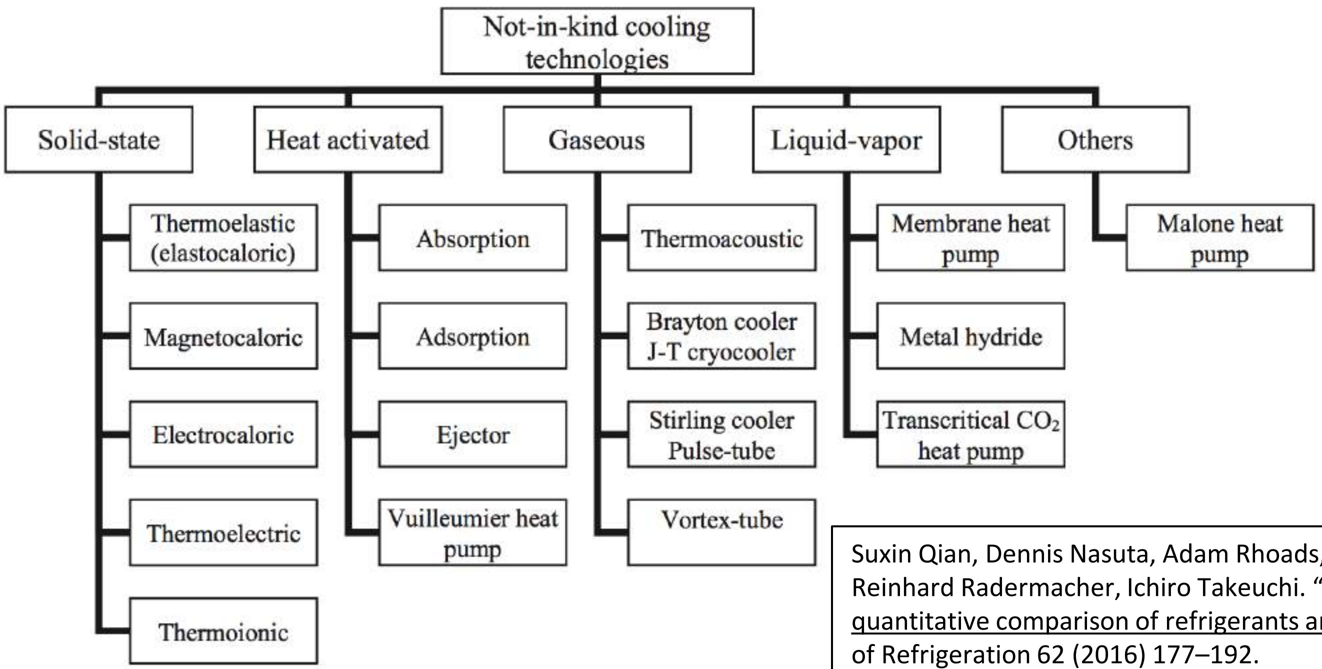


Bacellar, D., Aute, V., Huang, Z., and Radermacher, R., 2016, Airside friction and heat transfer characteristics for staggered tube bundle in crossflow configuration with diameters from 0.5 to 2.0mm, Technical Note, Intl J. of Heat and Mass Transfer, Vol. 98, pp. 448-454

Not-In-Kind (NIK) Cooling Technology Review and Comparison

Not-In-Kind Technology Review

- Not-in-kind (NIK) technologies: cooling systems other than the typical vapor compression cooling technology of today
- Viewed as potentially disruptive technologies



Suxin Qian, Dennis Nasuta, Adam Rhoads, Yi Wang, Yunlong Geng, Yunho Hwang, Reinhard Radermacher, Ichiro Takeuchi. "Not-in-kind cooling technologies: A quantitative comparison of refrigerants and system performance." International Journal of Refrigeration 62 (2016) 177–192.

Not-In-Kind Technology Review

- Elastocaloric cooling – uses the latent heat associated with a martensitic transformation in shape memory alloys (SMAs)
- Magnetocaloric cooling – employs an alternating magnetization/demagnetization process in a special material to generate/reject heat to a working fluid
- Electrocaloric cooling – similar principle to magnetocaloric cooling but uses an electric field rather than a magnetic field
- Thermoelectric cooling – based on the reverse Peltier effect where a flowing current will induce a temperature difference in a junction of two different materials
- Stirling/Brayton cooling – well established gas cooling cycles typically used in cryogenic applications

Not-In-Kind Technology Comparison

Performance comparison of various NIK cooling technologies

Technology	Normalized Overall COP at (medium) 10K Temperature Lift	Comments
Vapor compression	**0.20**	**Baseline**
Elastocaloric	0.14	Need material advances
Magnetocaloric	0.29	Competitive advantage over VC
Electrocaloric	n/a	Not possible today to achieve a ΔT of 10K. Still need significant material advances
Thermoelectric	0.13	Need material advances
Stirling cycle	0.04	Superior in high ΔT applications, but does not perform well for medium ΔT
Brayton cycle	0.02	Superior in high ΔT applications, but does not perform well for medium ΔT

Not-In-Kind Technology Comparison

- Future of magnetocaloric refrigeration
  - Magnetocaloric refrigeration is the only NIK technology that is shown to have superior performance to the baseline vapor compression system
  - Several companies have announced an intent to commercialize magnetocaloric refrigeration systems

"Overall, advances in both magnetocaloric materials and permanent magnets to induce higher magnetic field, as well as highly efficient system integration are still needed. Major drawbacks in size, mass, pumping power, and especially the cost of the magnetocaloric materials are still challenges prohibiting its market penetration."

New Refrigerants For Future HVAC&R Applications

New Refrigerants for HVAC&R

- Early refrigerants were naturally occurring substances with thermodynamic properties that could be easily exploited for cooling purposes

Substance	**Refrigerant Number**	**Technical Challenges**
Ammonia	R-717	Toxic, mildly flammable
Carbon Dioxide	R-744	High operating pressure
Ethyl Ether	R-610	Flammable
Dimethylether	E-170	Flammable
Methyl Chloride	R-40	Toxic; mildly flammable
Sulphur Dioxide	R-764	Strong odor; toxic
Water	R-718	Low suction pressures; high freezing point

New Refrigerants for HVAC&R

- Engineering challenges associated with natural refrigerants led to the development of synthetic refrigerants that are non-toxic, and non-flammable
- Development timeline
  - 1890's: Frédéric Swarts synthesized the first CFC's
  - Late 1920's: Charles Franklin Kettering with General Motors,
    - Formed a research team to find a replacement for the refrigerants being used at the time
    - The team was led by Thomas Midgley, Jr.
    - In 1928 they improved the synthesis of CFC's refrigerants and demonstrated their usefulness, stability, and nontoxicity
    - In 1930 General Motors and DuPont formed Kinetic Chemicals to produce CFC's under the trade name "Freon"

New Refrigerants for HVAC&R

- Ozone Depletion:
  - Occurs when refrigerant molecules in the atmosphere encounter UV radiation from the sun which breaks apart the molecule. The Chlorine atom binds with an Oxygen atom. The net reaction reduces ozone levels.
- Regulation
  - 1974 Molina and Rowland propose a CFC ozone depletion hypothesis
  - 1978 CFCs banned in aerosols in USA
  - 1984 First ozone hole over Antarctica was discovered
- 1985 Vienna Convention
  - Formalized international cooperation
- 1987 Montreal Protocol
  - Reduce CFC production by 50% by 1998
- 1988 Documented losses of ozone over the Northern Hemisphere
- Amendments:
  - 1990 London
  - 1992 Copenhagen
  - 1997 Montreal

New Refrigerants for HVAC&R

- Phase-out schedule for ozone depleting substances

Year	Action
1996	Stop the production of CFC refrigerants
2010	Ban the use of HCFC-22 in new equipment
2020	Stop the production of HCFC-22
	Eliminate the use of all other HCFC's in new equipment
2030	Stop the production of all other HCFC's

- Proposed HFC replacements

Refrigerant	Replacement	Application
R-12	R-134a	Refrigerators & Auto A/C
R-22	R-410A/R407C	Residential A/C & H/P
R-502	R-507/R-404A	Commercial Ref & A/C
R-11	R-245fa	Large scale chillers

New Refrigerants for HVAC&R

- Global Warming
  - The earth radiates heat to space at various wavelengths, but global warming gases in the atmosphere absorb/reflect that heat back to the earth.
  - Result is a net increase of earth's temperature due to the "greenhouse" effect
- The global warming impact of a refrigerant is measured relative to the global warming impact of the same mass of CO_2

New Refrigerants for HVAC&R

- Global Warming Potential of selected refrigerants

» HFC-23	=	14,200
» HFC-236fa	=	9,820
» HFC-143a	=	4,180
» HFC-227ea	=	3,580
» HFC-125	=	3,420
» HFC-134a	=	1,370
» HFC-245fa	=	1,050
» HFC-32	=	716
» HFC-152a	=	133
» HFO-1234ze	=	6
» HFO-1234yf	<	4.4
» R744 (CO_2)	=	1.0

New Refrigerants for HVAC&R

- What's next…?
  - Hydrofluoroolefins (HFO's)
    - Chemical compounds composed of hydrogen, fluorine and carbon
    - Distinguished from hydrofluorocarbons (HFC's) by being derivatives of alkenes (olefins) rather than alkanes
  - Current HFO's
    - 2,3,3,3-tetrafluoropropene (HFO-1234yf)
    - 1,3,3,3-tetrafluoropropene (HFO-1234ze)
    - 1-Chloro-3,3,3-trifluoropropene (HFO-1233zd) under development
  - HFO's have zero ozone depletion potential and a very low global warming potential; however, the current HFO's are flammable substances with a classification of A2L

New Refrigerants for HVAC&R

- What's next…?
  - There are *no new synthetic refrigerant possibilities* beyond those we know of today. (Mark McLinden, Purdue Conferences 2014)
  - We must balance technical requirements against safety considerations and environmental concerns moving forward
  - Resurgence of interest in "natural" refrigerants
    - CO_2 in supermarket refrigeration and water heating
    - Hydrocarbons in small refrigeration systems
    - Ammonia used extensively for commercial cold storage facilities

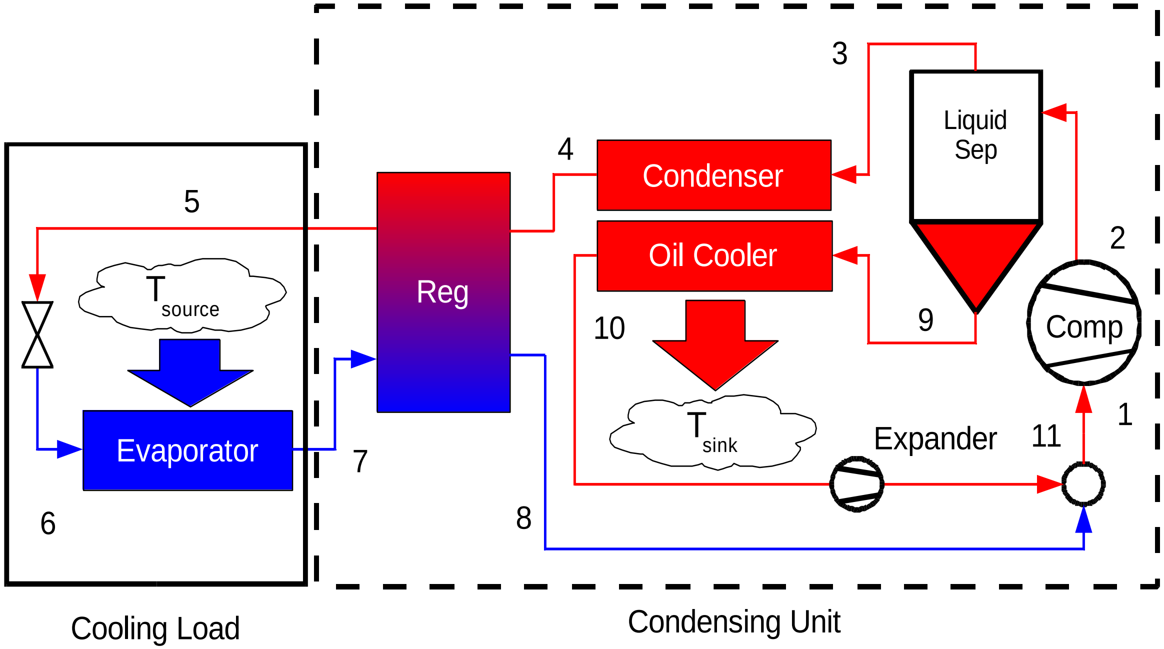
Vapor Compression Cycle System Enhancements to Improve Efficiency

Vapor Compression System Enhancements

- Liquid-flooded compression
  - Goal: to approach isothermal compression, which inherently requires less work
  - One approach is to construct high surface area compressors that can reject heat quickly during compression
  - Can also be accomplished by "flooding" or injecting a high specific heat liquid into the inlet gas stream of the compressor
  - The liquid absorbs the heat of compression with minimal temperature increase
  - The oil and refrigerant are separated after the compressor
  - Properly designed scroll and rotary compressors can tolerate sufficient liquid flooding to enable this technology

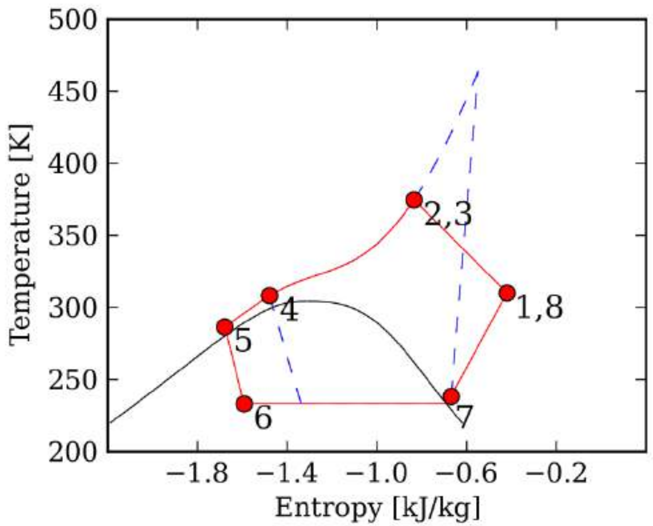
Vapor Compression System Enhancements

Liquid-flooded compression



Potential Cycle Diagram

T-s Plot for CO_2

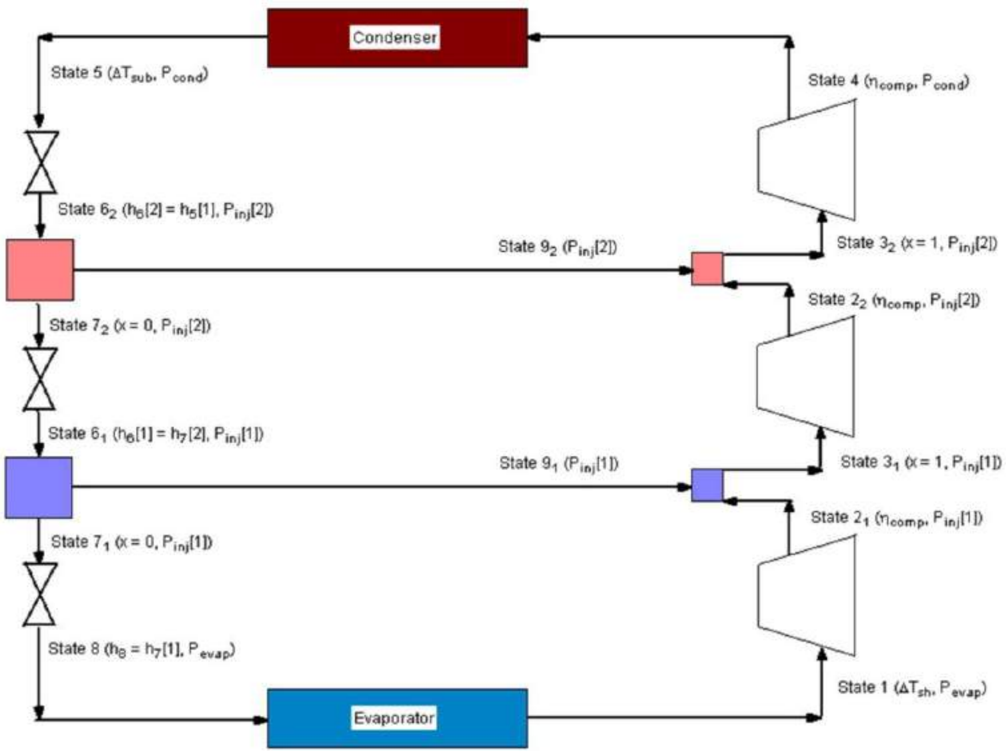


Vapor Compression System Enhancements

- Multi-port vapor injection with economizing
  - General idea is to approach the “saturation cycle” which follows the saturation curves both during compression and expansion
    - Approximately 22% more efficient in cooling mode at 35°C
    - Approximately 53% more efficient in heating mode at -25°C
  - Reduces desuperheating losses in the condenser
  - Reduces expansion losses by expanding predominantly low quality refrigerant
  - Enabled with properly designed scroll and rotary compressors
  - This is essentially multi-stage compression in one mechanism

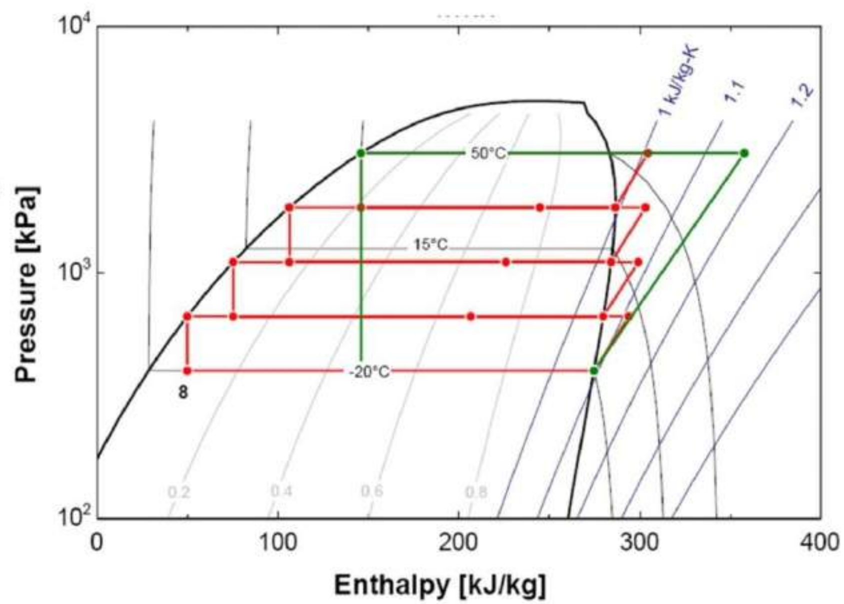
Vapor Compression System Enhancements

- Multi-port vapor injection with economizing



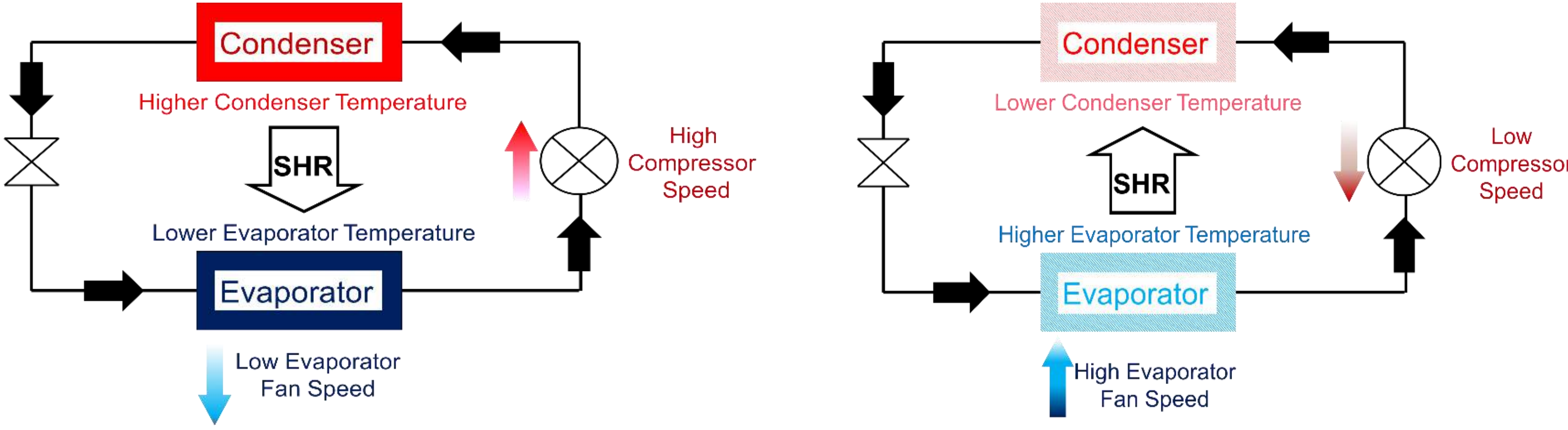
Schematic Cycle Diagram

P-h Plot for R410a



Vapor Compression System Enhancements

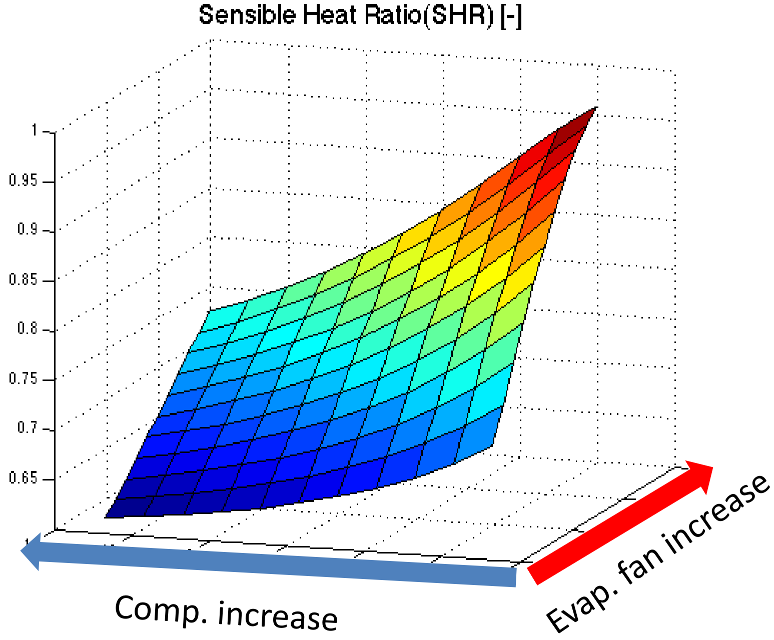
- Where can we go in the future with variable speed A/C technology?
- Separate sensible and latent cooling (SSLC)
  - Currently require two parallel systems
  - Variable speed systems can have multiple modes

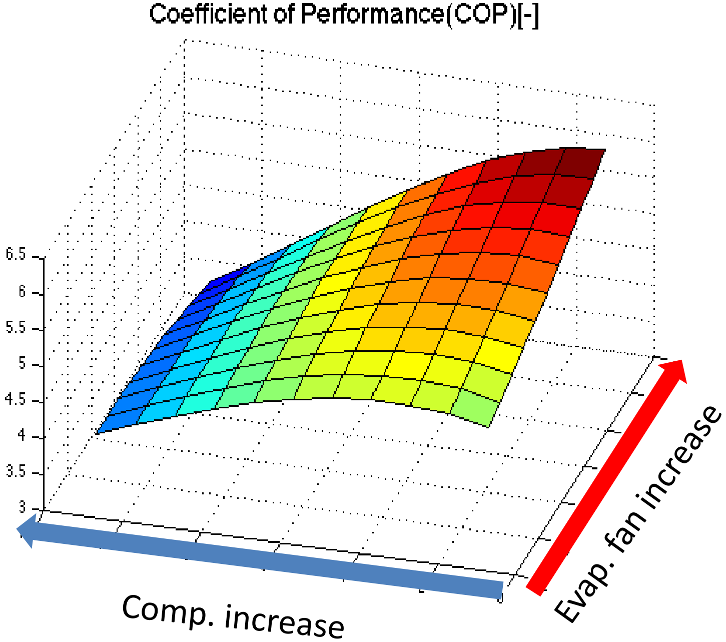


Vapor Compression System Enhancements

- A single VS A/C operated sequentially can meet both sensible and latent loads

T_outdoor	RH_outdoor	T_indoor	RH_indoor
34.7	30%	26.7	51%





Vapor Compression System Enhancements

- Benefits of a sequential SSLC system
  - Modeling and validation efforts have shown seasonal energy savings of ~25% or more
  - Based on readily available variable speed compressor/fan technology
  - Enables active humidity control in spaces without additional equipment
  - Extensive opportunities to implement in both new construction and retrofits
- Challenges
  - Requires careful control development
  - No recognition based on current rating standards

Automated Fault Detection and Diagnosis

Automated Fault Detection & Diagnosis

- Automated Fault Detection and Diagnosis (AFDD)
  - Studies indicate that as much as 30% energy savings could be achieved by fixing current HVAC systems in the field that are faulty
  - Around 20% annual energy savings could be achieved by maintaining HVAC systems at their optimum state of health
  - The impact of faulty system operation is not captured in current standard rating systems
  - Non-catastrophic faults can often be difficult to identify by system operators
    - Partially blocked air coils (evaporator and condenser), leaky compressor valves, non-condensable gases in the system, slow charge leakage, etc…

Automated Fault Detection & Diagnosis

- System level AFDD
  - Enabled through the use of a few inexpensive sensors that can infer the value of more complicated measurements (virtual sensors)
    - i.e. with 4-6 thermocouples it is possible to detect around 6 VC system faults
    - Virtual sensors require test data fro training
- Component level AFDD
  - Each component in the VC system has its own model and FDD predictive capability
  - Requires plug-and-play technology
  - Allows agent-based real-time optimization

Automated Fault Detection & Diagnosis

- Develop "Intelligent Vapor Compression System Components" with onboard AFDD
- Smart compressors
  - Accurate determination of compressor speed, power, torque, flow rate
  - Fault detection potential
    - Faulty capacitor (start and/or run)
    - Air gap eccentricity (bearing wear?)
    - Insufficient lubrication
      - Lack of oil return
      - Oil thinning due to liquid refrigerant return
      - Contaminated oil
    - Valve leakage

Automated Fault Detection & Diagnosis

- Smart heat exchangers
  - Accurate determination of capacity (sensible and latent), airflow rate, air and refrigerant-side pressure drop
  - Fault detection potential
    - Air-side fouling
    - Frost formation
    - Excessive oil accumulation in the heat exchanger
- Smart expansion devices
  - Accurate determination of refrigerant flow rate, high and low-side pressures
  - Fault detection potential
    - Non-condensable gases in the system
    - Expansion valve blockage

Automated Fault Detection & Diagnosis

- Already seeing regulation for AFDD in California (economizers for rooftop units)
- Current research efforts
  - Development of virtual sensors
  - Plug-and-play intelligent air conditioning systems
  - Automated procedures for training virtual sensors
  - Utilizing FDD data to determine optimal maintenance intervals

Thank You!