Energy Efficiency Opportunities in Industrial Refrigeration

Presented by the University of Delaware Industrial Assessment Center with the US EPA

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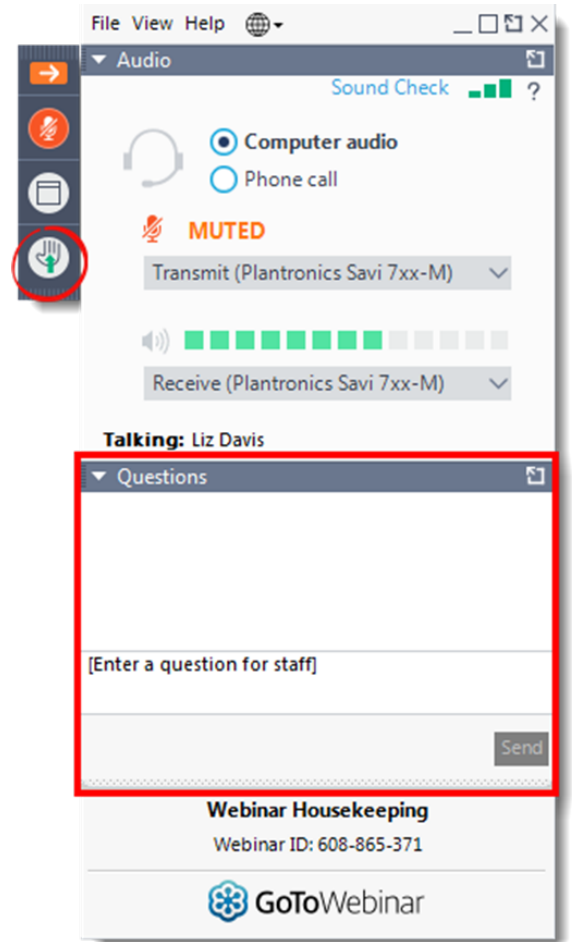

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Presenter Bio

Ralph Nigro, PE is the Assistant Director of the University of Delaware's Industrial Assessment Center. He began his career with Delmarva Power, spending 15 years on the planning, licensing, design, construction and start-up of power generation and environmental control projects. For the following 25 years he worked as Senior Vice President of Engineering and Technical Services for Applied Energy Group, where he oversaw the administration and implementation of numerous energy efficiency and renewable energy programs for utility clients, especially large commercial and industrial programs.

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- Established in 2006 in the Department of Electrical and Computer Engineering at UD
- We provide no-cost industrial energy assessments throughout the Mid-Atlantic region to manufacturing and process industries of all types while offering real-world training for engineering students
- Since 2017, we have provided assessments targeting food and beverage processing under an EPA Pollution Prevention Program grant
- Over 200 industrial assessments since our founding

Webinar Overview

- Focus on the most common industrial refrigeration systems and components
- Refresh the basics of the industrial vapor compression refrigeration cycle and key components
- Summarize efficiency opportunities at component and system levels
- Summarize efficiency opportunities for refrigerated space management
- Brief wrap up

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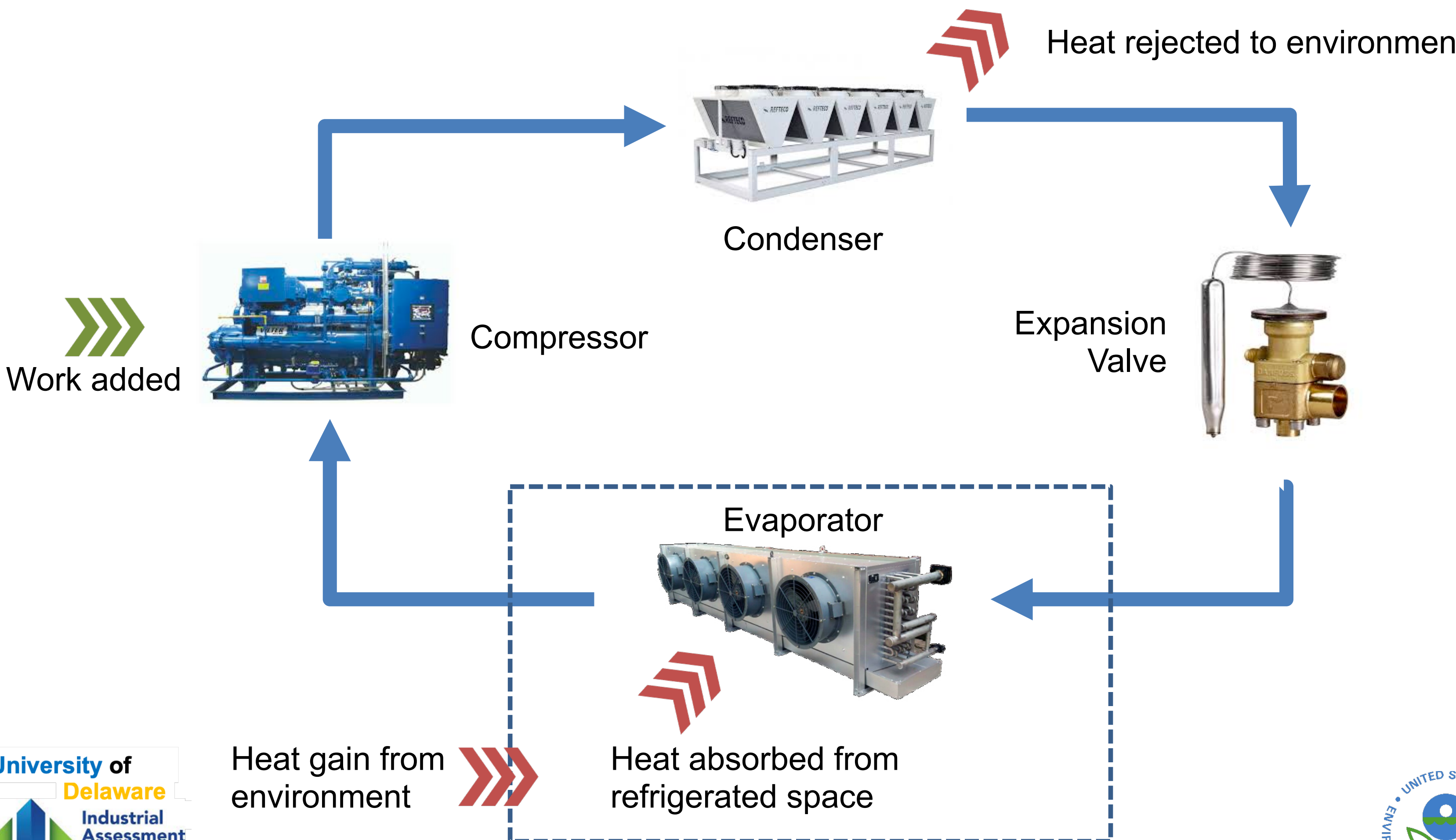
Refrigeration Basics

What is Refrigeration?

- In vapor-compression refrigeration, a refrigerant is used to move heat from a cooler to a warmer environment by adding work



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Basic Vapor-Compression Refrigeration Cycle

- The basic refrigeration cycle consists of:
  - Compression
    - Increasing pressure of cold refrigerant gas from evaporation stage
  - Condensation
    - Condensing high pressure gas by rejecting heat absorbed in evaporation stage and heat of compression to external environment
  - Expansion
    - Throttling warm, high pressure liquid refrigerant through an expansion valve, resulting in cold, low pressure liquid/gas refrigerant
  - Evaporation
    - Circulating cold refrigerant through a heat exchanger, absorbing heat from refrigerated space and evaporating the refrigerant

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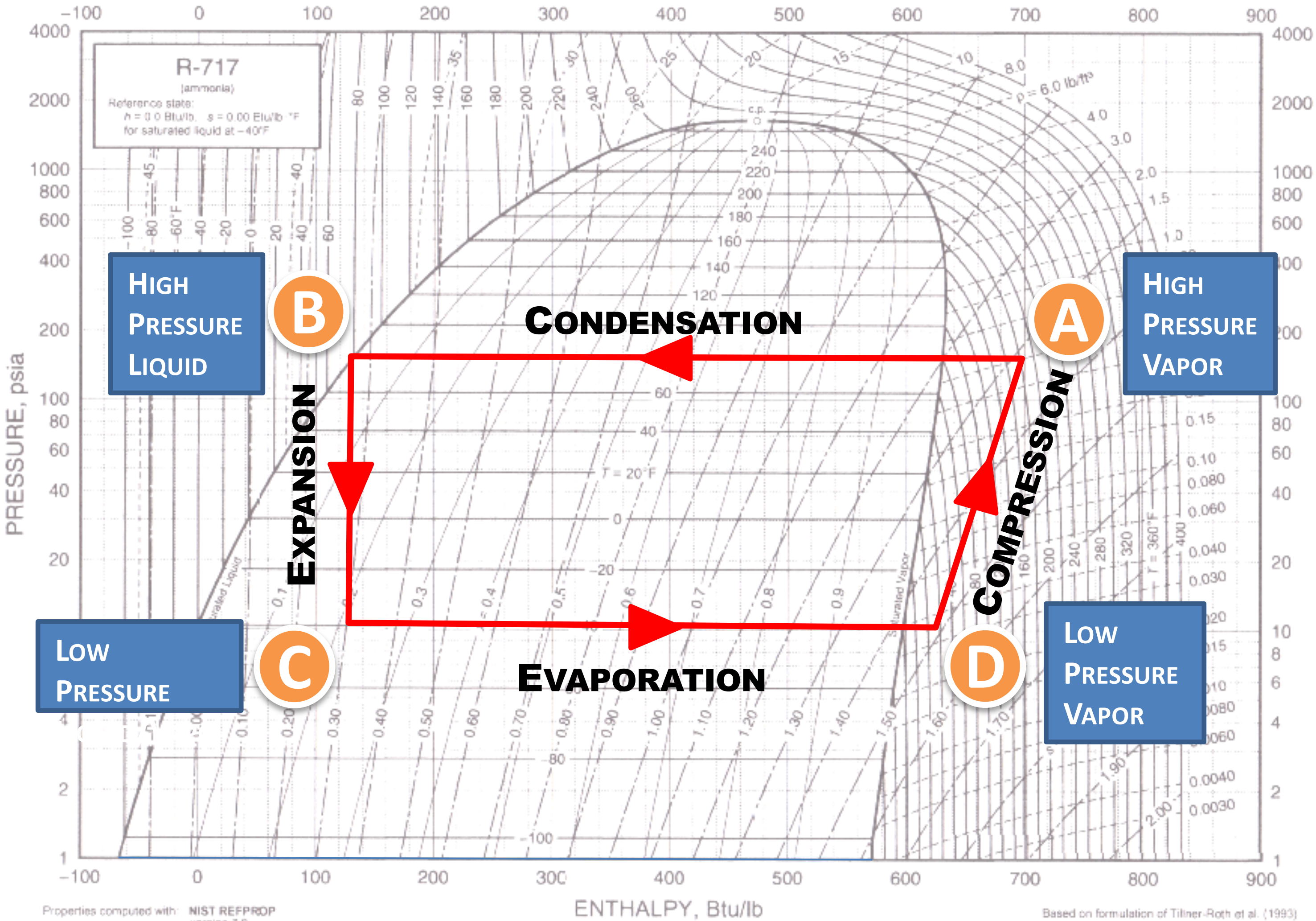
Simple Pressure-Enthalpy Diagram (Ammonia Refrigerant)



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Common Industrial Refrigerants

- Refrigerants are the working fluids in any refrigeration system
- Families of refrigerants:
  - Halocarbons (CFCs, HCFCs, HFCs)
  - Hydrocarbons (ethane, propane)
  - Inorganic (ammonia, CO_2)
- Common refrigerants used in industrial applications are:
  - Ammonia (R-717)
  - Chlorodifluoromethane (R-22)
  - Refrigerant blends (R-404a, R-410a, etc.)
- Large industrial systems primarily use ammonia

Refrigerant Performance Characteristics per Ton Refrigeration[1]

Refrigerant	Evap. Press. (psia)	Cond. Press. (psia)	Latent heat (Btu/lb)[2]	Mass flow rate (lb/min)	Spec. vol. suc. vapor (ft^3/lb)	Compr. Displ. (ft^3/min)	Compr. Power (hp)	Compr. Disch. Temp. (°F)	COP
R-11	2.9	18.1	83.72	0.84	12.32	10.35	0.264	109.1	5.02
R-123	2.3	15.8	80.54	0.93	14.28	13.26	0.274	91.1	4.90
R-12	26.3	107.5	68.76	1.12	1.48	1.66	0.284	100.1	4.70
R-134a	23.6	111.2	90.13	0.89	1.95	1.74	0.290	98.3	4.60
R-22	42.8	172.2	93.13	0.81	1.25	1.01	0.287	127.1	4.66
R-125	58.5	226.4	61.98	1.51	0.631	0.952	0.327	87.5	3.99
R-717	34.1	168.5	564.93	0.12	8.197	0.981	0.282	209.9	4.76
R-744	326.9	1041.4	115.99	0.51	0.269	0.138	0.257	157.7	2.69
R-290	41.5	155.9	169.79	0.47	2.502	1.17	0.292	96.5	4.50
R-404A	52.9	206.0	77.43	1.16	0.860	0.996	0.318	96.53	4.21
R-410A	69.3	271.5	102.55	0.77	0.873	0.674	0.298	123.5	4.41
R-507A	55.0	211.6	75.13	1.20	0.814	0.977	0.321	94.7	4.18

[1] Calculation basis: 5°F evaporating and 86°F condensing temperatures. Saturated suction vapor and isentropic compression. ASHRAE Fundamentals (2005).

[2] at 5°F.

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Refrigeration System Types

System Classifications

- By equipment configuration:
  - Direct expansion
  - Single stage overfeed/flooded
  - Two stage overfeed/flooded

ammonia refrigeration systems

- By temperature range:
  - High (greater than about 40°F)
  - Medium (between about -25°F and 40°F)
  - Low (less than -25°F)
- Systems can be packaged or built-up

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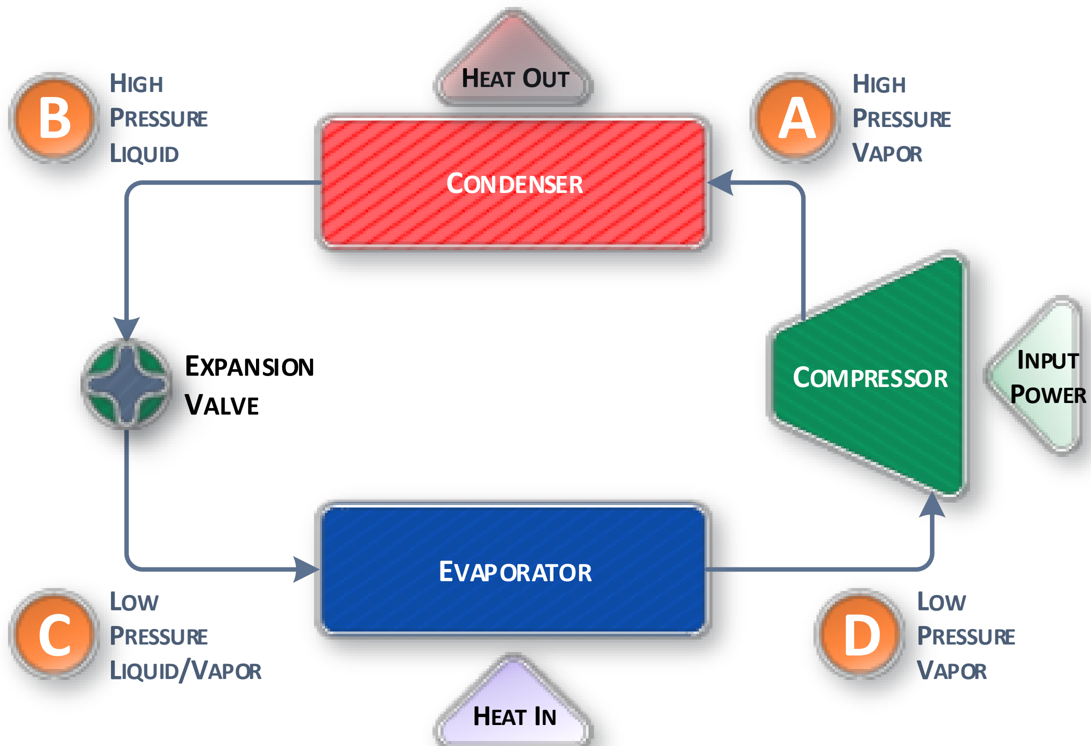
DX System - Schematic Diagram

- Commonly used for higher temperature HVAC and chilled water systems
- Often used in smaller, stand-alone, packaged medium and low temperature systems
- Mostly HFC and HCFC refrigerants



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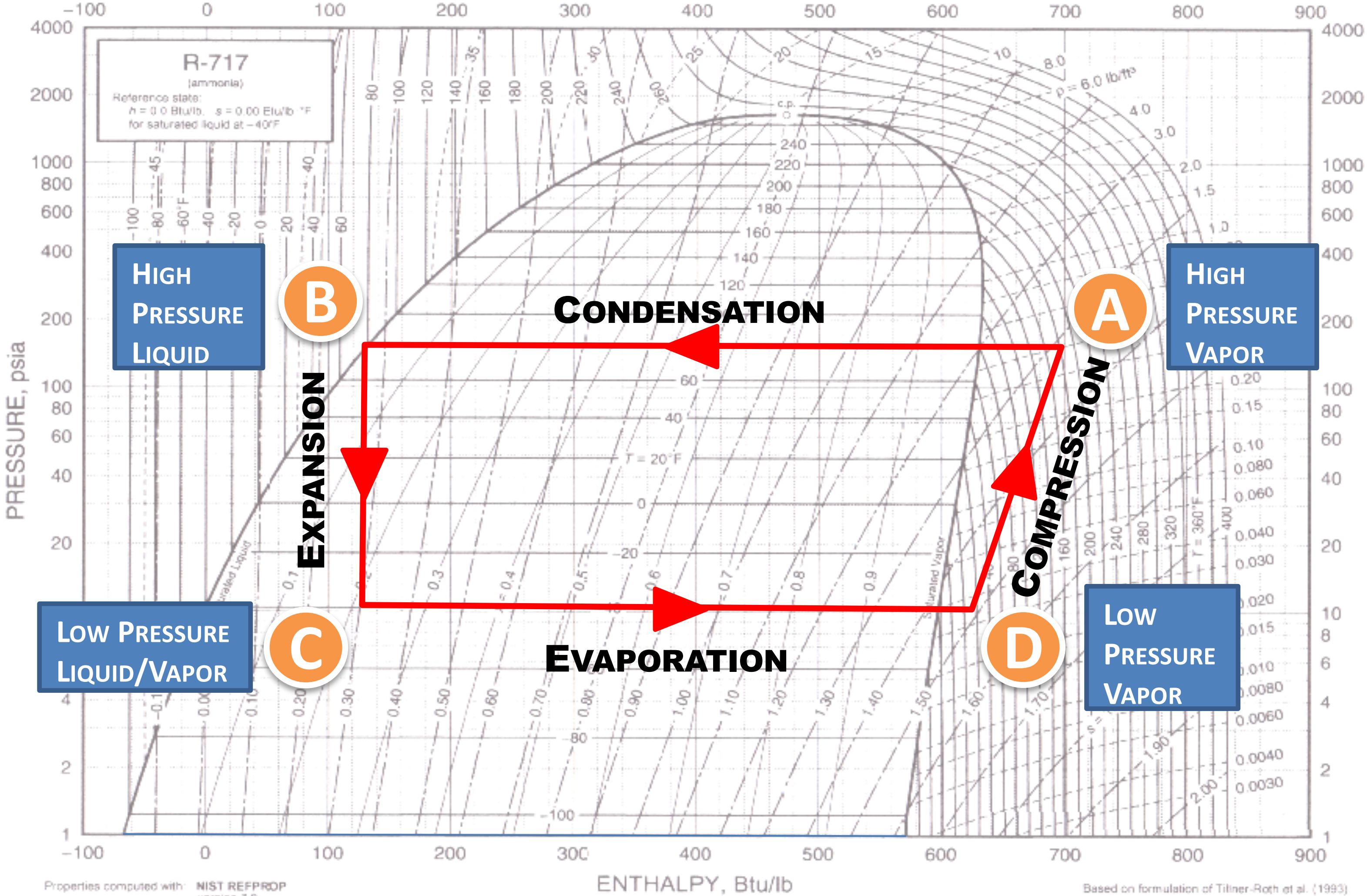
DX System



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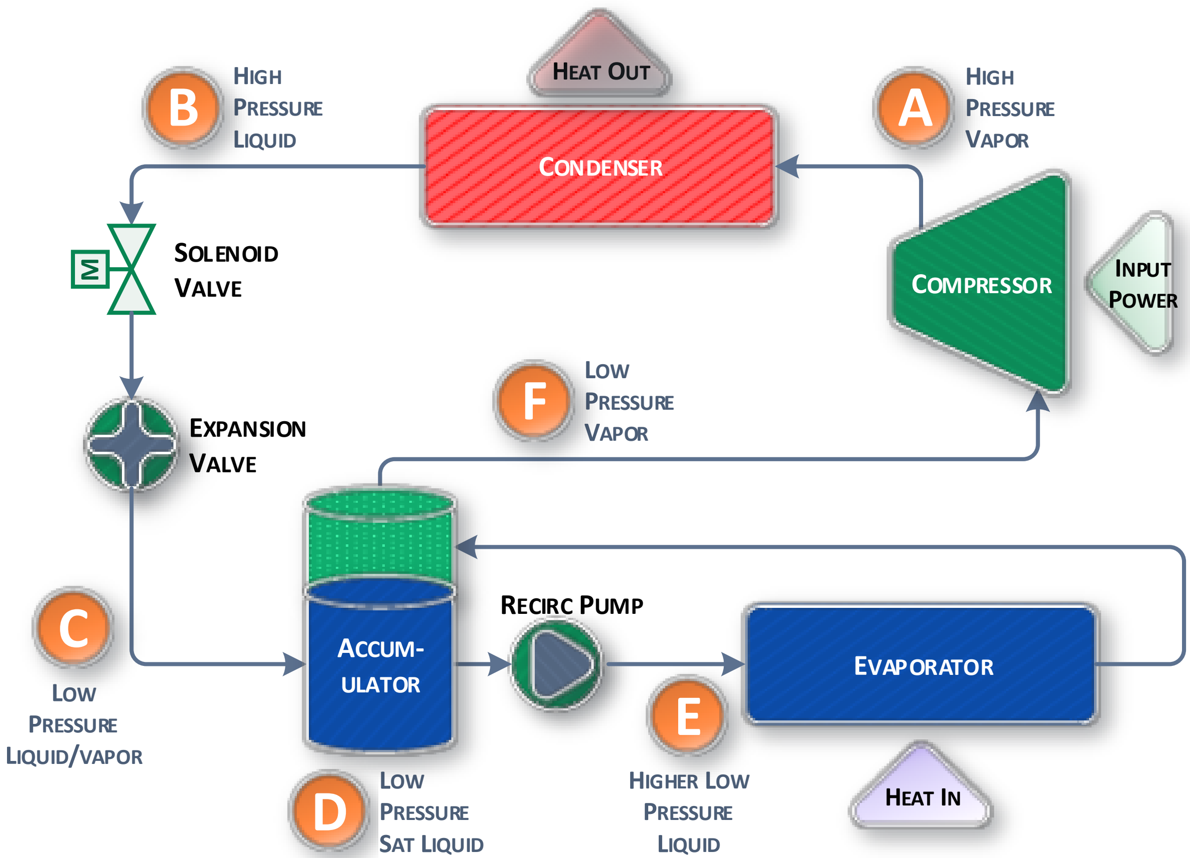
Single Stage Ammonia System

- Commonly used in large low and medium temperature applications
- Can be designed with or without recirculation pumps (“overfeed” vs “flooded”)



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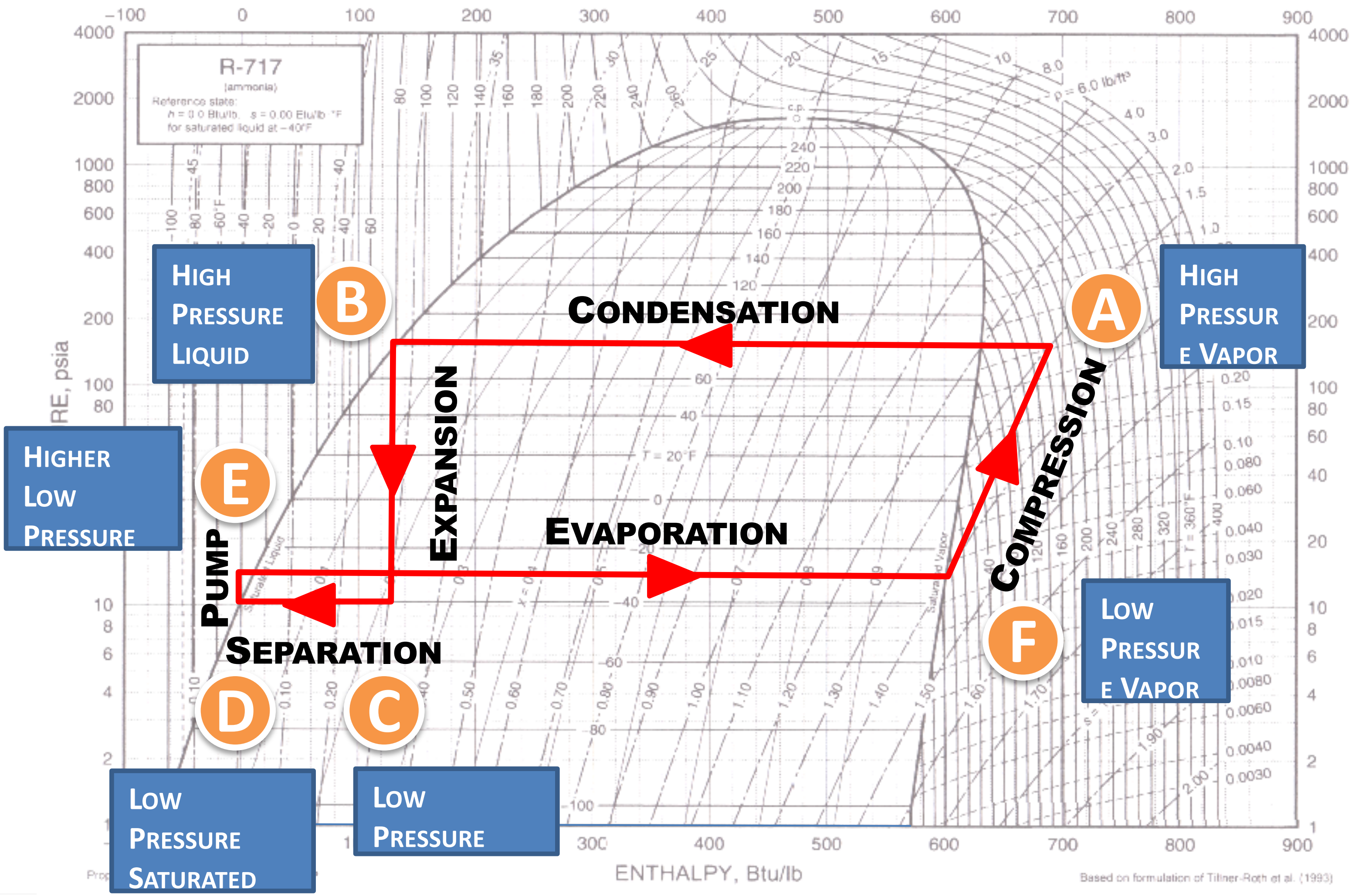
Recirculated System - Ph Diagram



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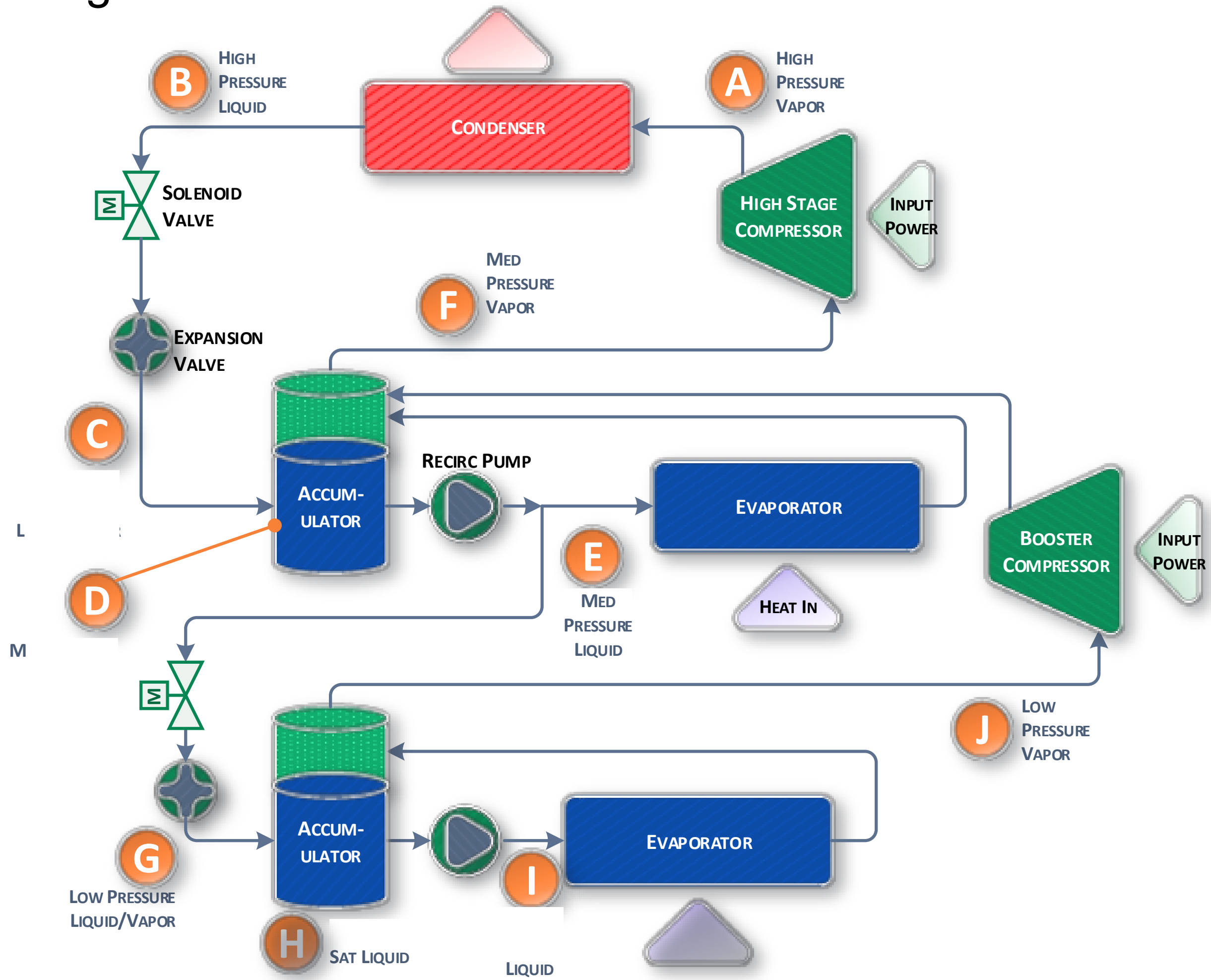
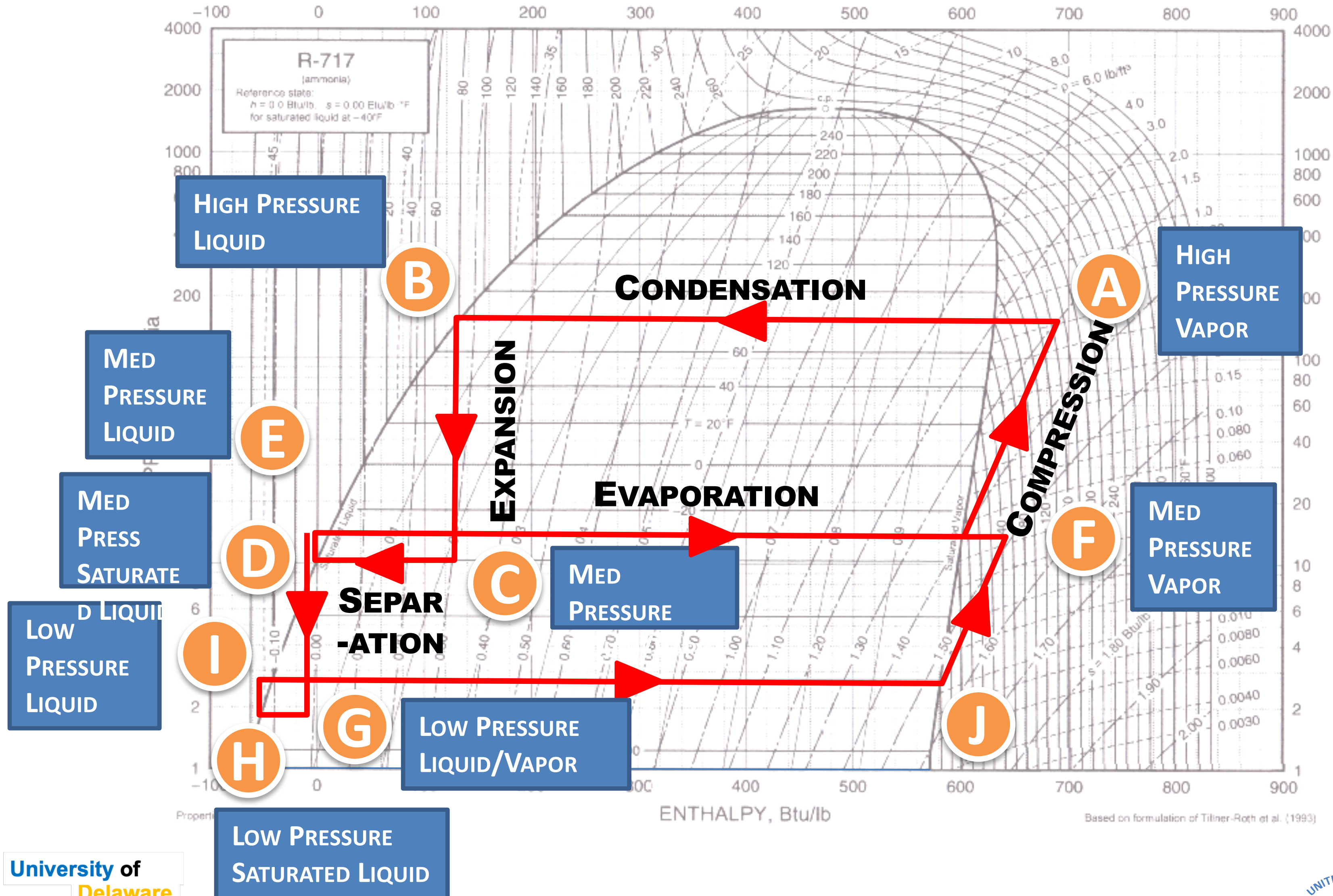
Two Stage Liquid Overfeed System

- Commonly used in low and multi-temperature refrigeration systems
- Can be designed with or without recirculation pumps
- Ammonia refrigerant



2-Stage Recirculated System - Ph Diagram



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Components of Refrigeration

Refrigeration System Components

Compressors

- The driving force to move heat
- Largest energy user in the system
- Compresses refrigerant from low pressure vapor to high pressure vapor
- Many different technologies in the market

Condensers

- The point of heat rejection
- Heat dissipated to atmosphere
- Energy is used for fan forced circulation and spray pumps for water.
- Typically air-cooled or evaporative-cooled

Evaporators

- The point where heat is removed from the material or space
- Exist in the form of air coils, heat exchangers, chillers
- Fan/Pump loads add heat
- Typically second largest energy user in the system

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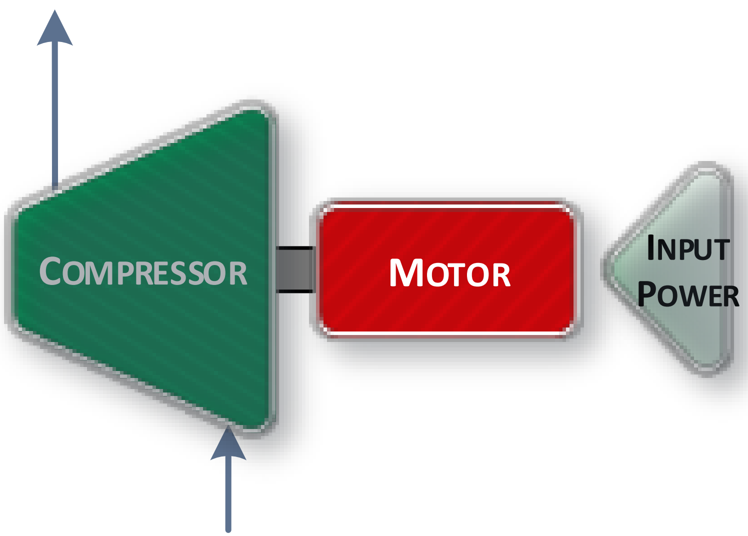
Compressors and Compressor Controls

Compressor Types

- Positive Displacement
  - Very common in medium and low temperature refrigeration systems
  - Reciprocating
  - Screw
  - Scroll
- Centrifugal
  - Most common in HVAC and process chiller systems

COMPRESSOR OUTLET:
HIGH PRESSURE
REFRIGERANT VAPOR



COMPRESSOR INLET:
LOW PRESSURE
REFRIGERANT VAPOR

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Reciprocating Compressors

- Oldest technology and still common in smaller systems
- Suitable for single stage or booster operation using most refrigerants
- Compressors may have up to 16 cylinders depending on size
  - May be as small as 10 HP or more than 300 HP for ammonia systems
  - Compression ratios up to 8:1 for ammonia
- Most common capacity control is staged unloading
  - Uses external actuator to hold the suction valves open

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Screw Compressors

- Suitable for single stage or booster operation using R22 or Ammonia
- Can operate with pressure ratios above 20:1 single stage
- Max sizes can exceed 1000 HP
- Available as lubricated (with oil) or non-lubricated (without oil)
- Can be single or twin-screw configuration
- Most common capacity controls
  - Variable displacement
    - Slide valves
    - Other means of varying the inlet or discharge point
    - Capable of operating within a wide capacity range (10 to 100%)
  - Changing compressor speed
    - Install a VFD on the compressor motor to be used in conjunction with slide valve
    - Provides better part load efficiencies below 60% slide valve

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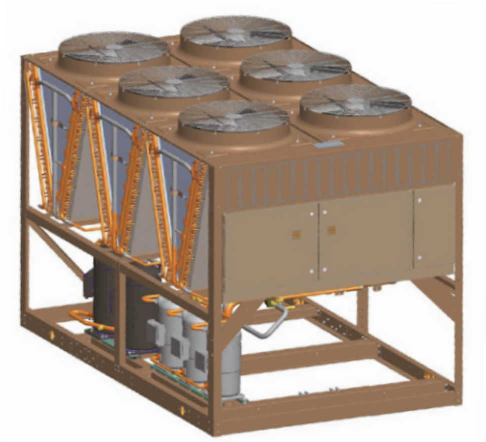
Condensers

Air-Cooled Condensers (Dry Coolers)

- In an air-cooled condenser, the following actions take place:
  - Refrigerant vapor is condensed in a coil.
  - Air is circulated over the coil.
- Usually configured as induced draft unit with multiple low HP fans
- Typically less efficient for the refrigeration system as the lack of evaporative cooling requires higher compression ratio on compressors
- Low operating costs and maintenance
- Performance is based on **<u>Outside Air Dry Bulb Temperature</u>**



Evaporative Condensers

- Evaporative condensers provide lower condensing temperatures and enable compressor horsepower savings of up to 15 percent compared with air-cooled systems.
- In an evaporative condenser, the following actions take place:
  - Refrigerant vapor is condensed in a coil, which is continually wetted on the outside by a recirculating water system
  - Air is circulated over the coil, causing a small portion of the recirculating water to evaporate
  - The evaporation removes heat from the vapor in the coil, causing it to condense
- Performance is based on **Outside Air Wet Bulb Temperature**

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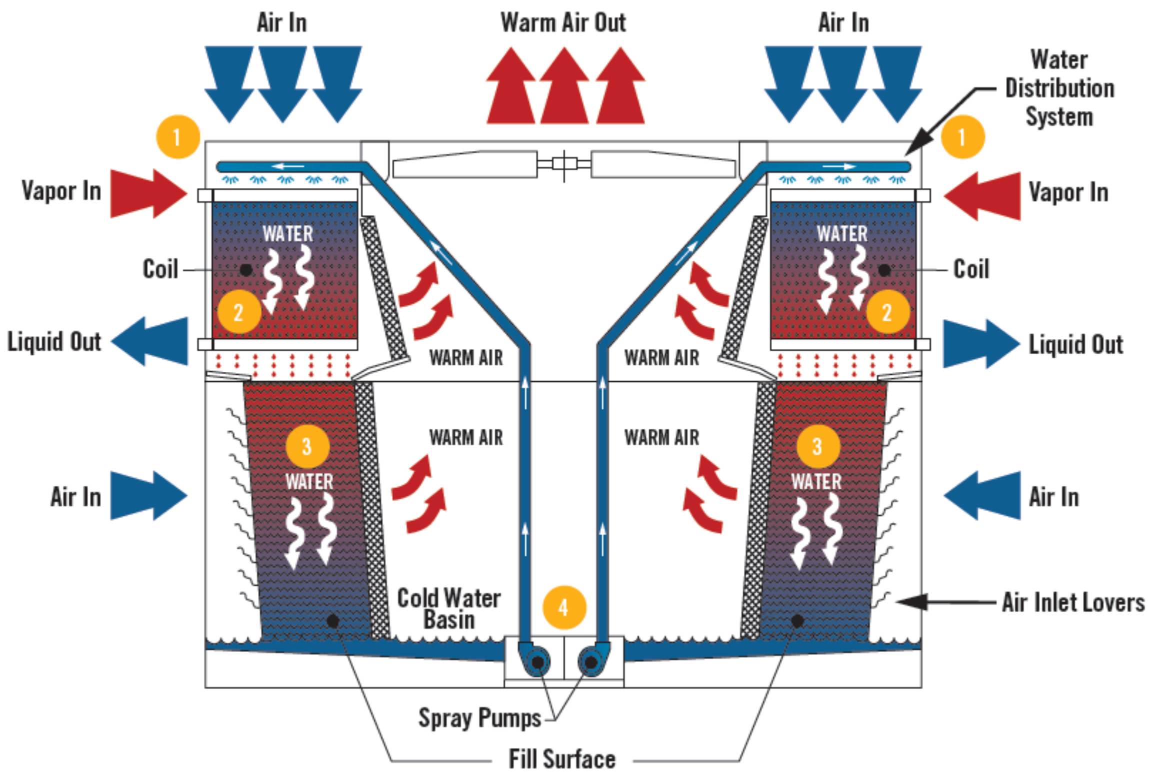
Evaporative Condensers



- Uses of both a condensing coil and fill surface for heat transfer in an evaporative condenser. The addition of fill surface to the traditional evaporative condenser design reduces evaporation in the coil section, reducing the potential for scaling and fouling.
- Some combined flow evaporative condensers utilize parallel flow of air and spray water over the coil, and crossflow air/water flow through the fill surface.
- In parallel flow, air and water flow over the coil in the same direction. In some fill sections in combined flow evaporative condensers, air and water interact in a crossflow configuration: water flows vertically down the fill as air flows horizontally across it.

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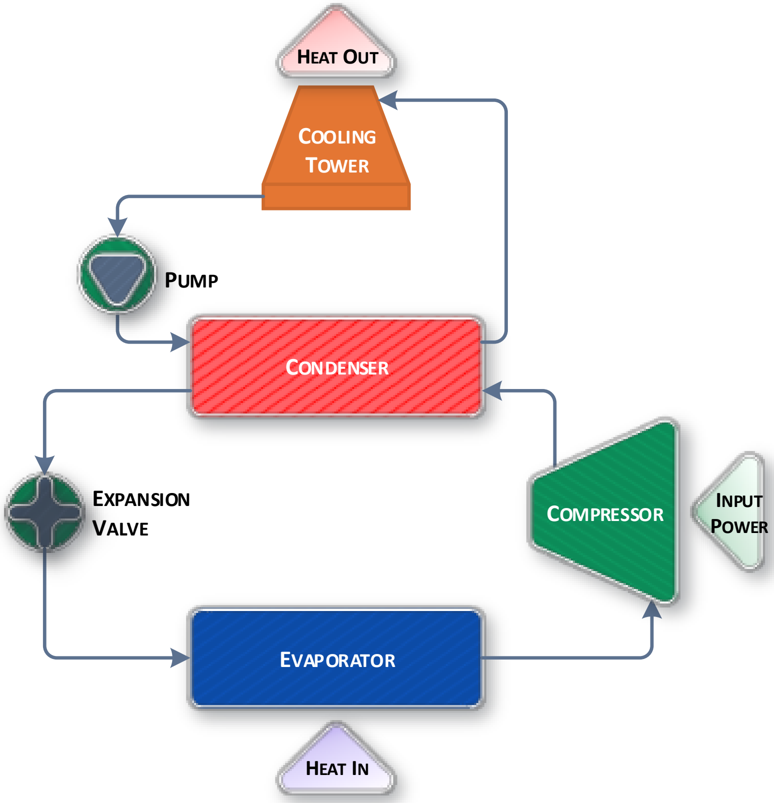
Cooling Towers

- In some cases the condenser on a refrigeration system is just a heat exchanger that moves heat to a secondary fluid before rejecting to atmosphere
- This requires the use of a cooling tower which cools a fluid using air
- There are two types of cooling towers
  - Closed Loop
    - A coil inside of the cooling tower does not allow the secondary fluid in direct contact with atmosphere
    - Water is sprayed over the coil to achieve the evaporative cooling effect similar to evaporative condensers
    - This method results in higher approach temperature
  - Open Loop
    - Water is circulated over the cooling tower in direct contact with atmosphere
    - As water evaporates from cooling it leaves behind the dissolved solids
    - The water needs to be treated or the solids can reduce the efficiency of the heat exchanger and cooling tower
    - This method results in a lower approach temperature
- Cooling towers in general operate in a very similar manner to evaporative condensers



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Evaporators

Evaporator Overview

- Provides cooling or freezing temperatures and proper airflow to the space
- Consists of a cooling coil and one or more motor driven fans
- Coil defrost equipment for low temperature operations when ice buildup may impede performance
- Other considerations and features
  - Coil type, fin spacing, overall surface area
  - Electric, hot gas, air, water, or hot brine defrosting
  - Discharge air velocity and direction
  - Centrifugal or propeller fans, belt or direct driven, blow through or draw through, ducted or non-ducted
  - Freestanding, ceiling-suspended, or penthouse (roof mounted)
  - Liquid Overfeed or DX refrigerant piping
  - Humidity control (reheat coil)

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Forced Circulation Air Cooler Examples

A+L High Profile Unit

- High profile for medium to large industrial applications
- "Plug-in" fan section for horizontal, 45° down, or penthouse air discharge
- High efficiency fans and premium efficiency motors standard
- Hinged fan panels standard
- Capacity range: 5 – 100 TR

A+M Medium Profile Unit

- Medium profile for small to medium industrial applications
- High efficiency fans and ***foot mounted motors*** up to 3 Hp
- Hinged fan panels standard
- Optional full coverage drain pan
- Capacity range: 2 – 50 TR

A+S Low Profile Unit

- Low profile for small to medium industrial applications
- High efficiency fans and motors up to 1 Hp
- Hinged fan panels standard
- Optional full coverage drain pan
- Capacity range: 2 – 35 TR

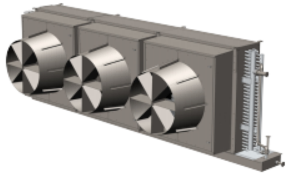
A+R Process Rooms

- "Above Rail" style air cooler for use in food processing rooms where cleanability is critical
- Optional CIP piping available
- Hinged access panels standard
- Full coverage insulated drain pan standard
- Capacity range: 3 – 25 TR

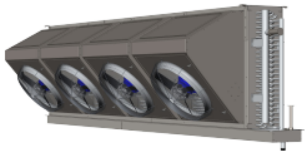
AIR DISCHARGE ARRANGEMENTS:

On applicable models, air discharge alternatives include:

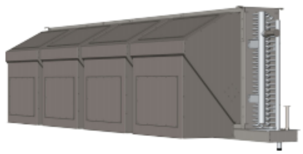
- Long throw adapters



- 45° down discharge

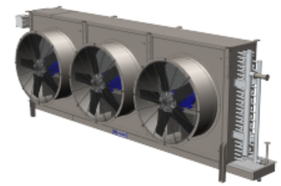


- 90° down discharge (penthouse adapters)



45° and 90° penthouse options feature heavy-duty discharge housings that tilt the fans 45° down from the vertical plane. These housings ship installed for ease of installation. Access panels are provided on penthouse adapters to permit service access.

- Fans selected for external static pressure (ESP)



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Coil Defrost Summary

Defrost Method	Applications	Advantages	Disadvantages
Hot Gas	Widely used in all industrial and commercial refrigeration. Uses compressed refrigerant vapor.	• Able to achieve effective defrosts • Uses lower grade of energy (“waste heat” from refrigeration system) • Can be effective at scavenging and returning oil that may accumulate in evaporator	• Increased safety risks due to hydraulic hammering from liquid slugs if sequence of operation not managed properly • Extremely high pressures (for CO2 refrigerant) • Increased parasitic energy consumption with improper valve group design and mis-adjustment
Electric	Used in some commercial systems and in industrial systems where CO2 is used as a cascade refrigerant or secondary loop phase change fluid. Requires electrical resistance heating element to remove frost from coil.	• Decreased risk of damage from events such as hydraulic hammer • Minimizes parasitic load • Avoid extreme refrigerant-side pressure (CO2 refrigerants)	• Poor use of high grade primary energy (electricity) • High maintenance due to frequent failure of resistance heating elements • Not effective at removing oil accumulation from evaporators
Off-Cycle (Air Defrosting)	Used in industrial and commercial systems for spaces operating above freezing point.	• Efficient means of defrost • Simple implementation • Inherently safe • Lower capital and maintenance costs	• Not relevant in applications where space temperature is below freezing • Not effective at removing oil accumulation from evaporators
Water	Found in some low temperature freezing systems where defrost is integrated into the normal clean up operations.	• Applies heat directly to the accumulated frost • The defrost process may be integrated into normal sanitation cycle	• Difficult to apply during “defrost on the fly” for low temp applications • Not effective at removing oil accumulation from evaporators • Extremely high water usage
Secondary Fluid (indirect)	An alternative to electric defrost in CO2 cascade and secondary phase change systems. Uses fluid like glycol to flow over outside of coil to remove frost.	• Conceptually simple • Avoids risks of hydraulic hammering on refrigerant side of coil	• Additional secondary fluid system and circuiting • Not effective at removing oil accumulation from evaporators • Requires energy to heat secondary fluid

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Energy Efficiency Opportunities

Causes of Inefficiency

- Excessive compressor lift
- Poor part-load performance
- Defrost controls
- Unnecessary refrigeration loads
- Auxiliary component efficiencies

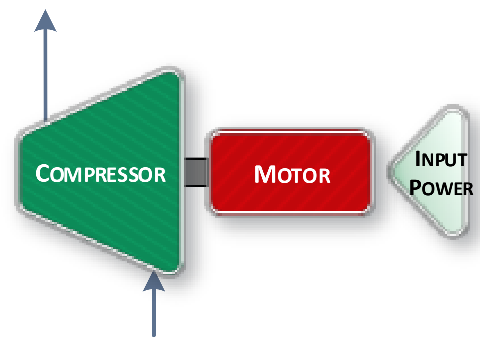
Excessive Compressor Lift

- The compressor is the largest energy-using component
- Two methods to reduce the lift across the compressor
  - Increase suction pressure
  - Floating head pressure control

Compressor Lift

- Refrigerant properties fix pressure-temperature relationship
- Compressor input power is proportional to the pressure differential between suction and discharge (lift)
  - Condensing and evaporation temperatures are often fixed setpoints
  - Condensing temperature is usually 15°F to 20°F higher than highest ambient temperature (wet or dry bulb)
  - Suction pressure is usually based on an evaporator design TD of 12°F to 15°F
- Increasing suction pressure and/or decreasing discharge pressure reduces lift and energy consumption by the compressor

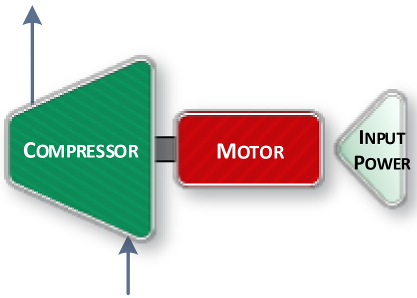
Discharge pressure is determined by the condensing temperature



Suction pressure is determined by the lowest evaporator temperature in the system

Increasing Suction Pressure

- Reduce suction pressure drop
  - Select larger evaporator coils
  - Evaluate suction piping size and pressure drop
  - Target low temperature systems where pressures are also lower
- Evaluate the lowest temperature parts of the system
  - It could be beneficial to segregate smaller, low temperature systems from larger medium temperature systems served by the same compressors
  - Can lowest temperatures be increased even slightly?
- Annual system energy savings up to about 10%



Increasing suction temperature by 1°F will reduce input power by approximately 2%

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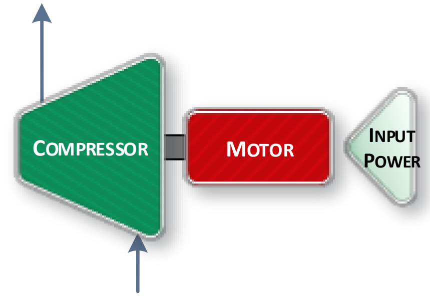
Decreasing Discharge Pressure

- Condenser temperatures are usually designed to be 15°F to 20°F higher than the highest expected ambient temperatures
  - If fixed setpoint is used, this means that compressor discharge pressures are also fixed
  - In the mid-Atlantic this can be more than 180 PSIG (about 75°F WB, 95°F condensing temp) for evaporative condensers; 250 PSIG (about 95°F DB, 125°F condensing temp) for dry coolers
- Floating head pressure control
  - Allows the condensing temperature to "float" with ambient conditions
  - In cooler weather, condensing temperatures can be decreased to stay at or around 15°F to 20°F above ambient wet or dry bulb by operating fans differently/more frequently
- Annual system savings will vary
  - Some systems require minimum compressor discharge pressures for defrost, liquid injection oil cooling, and other requirements
  - Condenser fan energy consumption will increase
- Annual system energy savings range is typically 5% to 12%

Decreasing condensing temperature by 1°F will reduce input power by approximately 1.5% to 2%



Poor Part-Load Performance

- Systems operate most of the time at partial load
- Equipment and operating strategies play an important role in maximizing efficiency.
  - Compressor staging, loading and unloading
  - Use VFDs

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Reciprocating Compressors

- Reciprocating compressors with cylinder unloading have very good part-load efficiency
  - Compressor staging (multi-compressor systems) and unloading strategies help manage suction pressure
  - Generally, more unloading stages allows better control and load matching

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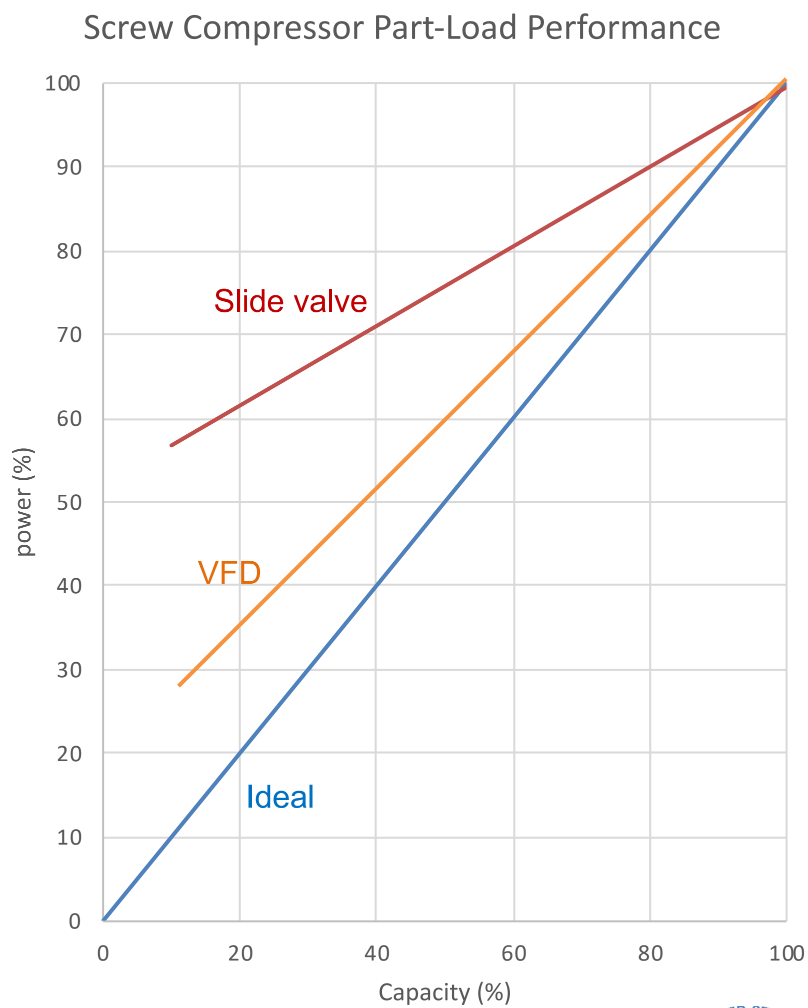
Screw Compressors

- Screw compressors have poor part load performance
  - Screw compressors using slide valves should be base-loaded most of the time if possible
  - Variable frequency drives increase part-load efficiency significantly



Sequencing Strategies

- Compressor sequencing strategies should be designed to match load with all but the last compressor operating at or near full load
- In systems with both screw and reciprocating compressors, screw compressors should be base loaded as much as possible
- Screw compressors with VFDs should be used as “trim” compressors
- Operating multiple screw compressors (without VFDs) at partial load is the least efficient approach
- Proper staging can reduce annual system energy usage by 5% to 15%

Defrost Controls

- Defrosting is required to prevent ice build-up on evaporator coils
- Defrosting should be carefully controlled.
  - Most defrost methods increase refrigeration loads by adding heat to the refrigerated space
  - Frost build-up depends on many factors, including local humidity, infiltration rates, product being stored, etc.

Defrost Methods

- Air defrost
  - Evaporator fans stay on to melt frost when refrigerant is shut off
  - Can be used when the refrigerated space temperature is above 32°F
  - Does not add heat to the refrigerated space
- Electric defrost
  - Uses electric heating elements to melt frost
  - Lowest efficiency in terms of electricity usage
- Hot gas defrost
  - Uses hot gas from compressor discharge to melt frost

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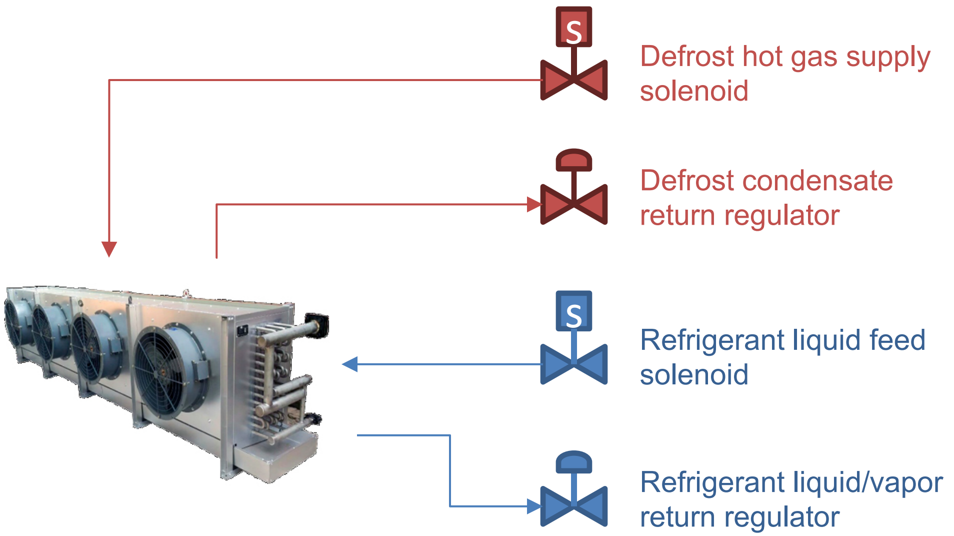
Improving Defrost Controls

- Regardless of the defrost method, a key objective is to minimize defrosting frequency and duration
  - Time clocks are common, but imprecise
  - Liquid run-time controls measure the amount of time an evaporator is in cooling mode; defrosting is less frequent during low demand periods
  - Frost sensors measure frost build-up directly to initiate and terminate defrosting
- Actively managing defrost frequency and duration can reduce annual system energy usage by about 3%

Improving Defrost Controls

- For hot gas defrost
  - Objective is to avoid returning a large amount of vapor to the compressor suction
  - In multi-stage systems, condensed gas should be returned to the compressor(s) with highest suction pressure
  - Regulators should be sized and adjusted properly to avoid too much defrost gas flow
  - Automatic liquid drainers (much like steam traps) should be considered to minimize vapor return



Unnecessary Refrigeration Loads

- Reduce unnecessary refrigeration loads
  - Refrigerated space design and insulation
  - Refrigerated space infiltration reduction
  - Refrigerant line insulation
  - Reduce internal parasitic loads
  - Destratification
  - Inventory management

Refrigerated Space

- Review design and operations
  - Is the space being used for designed purpose?
  - Review insulation levels, operating temperatures
  - Manage inventory loading/unloading to avoid unnecessary entry
- Reduce infiltration sources
  - Reduces both sensible and latent loads
  - Reduces defrost requirements
  - Strip curtains, fast roll doors, vestibules can be installed
- Reduce parasitic heat loads for lighting
  - Replace fluorescent and metal halide lighting with LED
  - Use occupancy sensors
- Destratification
  - In high bay refrigerated spaces, cold air tends to settle, but temperature sensors are usually located near ceiling causing unnecessary evaporator operation
  - Use evaporator hoods or destratification fans to equalize temperatures

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Other Component Efficiencies

- Evaporator fan motors
  - Use the most efficient motors possible for the application
  - For smaller fans, replace single-phase shaded pole motors with electronically commutated motors (ECMs)
  - Use VFDs where possible – up to 2% annual system energy savings
- Condenser fan motors
  - On smaller, packaged systems, use ECMs where applicable
  - Use VFDs on larger evaporative condensers and cooling towers in conjunction with floating head pressure control – up to 3% annual system energy savings
- Heat recovery
  - Consider compressor heat recovery for underfloor heating, boiler make-up feedwater pre-heating, and hot water for cleaning
  - Up to 4% annual system energy savings

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Wrap Up

- Significant savings can be found in industrial refrigeration systems if you know where to look
- Consider a refrigeration audit
- The low hanging fruit can often be addressed through relatively inexpensive controls and operating modifications

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Contact Information

Please contact us with questions or if you are interested in conducting an assessment in the Mid-Atlantic region

- UD-IAC Director:
  - Dr. Keith Goossen goossen@udel.edu
- UD-IAC Assistant Director:
  - Ralph M. Nigro, PE rnigro@udel.edu

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