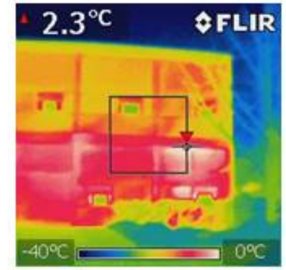
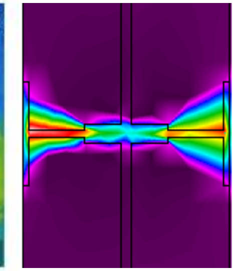
CAE 331/513
Building Science
Fall 2015





Week 9: October 22, 2015
Mechanical properties of HVAC systems: Refrigeration cycles

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Dr. Brent Stephens, Ph.D.
Civil, Architectural and Environmental Engineering
Illinois Institute of Technology
brent@iit.edu

Catch up from the last couple of weeks

- Exam 1 last week
  - I am still grading them
- Guest lecture on Tuesday
  - Benny Skelton and Irina Susorova, Cyclone Energy Group
  - Fionna Martin, ASHRAE IL student coordinator

The last few topics we covered (Oct 1 and 6)

- Mechanical systems and psychrometric processes
  - Primary and secondary equipment
  - Typical air distribution systems
  - Sensible and latent cooling
  - Heating and humidification
  - Evaporative cooling
  - Adiabatic mixing

Today’s objectives

- Introduce heating, ventilating, and air-conditioning (HVAC) systems and their mechanical properties
  - *How do building mechanical systems work?*

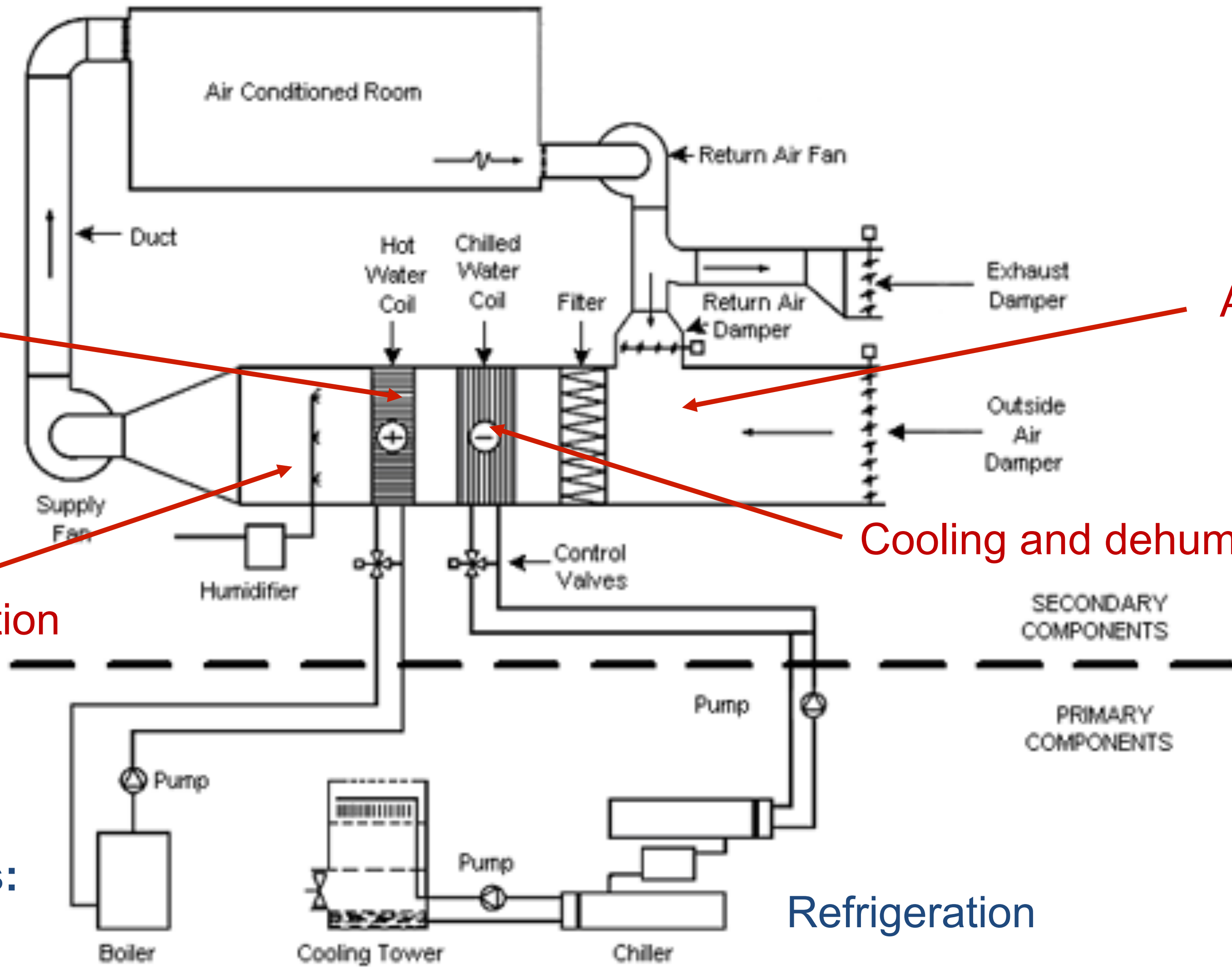
- Topics for the rest of the course:
  - Refrigeration cycles
  - Air and water distribution systems
  - Ventilation and indoor air quality
  - Heating load calculations
  - Cooling load calculations
  - Energy estimation and building performance

HVAC SYSTEMS

How do they actually work?

Primary and secondary components of HVAC systems

Some common psychrometric processes:



Heating

Air mixing

Cooling and dehumidification

Humidification

Common primary processes:

Refrigeration

Heat generation

Heating systems

- Heating systems are pretty straightforward
  – Add energy to heat a medium (e.g., air or water)

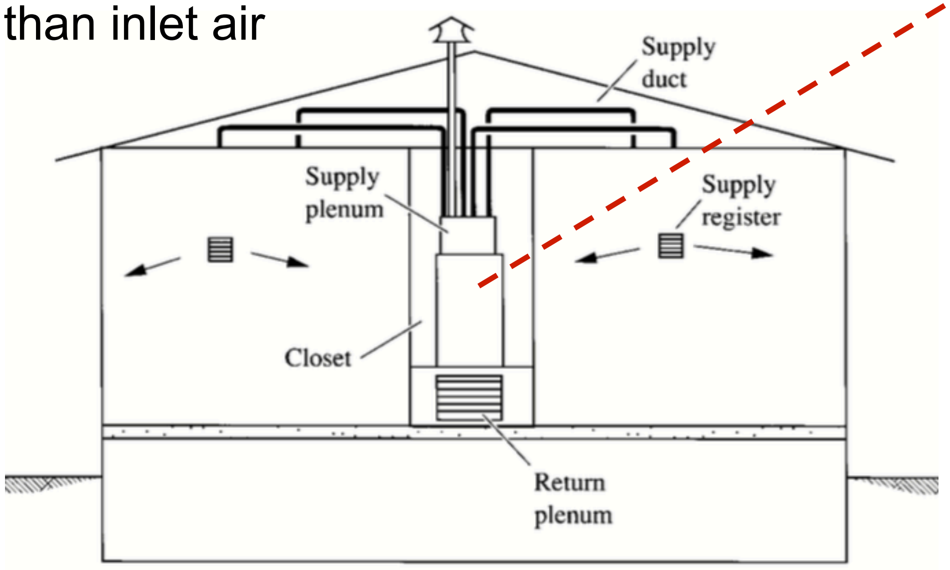
- Heating systems vary by building type:

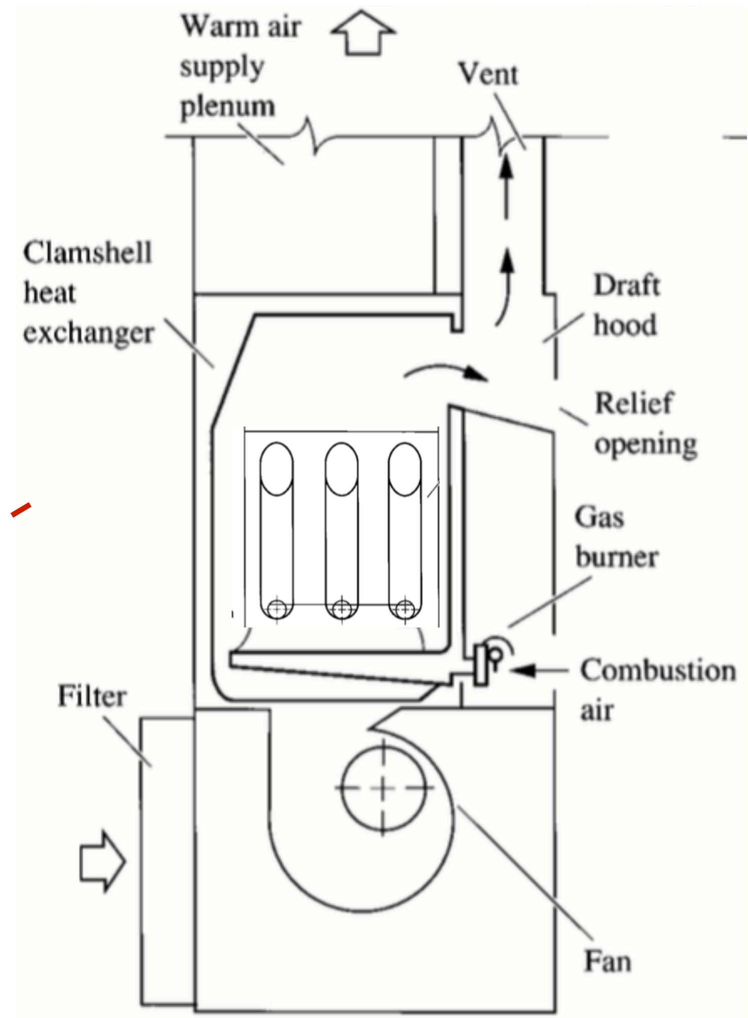
	Commercial, percent	Residential, percent
Heating systems using boilers	28	33
Warm air furnaces and packaged heating units	24	37
Heat pumps	10	30
Individual space heaters including electric, gas, and radiant heaters	28	
District heating	10	

Heating systems: Warm air furnaces

Warm air furnace

- Gas or oil is directly fired (combustion) to heat air passing through a heat exchanger (or air is directly heated by electric resistance elements)
- Most common fuel: Natural gas
  - Capacities up to 175,000 BTU/hr are typical
  - Exit air is typically 50-80°F (28-45°C) higher than inlet air





Heating systems: Warm air furnaces

- Thermal efficiency, E_t
  - Ratio of energy output of the fluid (air or water) to the fuel energy input

$$E_t = \frac{100\,(\text{fluid energy output})}{\text{fuel energy input}}$$

- Annual fuel utilization efficiency, AFUE
  - Ratio of *annual* energy output of the fluid (air or water) to the *annual* fuel energy input (accounts for non-heating season pilot losses)

$$\text{AFUE} = \frac{100\,(\text{annual output energy})}{\text{annual input energy}}$$

Construction characteristics	AFUE, percent
Natural vent	
Pilot ignition	64.5
Intermittent ignition	69
Intermittent ignition + venting damp	78
Power vent	
Noncondensing	81.5
Condensing	92.5

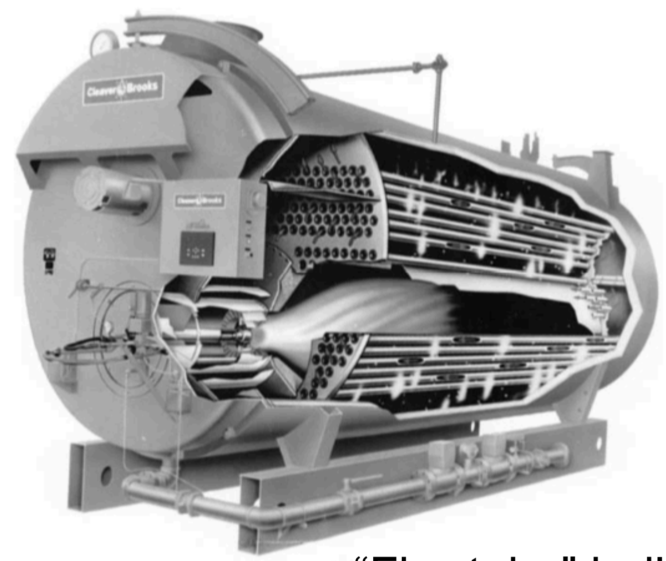
Heating systems: Hot water boilers

Hot water boiler

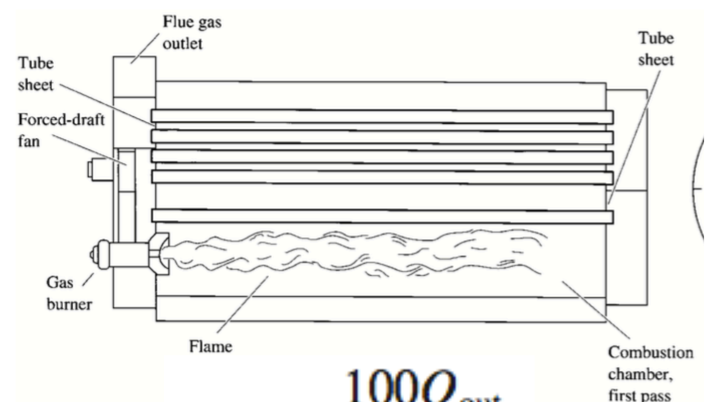
- Enclosed pressure vessel in which water is heated to a required temperature and pressure without evaporation
- Most common fuel: Natural gas
  - Capacities up to 50,000 MBTU/hr are typical

Gas-fired boilers	71 percent
Oil-fired boilers	15 percent
Electric boilers	11 percent
Others	2 percent

- Low pressure boilers
  - Working pressure up to 160 psig (1.1 MPa)
  - Working temperature up to 250°F (121°C)
    - Common for low temperature water (e.g., single buildings)
- High pressure boilers
  - Higher temperature and higher pressure (e.g., 300-400°F (150-205°C)
    - Common for large building complexes and campuses



"Fire-tube" boiler



$$E_c = \frac{100Q_{out}}{Q_{fuel}}$$

Cooling: Refrigeration systems

- **Refrigeration** is the process of extracting heat from a lower temperature heat source, substance, or cooling medium, and transferring it to a higher temperature heat sink
  - Refrigeration maintains the temperature of the heat source below that of its surroundings while transferring the extracted heat, and any required energy input, to a heat sink (such as atmospheric air or surface water)

- A **refrigeration system** is a combination of components and equipment connected in a sequential order to produce the refrigeration effect

Types of refrigeration systems

- **Vapor compression systems** (most commonly used)
  - Compressors activate the refrigerant by compressing it to a higher pressure and higher temperature after it has produced its refrigeration effect (high P, high T)
  - The compressed refrigerant transfers its heat energy to the sink (e.g., ambient air) and then is condensed into a liquid
  - The liquid refrigerant is then throttled (i.e., expands) to a low pressure, low temperature vapor (low P, low T) to produce the refrigerating effect during evaporation
  - The refrigeration cycle then repeats itself

Other types of refrigeration systems

- **Absorption systems**
  - The refrigeration effect is produced by thermal energy input
  - After absorbing heat from the cooling medium during evaporation, the vapor refrigerant is absorbed by an absorbent medium
  - The absorbent+refrigerant solution is then heated (by a furnace, waste heat, hot water, or steam), which converts the refrigerant to a vapor again, which then absorbs heat from the medium during evaporation and the cycle repeats
- **Air or gas expansion systems**
  - Air or gas is compressed to a high pressure by mechanical energy
  - It is then expanded to a low pressure
    - Because the temperature of the air or gas drops during expansion, a refrigeration effect is produced

What do these systems all have in common?

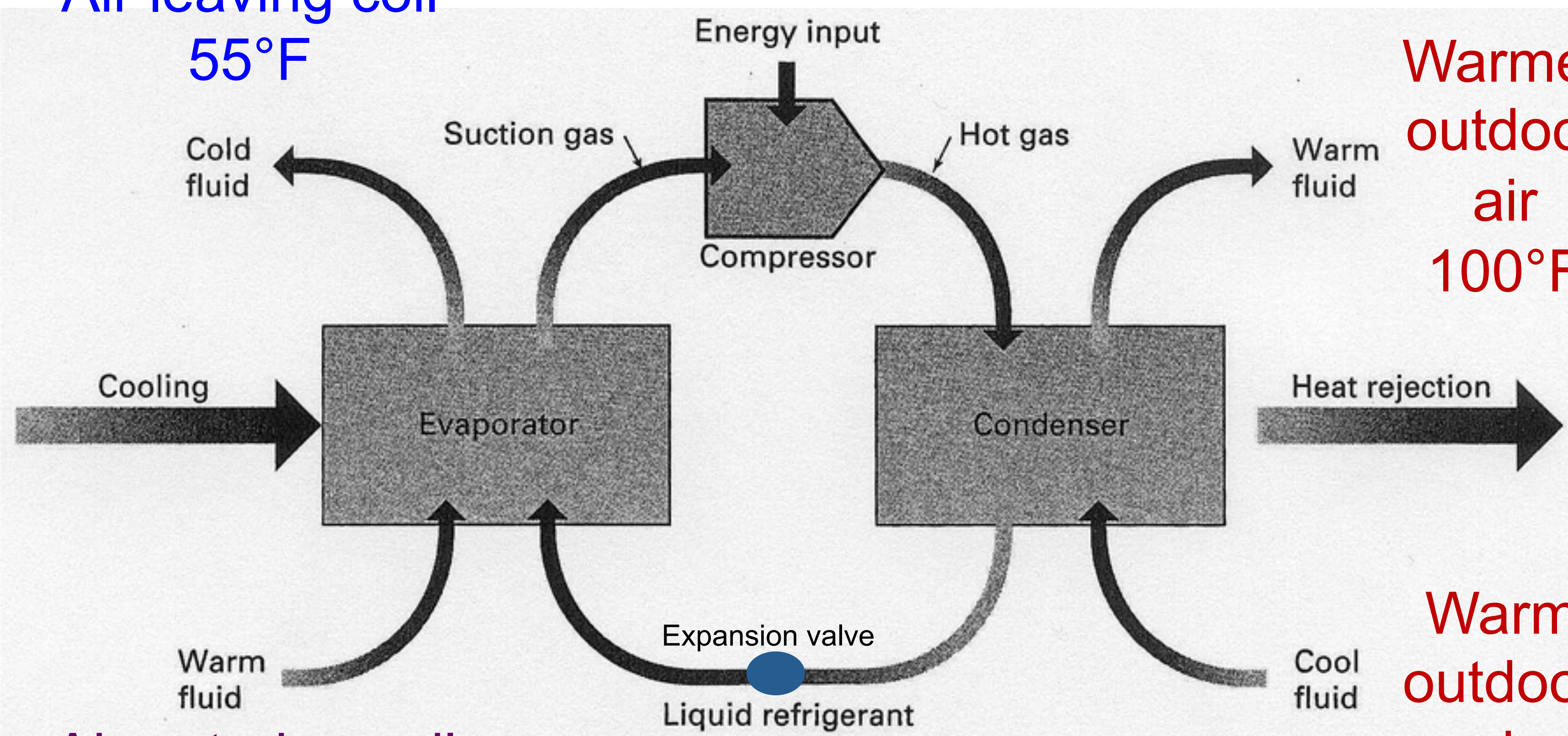
Fundamentals of vapor compression systems

https://www.youtube.com/watch?v=2wZb6HgIDE0

Typical vapor compression cycle: Air-conditioning unit

Air leaving coil
55°F

Warmer outdoor air
100°F

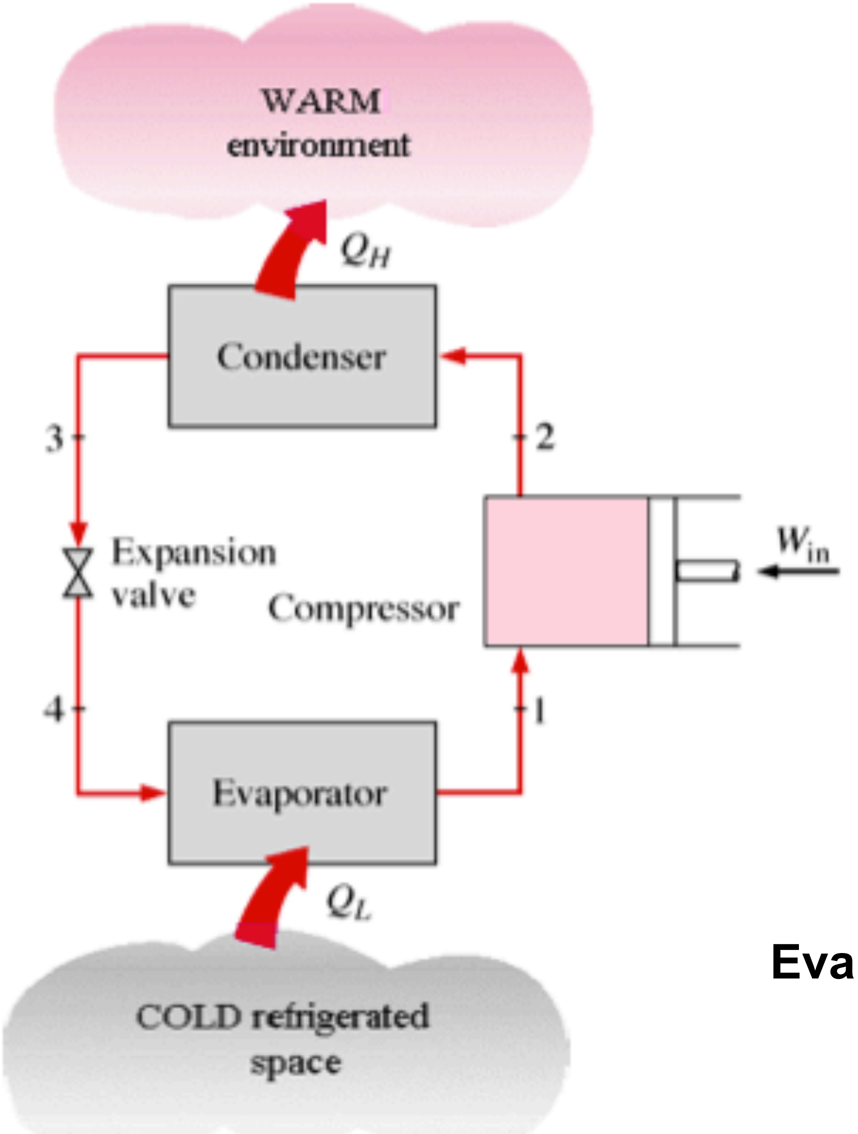


Air entering coil
75°F

Warm outdoor air
90°F

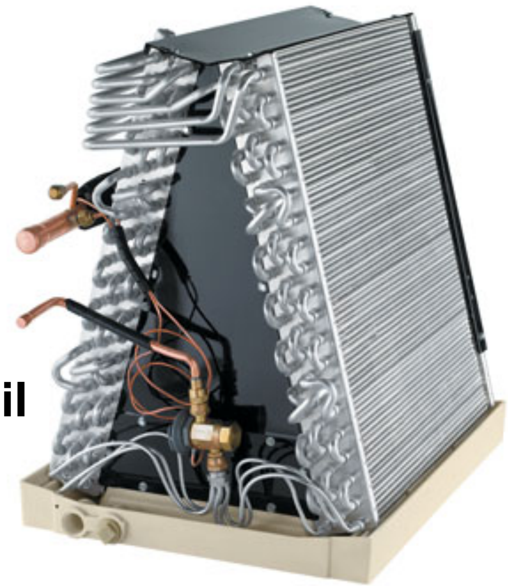
Changing refrigerant T and P

Ideal single-stage vapor compression cycle

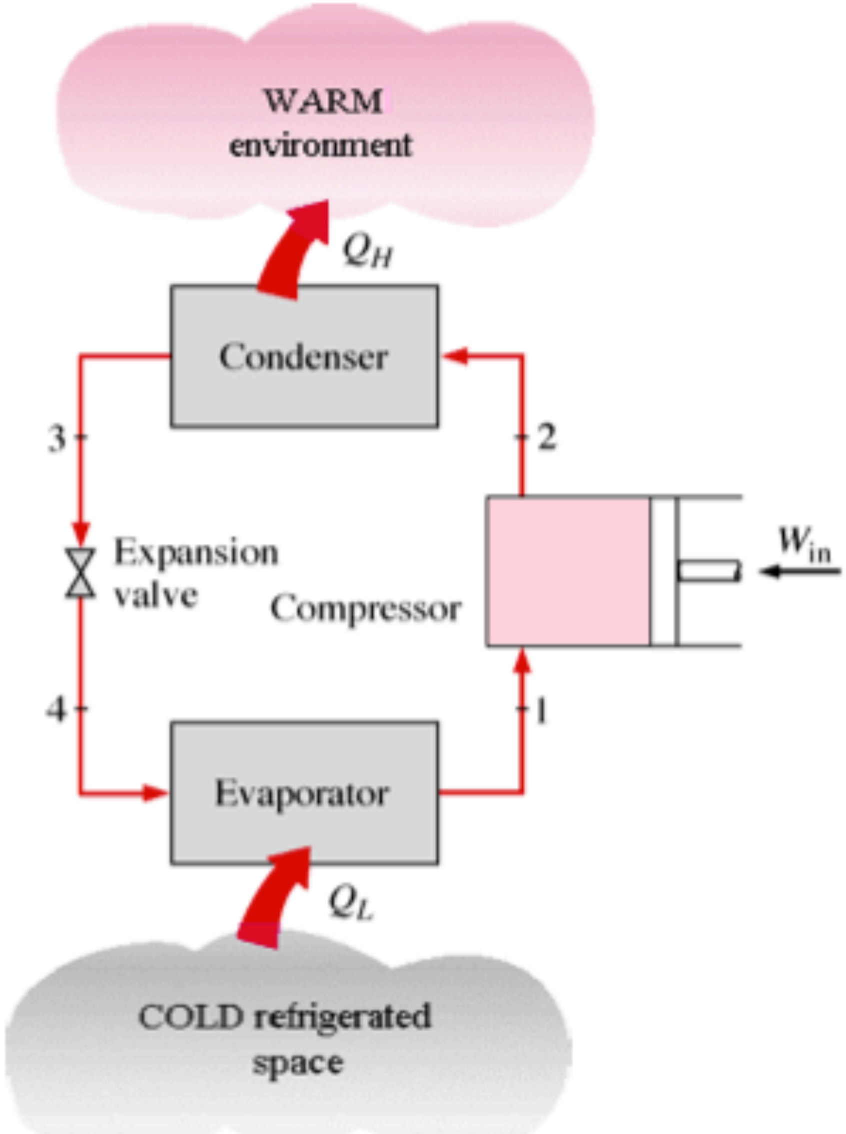


Expansion valve
(creates the high P restriction)

Evaporator coil

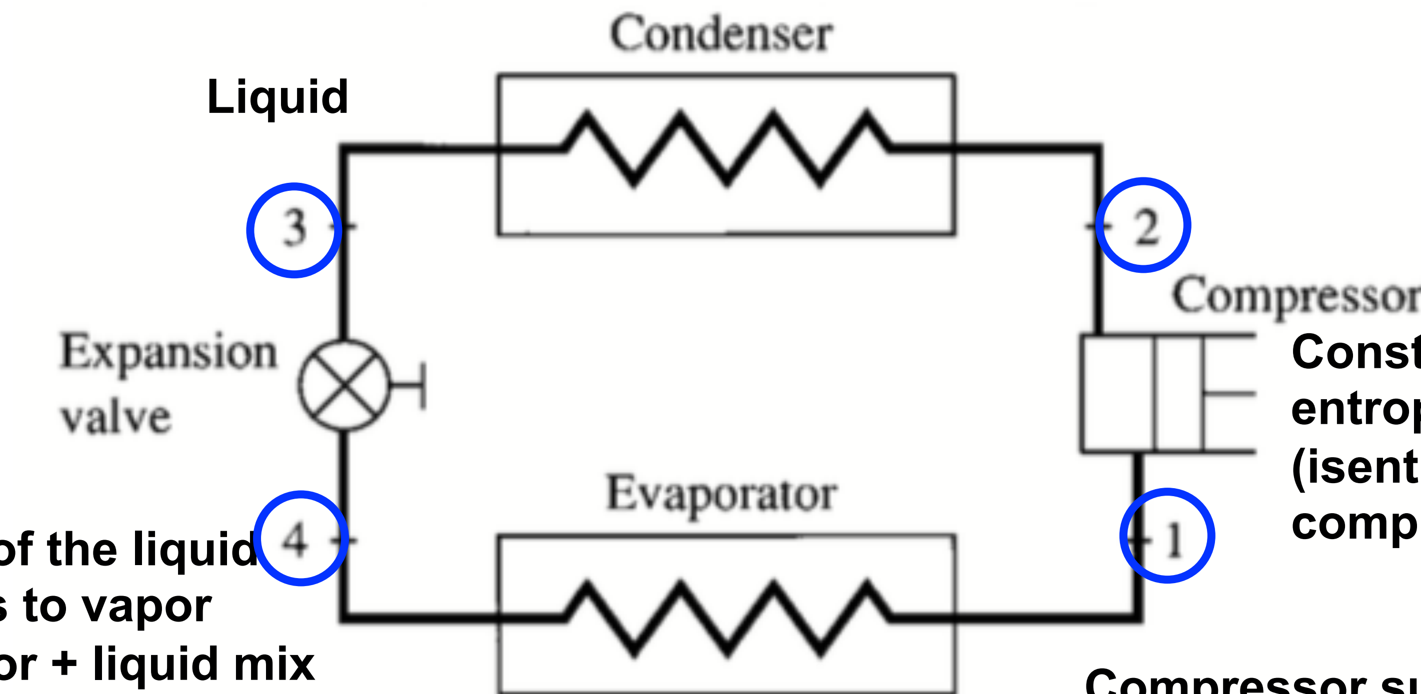


Ideal single-stage vapor compression cycle



Ideal single-stage vapor compression cycle

Latent heat of condensation (rejected to heat sink)



Liquid

Constant entropy (isentropic) compression

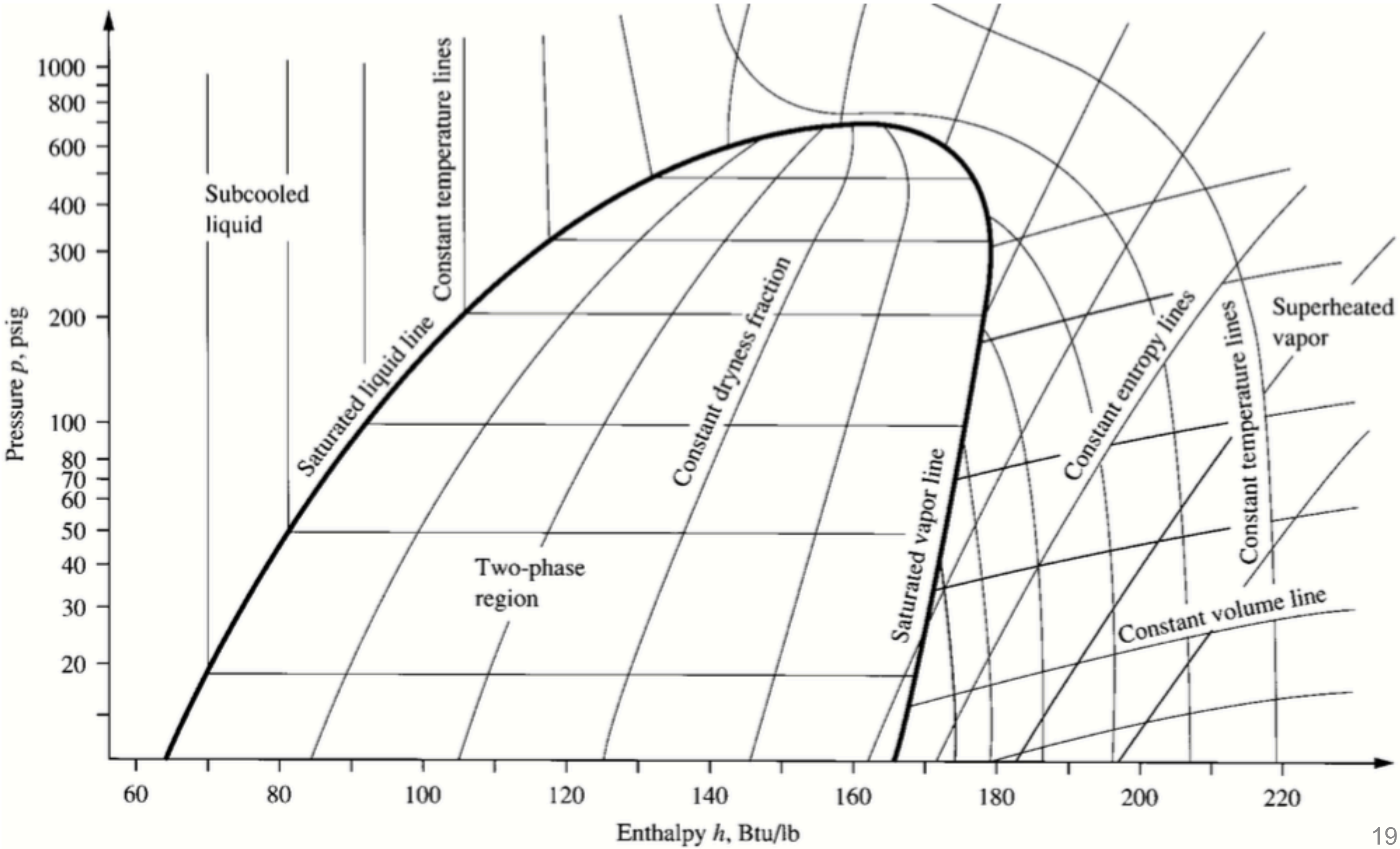
Some of the liquid flashes to vapor
- **Vapor + liquid mix**

Compressor suction
- **"suction pressure"**

Rest of liquid evaporates at evaporating temperature

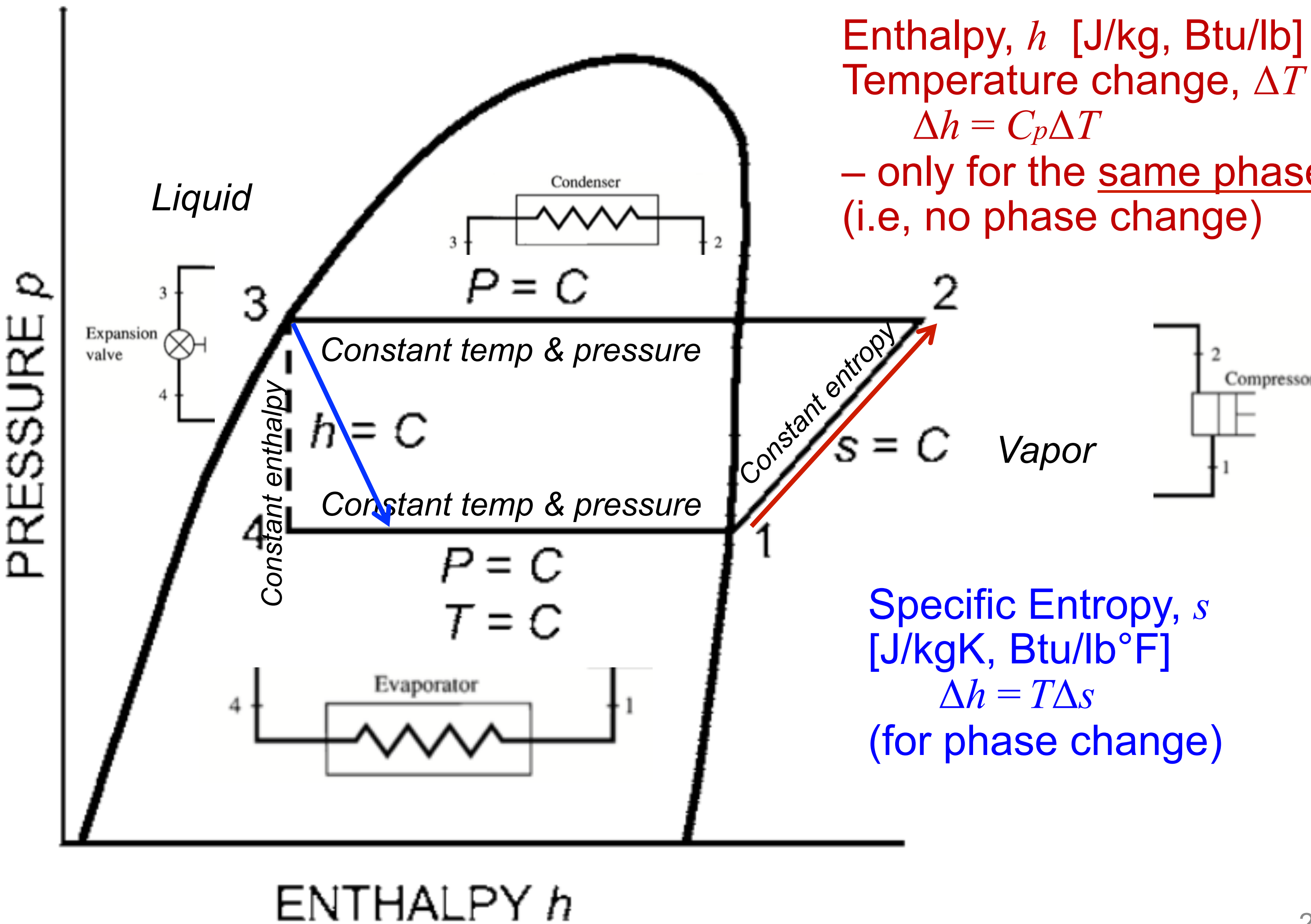
Ideal single-stage vapor compression cycle

Pressure-enthalpy (*p-h*) diagram for a given refrigerant



Ideal single-stage vapor compression cycle

Pressure-enthalpy (*p-h*) diagram for a given refrigerant



Enthalpy, h [J/kg, Btu/lb]
Temperature change, ΔT

$$\Delta h = C_p \Delta T$$

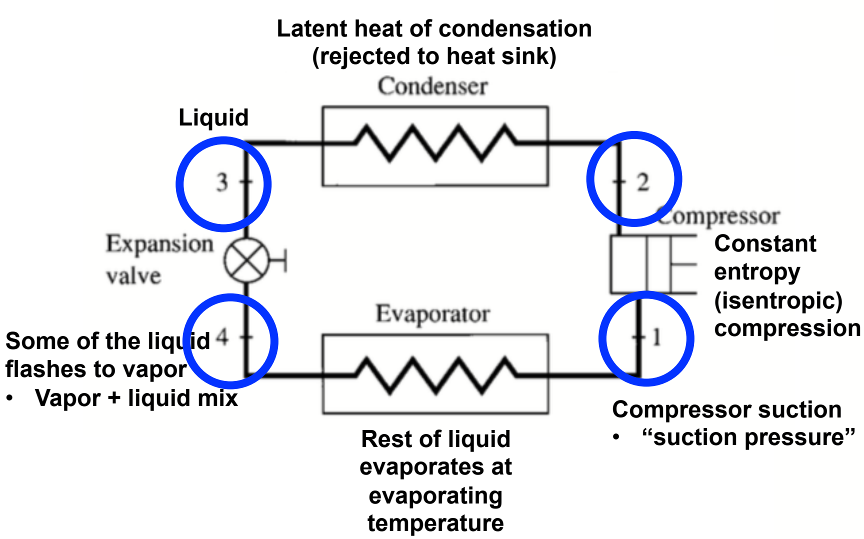
– only for the <u>same phase</u> (i.e, no phase change)

Specific Entropy, s [J/kgK, Btu/lb°F]

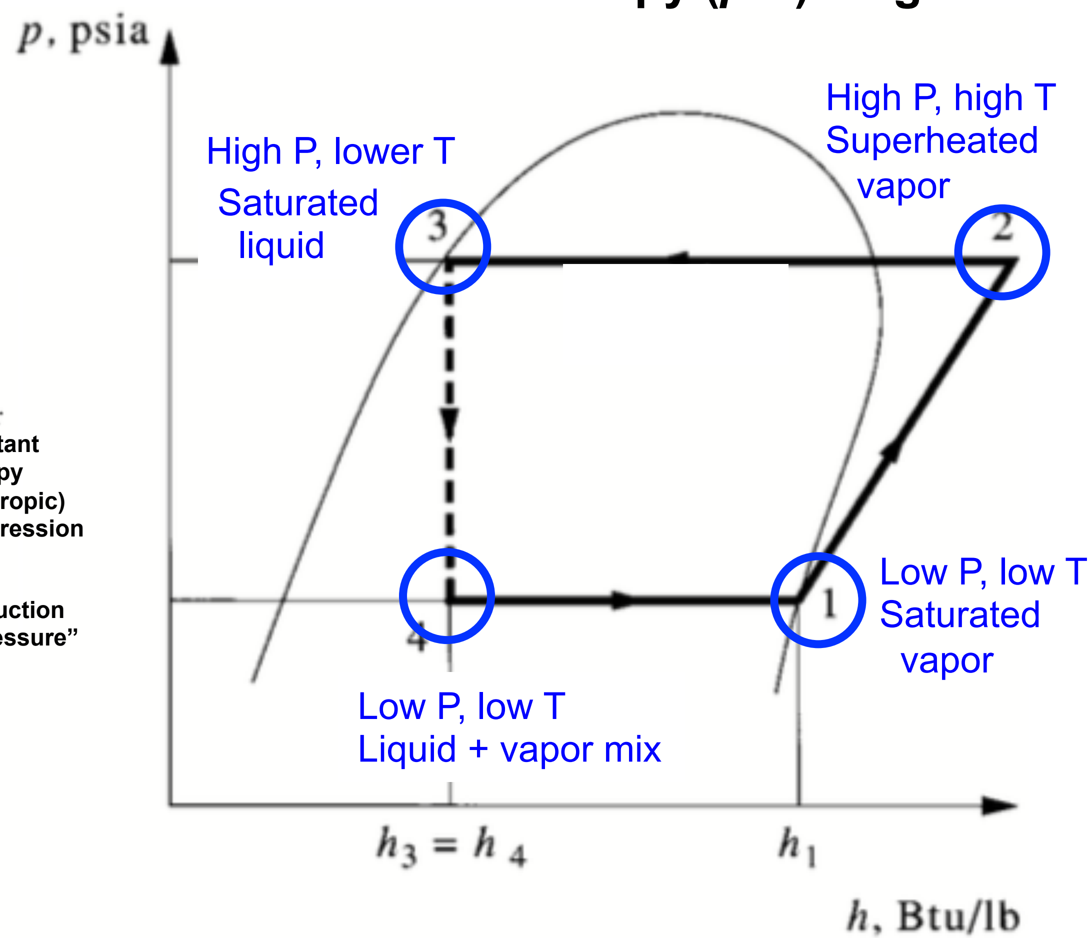
$$\Delta h = T\Delta s$$

(for phase change)

Ideal single-stage vapor compression cycle

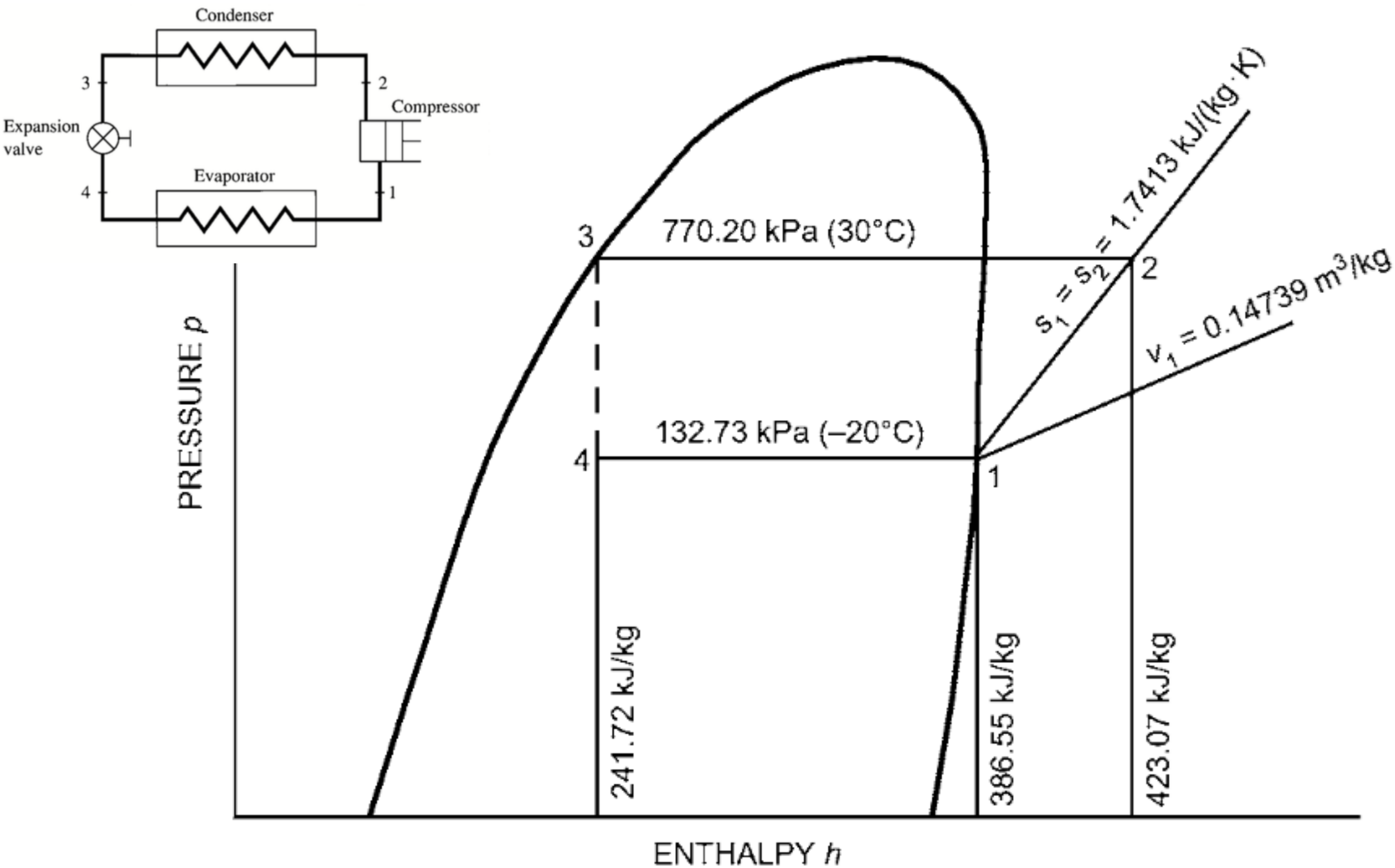


Pressure-enthalpy (*p-h*) diagram



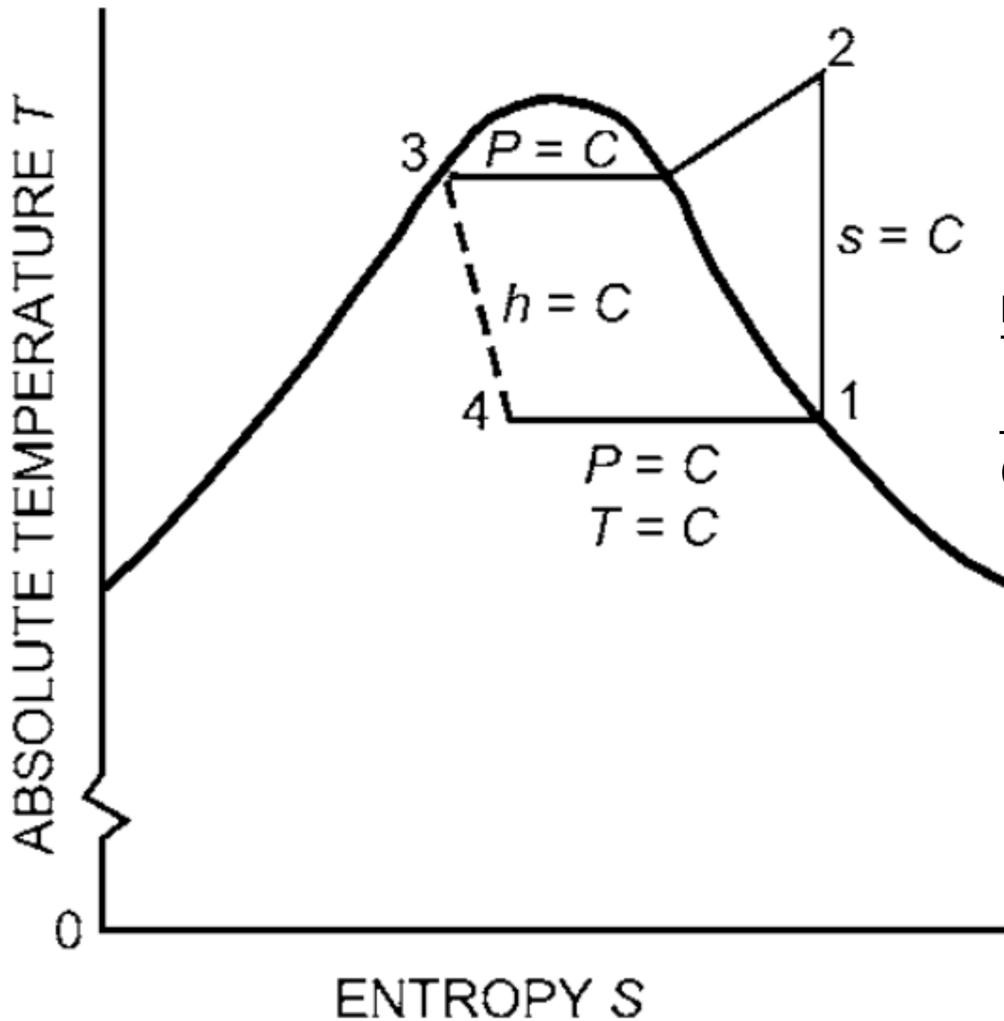
Ideal single-stage vapor compression cycle

Pressure-enthalpy (*p-h*) diagram for a given refrigerant



Ideal single-stage vapor compression cycle

Temperature-entropy (*T-s*) diagram for a given refrigerant



Enthalpy, h [J/kg, Btu/lb]
Temperature change, ΔT

$$\Delta h = C_p \Delta T$$

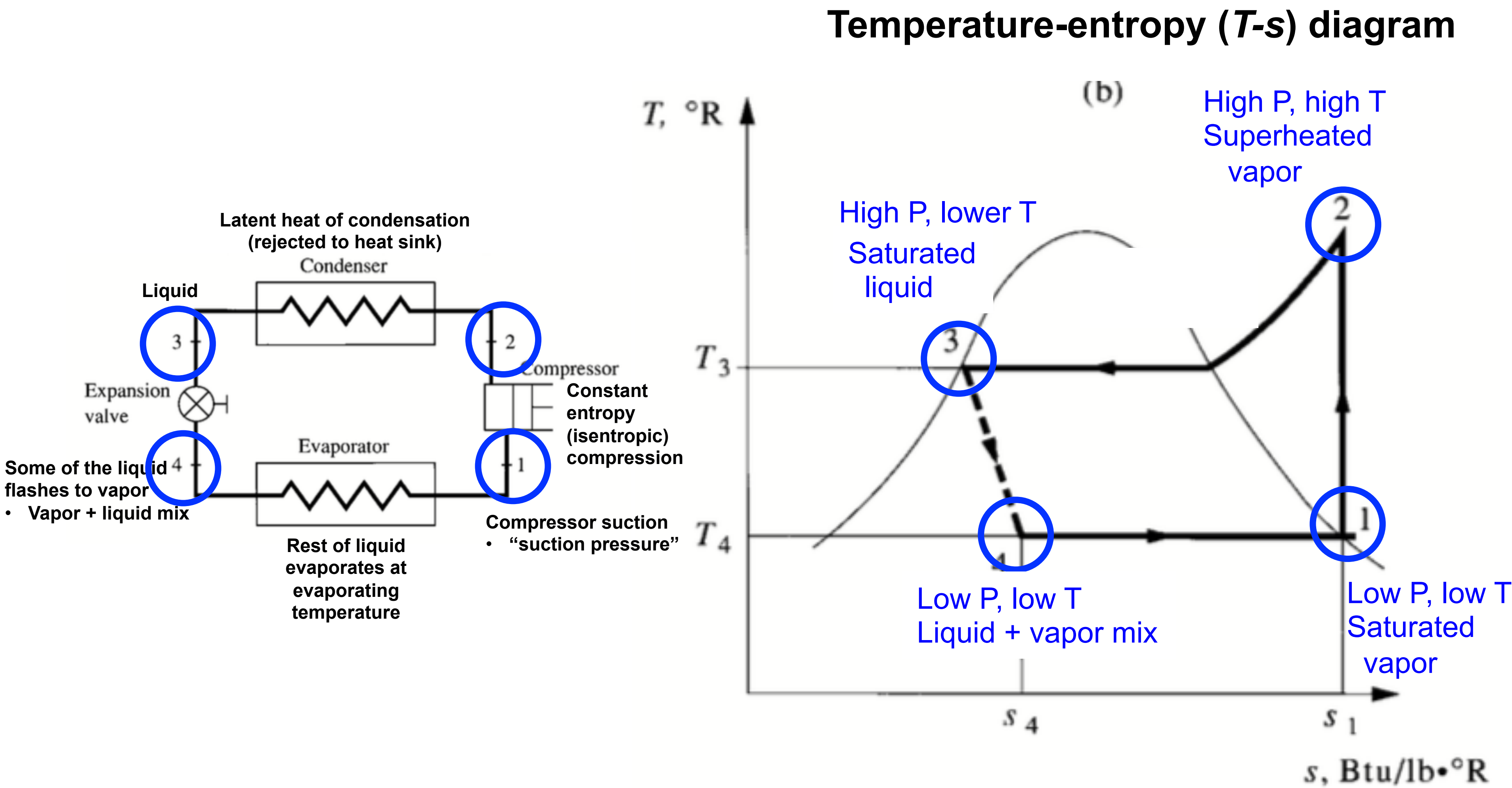
– only for the <u>same phase</u>
(i.e, no phase change)

Specific Entropy, s
[J/kgK, Btu/lb°F]

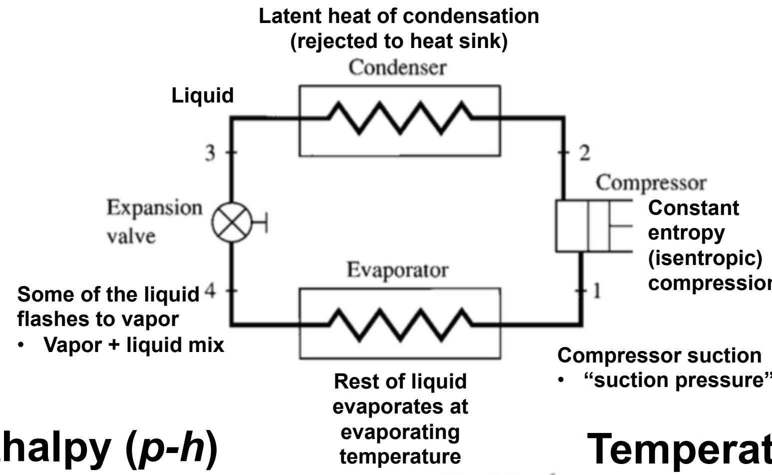
$$\Delta h = T \Delta s$$

(for phase change)

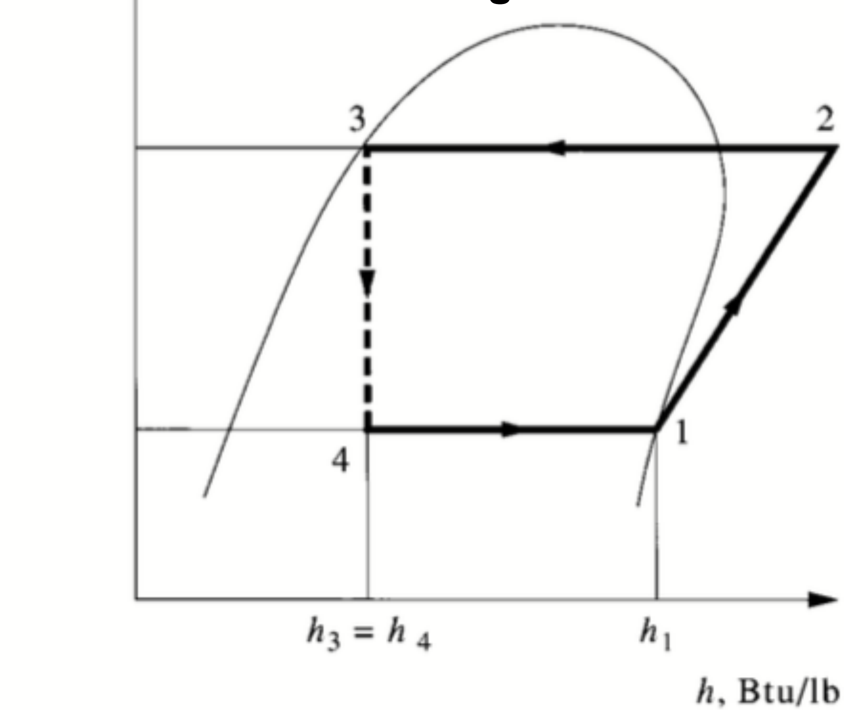
Ideal single-stage vapor compression cycle



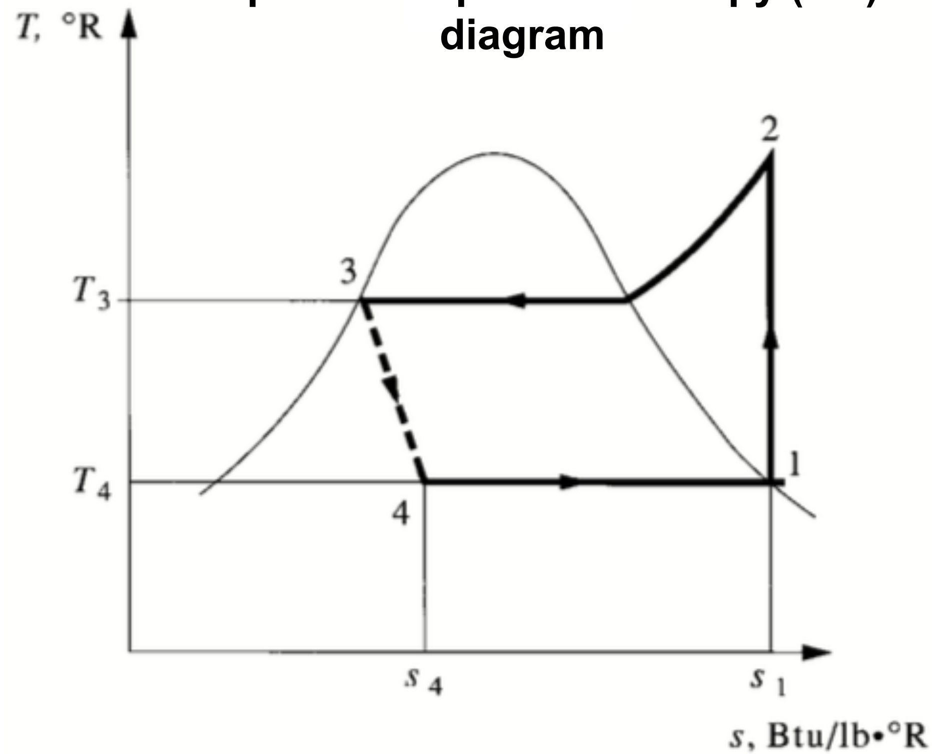
Ideal single-stage vapor compression cycle



Pressure-enthalpy (*p-h*) diagram



Temperature-specific enthalpy (*T-s*) diagram

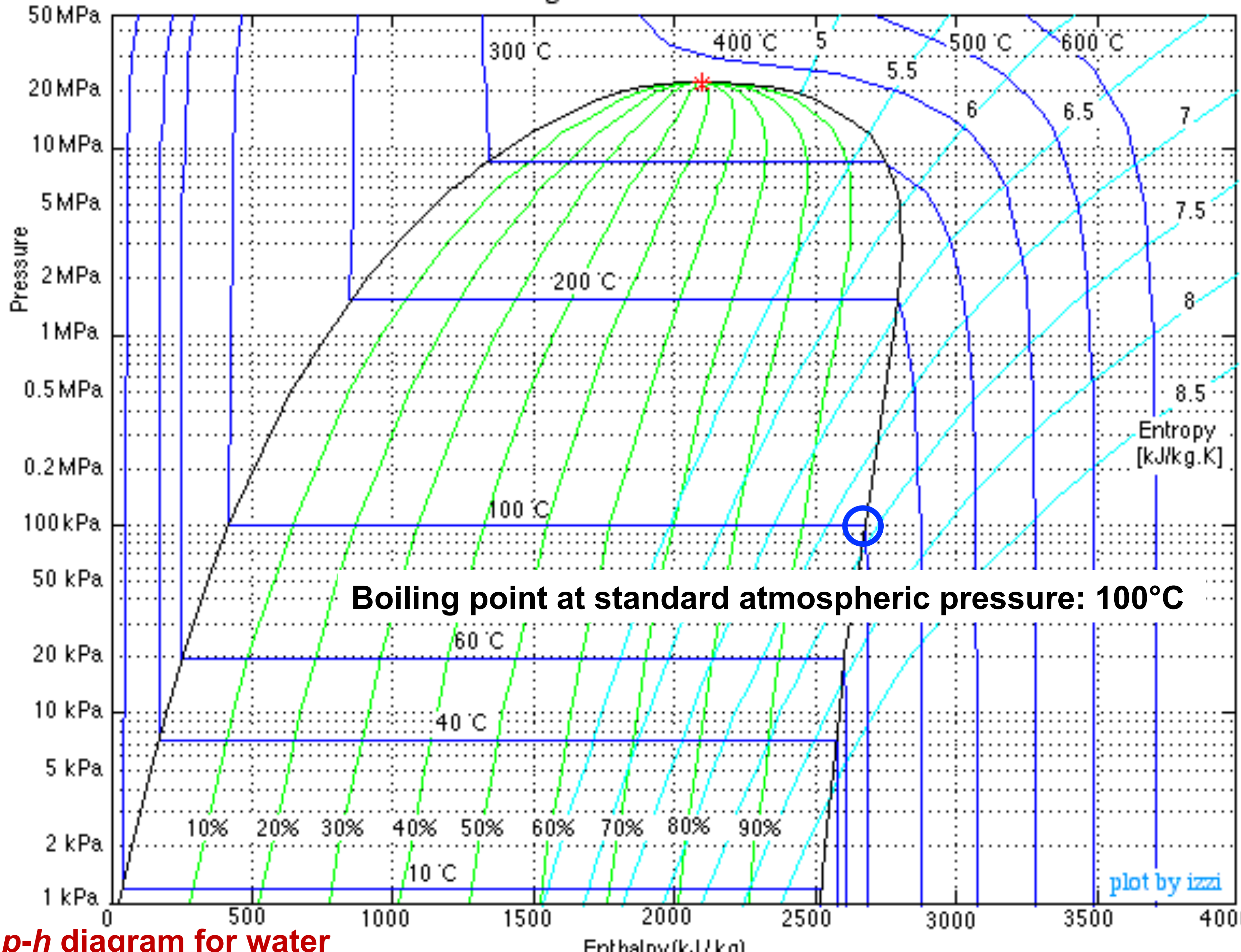


What makes a good refrigerant?

- The goal is to find a fluid that <u>absorbs</u> heat at a low temperature and low pressure and <u>releases</u> heat at a higher temperature and pressure
  - Most refrigerants will undergo <u>phase changes</u> during heat absorption (i.e., evaporation) and heat release (i.e., condensation)
- You want a refrigerant that:
  - Has an <u>evaporating pressure</u> that is higher than that of the atmosphere so that air and other gases will not leak into the system and increase the pressure in the system
  - Is <u>inert</u> (avoids corrosion)
  - Has a <u>high thermal conductivity</u> (increases heat transfer efficiency in heat exchangers)
  - Has a high refrigeration capacity (i.e., a high <u>latent heat of vaporization</u> and the specific volume at the suction pressure)

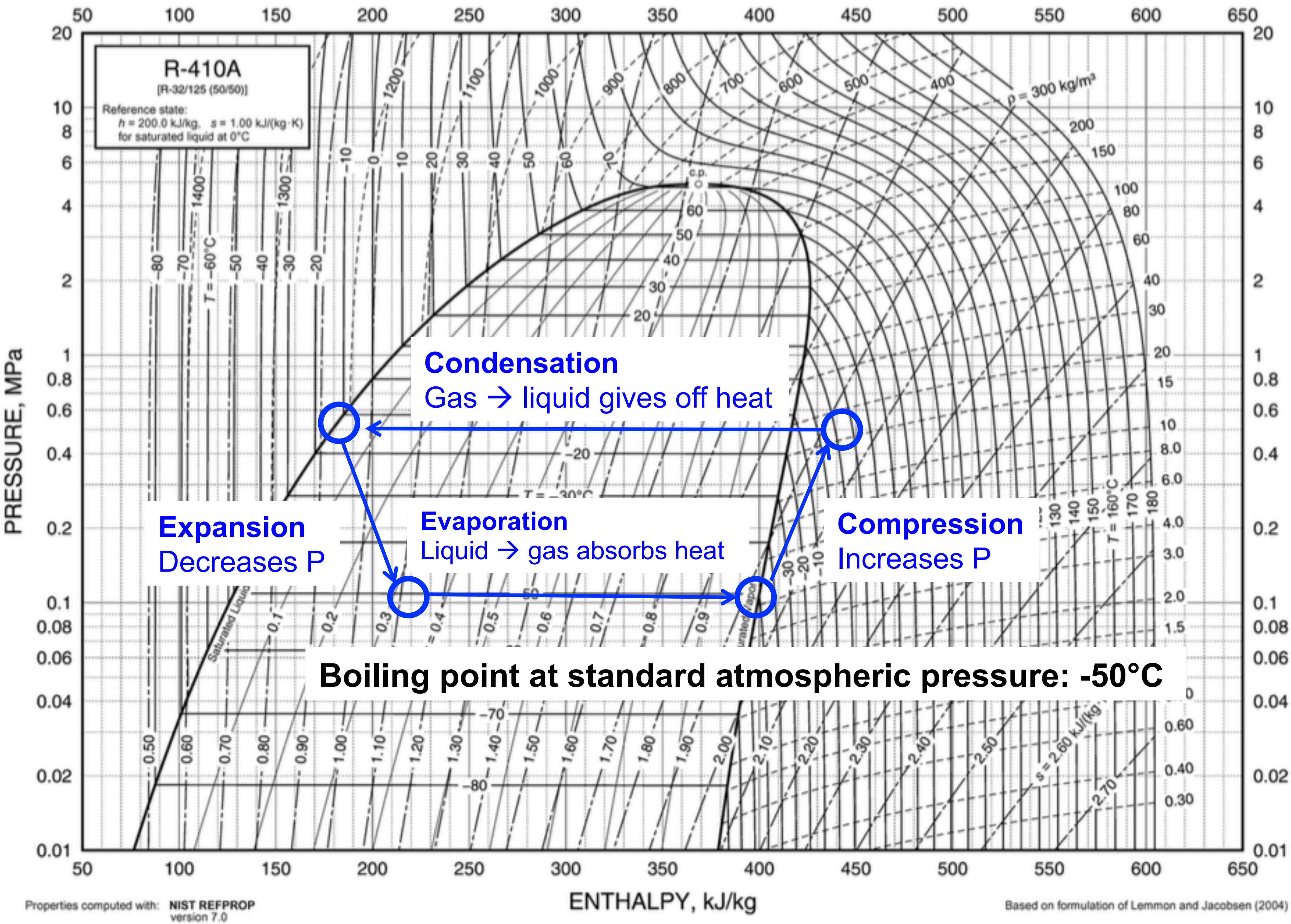
What makes a good refrigerant?

- In the past, we have used ammonia, sulfur dioxide, methyl chloride, and others
  - All are quite toxic
- Then we switched to chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs) such as R-22 (freon)
  - But they have high global warming and ozone depletion potentials
- Now phased out in favor of **R-410A** and others
  - Boiling point = -55°F
  - Liquid heat capacity = 1.8 kJ/kgK @ STP
  - Gas heat capacity = 0.84 kJ/kgK @ STP



Boiling point at standard atmospheric pressure: 100°C

***p-h* diagram for water**



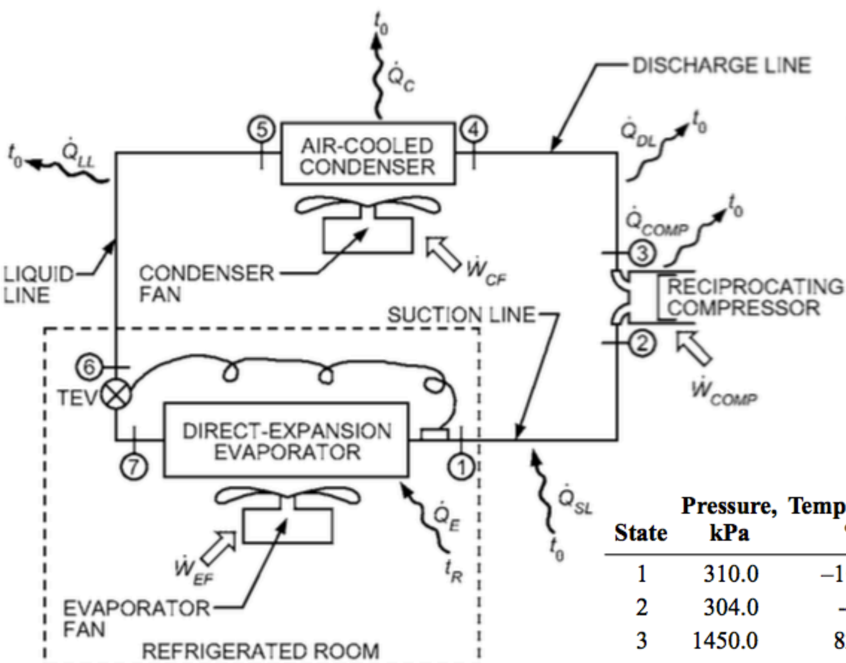
***p-h* diagram for R-410A**

Fig. 16 Pressure-Enthalpy Diagram for Refrigerant 410A

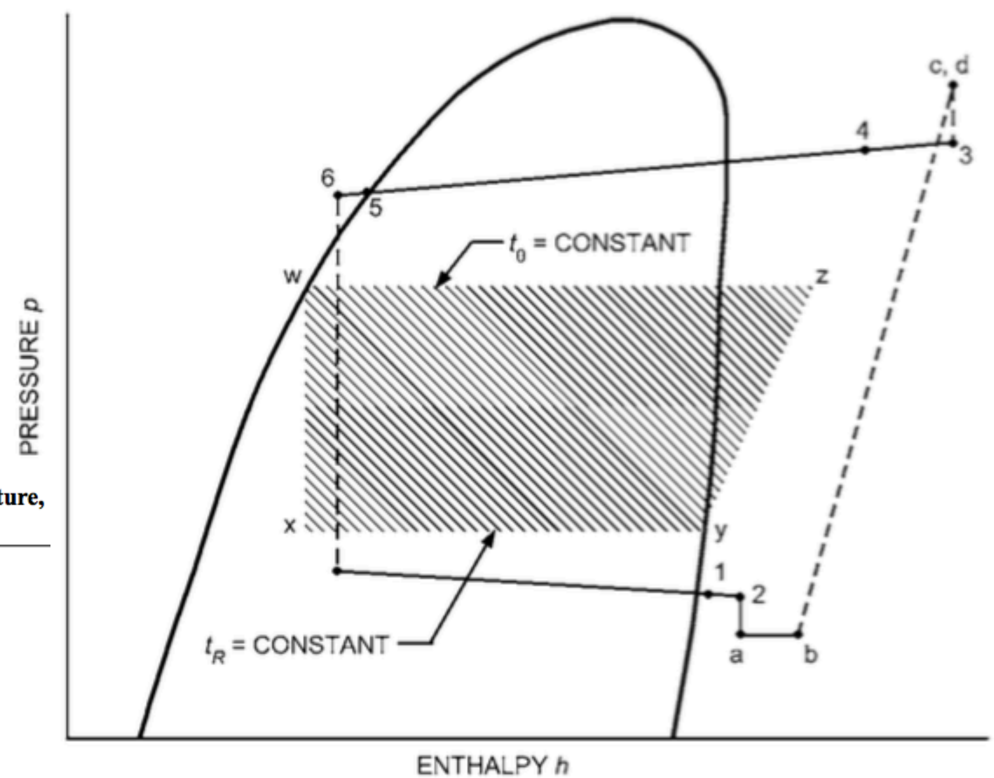
<u>Non</u>-ideal single-stage vapor compression cycle

<u>Actual</u> refrigeration systems differ from ideal cycles

- Pressure drops occur everywhere but the compression process
- Heat transfers between the refrigerant and its environment
- Actual compression process may differ
- Refrigerant might also have some oil mixed in to lubricate
- They all cause irreversibilities in the system that require additional compressor power



State	Pressure, kPa	Temperature, °C
1	310.0	–10.0
2	304.0	-4.0
3	1450.0	82.0
4	1435.0	70.0
5	1410.0	34.0
6	1405.0	33.0
7	320.0	–12.8



<u>Non</u>-ideal single-stage vapor compression cycle

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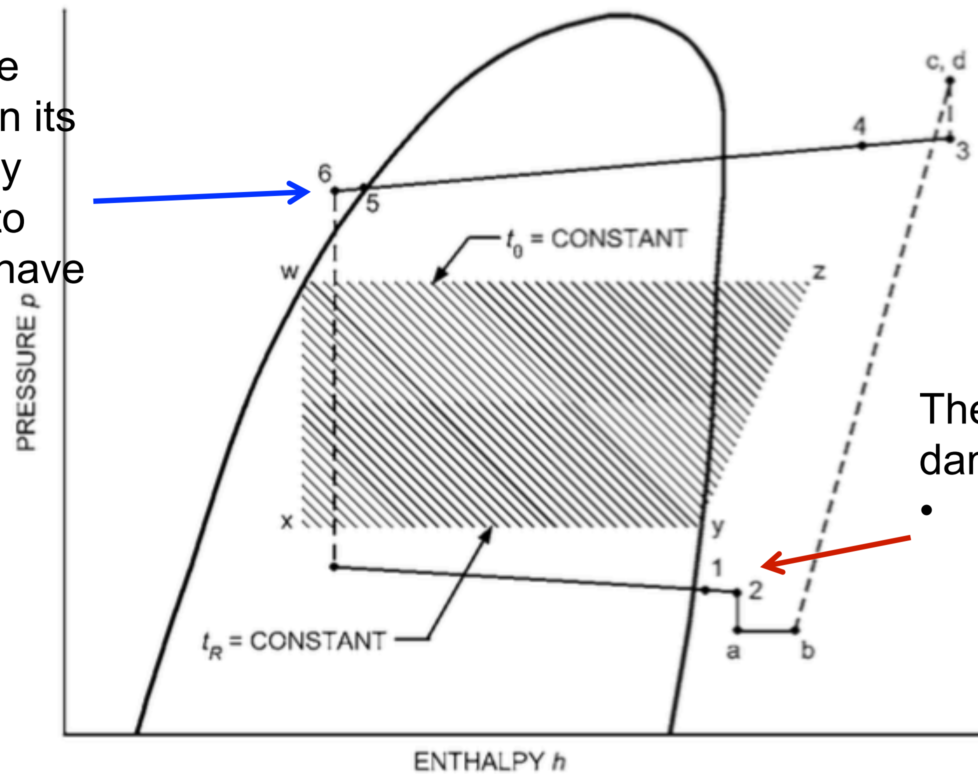
- Pressure drops occur everywhere but the compression process
- Heat transfers between the refrigerant and its environment
- Actual compression process may differ
- Refrigerant might also have some oil mixed in to lubricate
- They all cause irreversibilities in the system that require additional compressor power

The expansion valve needs 100% liquid in its inlet to work properly

- You "**subcool**" to ensure that you have only liquid



The compressor will be damaged if liquid enters

- You "**superheat**" to ensure that you have only vapor

Question: What is the COP?

A. Congressional Observer Publications
B. California Offset Printers
C. Coefficient of Performance ←
D. Slang for a policeman

$$COP = \frac{\text{Provided cooling energy [W or BTU/hr]}}{\text{Used electric energy [W or BTU/hr]}}$$

Equivalent to the efficiency of an air-conditioning unit

Coefficient of performance (COP)

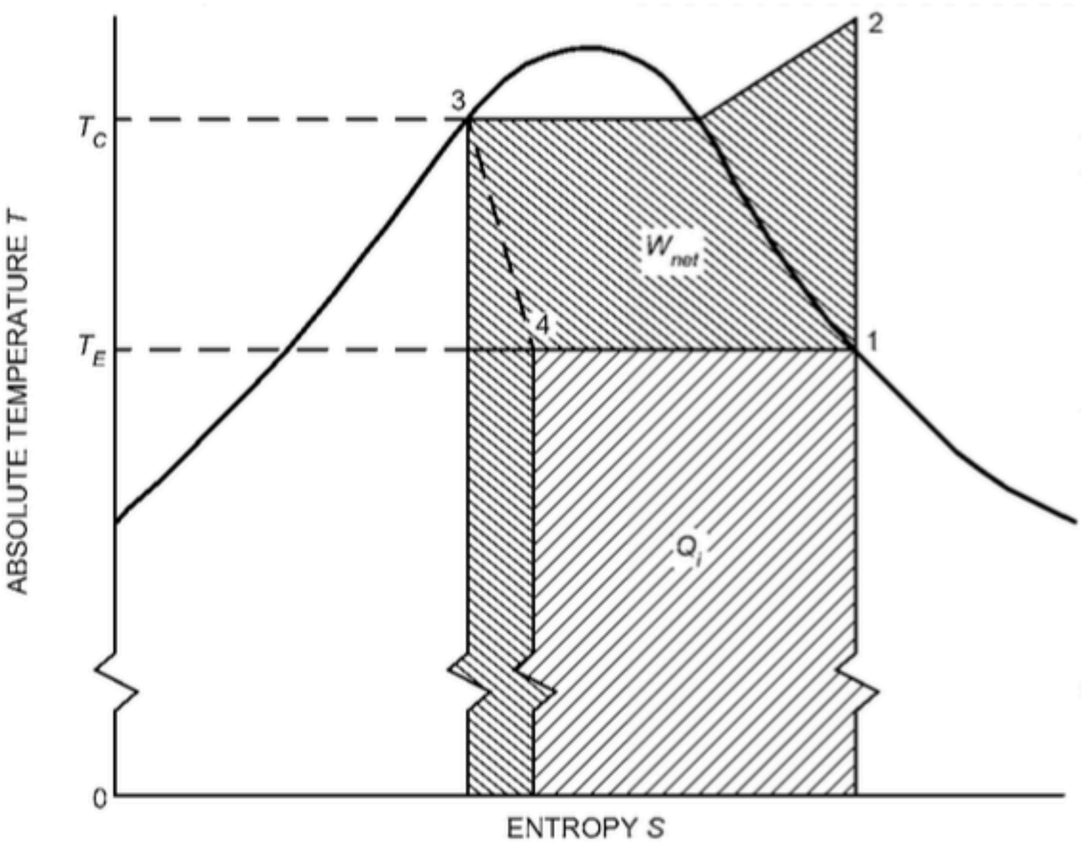
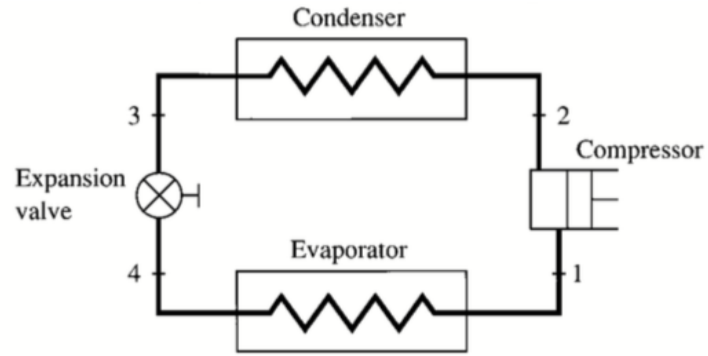


Fig. 10 Areas on *T*- *s* Diagram Representing Refrigerating Effect and Work Supplied for Theoretical Single-Stage Cycle

For an ideal refrigeration cycle:

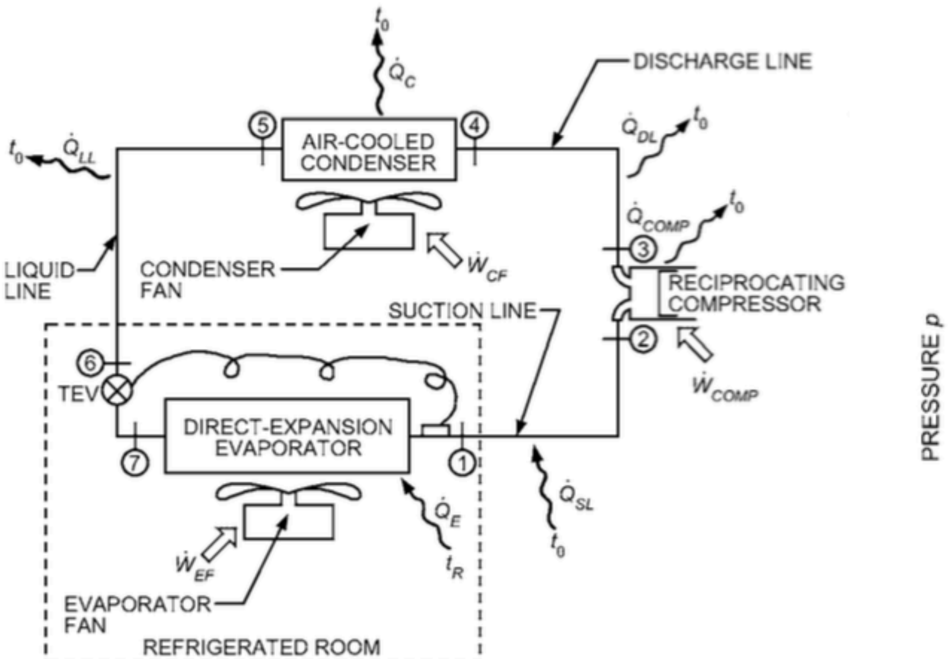
$$COP = \frac{Q_{cool}}{W_{elec}} = \frac{h_1 - h_4}{h_2 - h_1}$$

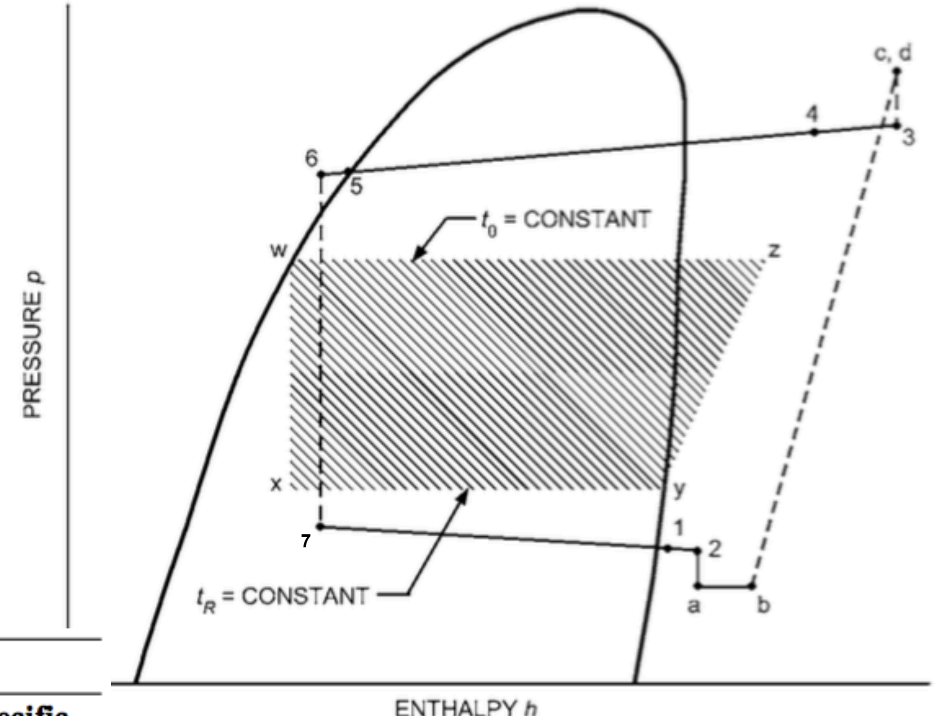


What is the efficiency of a typical residential AC unit?

A. 10%
B. 50%
C. 80%
D. 100%
E. 300% ←

COP example





	Measured		Computed		
State	Pressure, kPa	Temperature, °C	Specific Enthalpy, kJ/kg	Specific Entropy, kJ/(kg·K)	Specific Volume, m³/kg
1	310.0	–10.0	402.08	1.7810	0.07558
2	304.0	-4.0	406.25	1.7984	0.07946
3	1450.0	82.0	454.20	1.8165	0.02057
4	1435.0	70.0	444.31	1.7891	0.01970
5	1410.0	34.0	241.40	1.1400	0.00086
6	1405.0	33.0	240.13	1.1359	0.00086
7	320.0	–12.8	240.13	1.1561	0.01910

$$COP = \frac{\mathrm{Q_{cool}}}{\mathrm{W_{elec}}} = \frac{h_1 - h_7}{h_3 - h_2}$$

$$COP = \frac{\mathrm{Q_{cool}}}{\mathrm{W_{elec}}} = \frac{402 - 240}{454 - 406} = 3.38$$

Real life COP example: Residential AC unit

- Capacity = 3 tons
  - 36 kBTU/hr
  - 10.5 kW
- Power draw while operating:
  - 3500 W = 3.5 kW

ΔT_{coil} = 12°C - 24°C

$Abs(\Delta T_{coil})$ = 12 K

$\dot{V}_{air}$ = 400 CFM per ton (typical)

$\dot{V}_{air}$ = 1200 CFM

$\dot{V}_{air}$ = 0.566 m^3/s

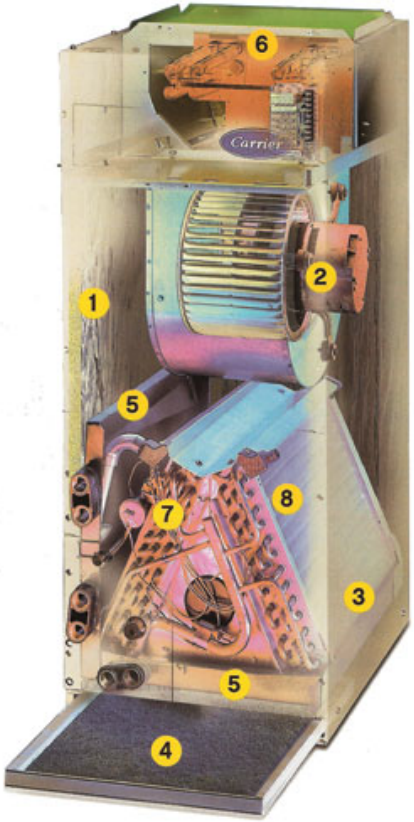
Q_{sens} = (1.15 kg/m^3)(1 kJ/kgK)(0.566 m^3/s)(12K)

Q_{sens} = 7.9 kW

SHR = 0.75 (typical)

Q_{total} = 7.9/0.75 = 10.5 kW

COP = 10.5 kW/3.5 kW = 3.0



What do we need to know about cooling systems?

Equipment selection example:

A load calculation determines you need 1.2 tons of water cooling

1 ton = 12000 Btu/hr
1.2 tons = 14,400 Btu/hr

You would choose a 1.35 ton capacity unit

<u>1.35 ton is accurate for:</u>
115°F air condenser temp and
50°F of leaving water temperature

SPECIFICATIONS	IK-	.25A	.33A	.5A	.75A	1A	1.5A	2A	2W	3W	3A	4A
COMPRESSOR	Capacity[2]	.25	.32	.41	.70	.98	1.35	2	2	3	3	4
	HP each	.25	.33	.50	.75	1	1.5	2	2	3	3	4
	Type[3]	H	H	H	H	H	H	H	H	H	H	H

Notes: **1.** Full load amps must be used for sizing disconnects and supply wiring. **2.** Tons of capacity at 12,000 BTU/ton @ 50°F LWT @ 105°F condensing temperature for water-cooled units and 115°F for air-cooled units. Capacities may be +/- 5% as reserved by the compressor manufacturer. Capacity multipliers are 50°F - 1.00; 40°F -.80; 30°F - .60; 20°F - .40. The minimum recommended operating temperature when no glycol is used is 48°F. **3.** H - hermetic compressor used on this model. **4.** Consult factory for 50hz operation. **5.** Approximate unit weight crated for shipment.

AC capacity and efficiency changes with outdoor T, indoor T/RH, and airflow rates

Table 4. Example Manufacturer EPT (Subset of Data Displayed)

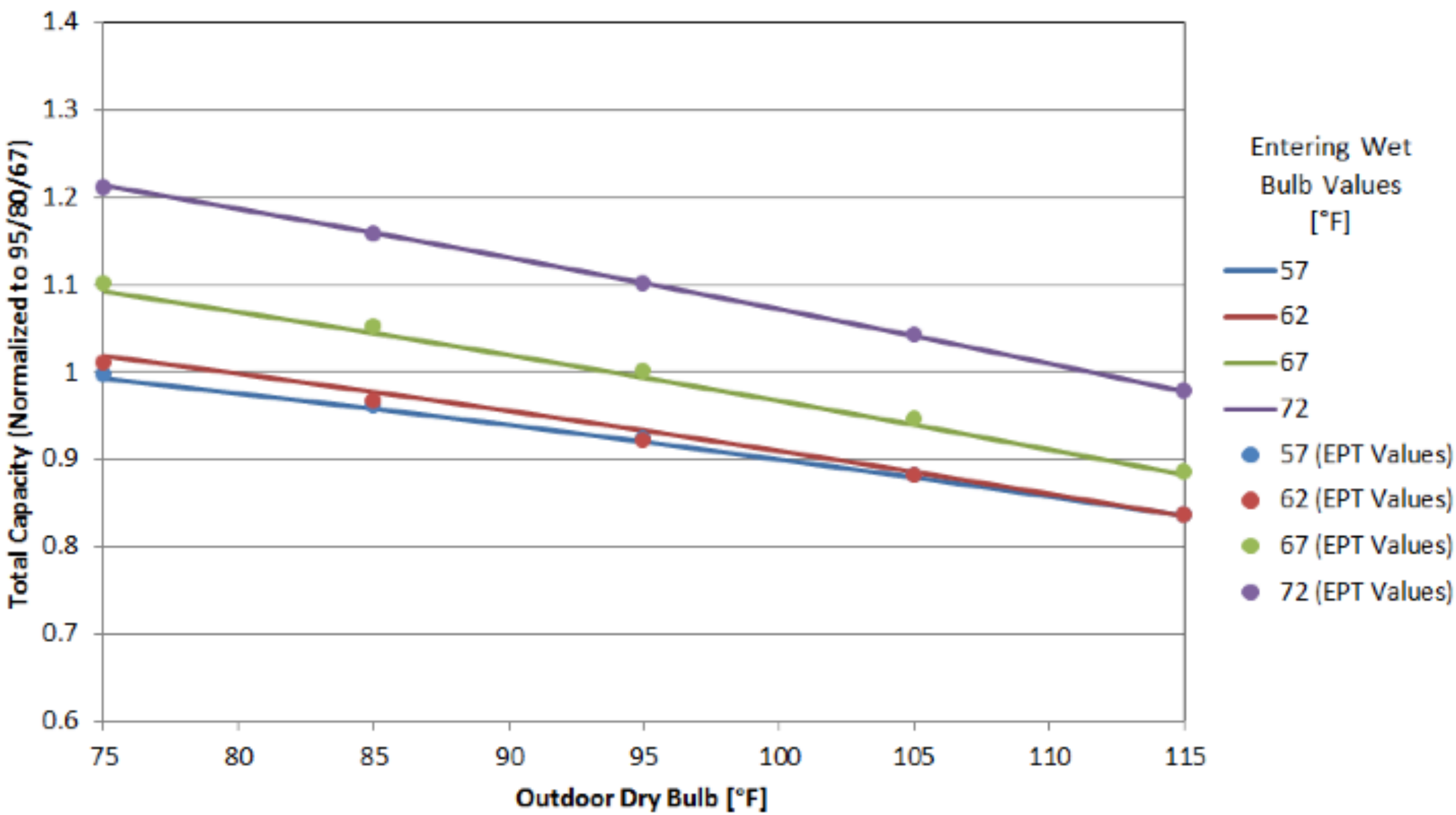
Evaporator Air		Condenser Air °F (°C)								
		75 (23.9)			95 (35)			105 (40.6)		
cfm	EWB °F (°C)	Capacity kBtu/h Total[1]	Capacity kBtu/h Sens[1,2]	Total Sys kW[3]	Capacity kBtu/h Total[1]	Capacity kBtu/h Sens[2]	Total Sys kW[3]	Capacity kBtu/h Total[1]	Capacity kBtu/h Sens[2]	Total Sys kW[3]
875	72 (22)	34.32	17.27	1.96	31.24	16.13	2.44	29.59	15.54	2.71
	67 (19)	31.45	21.21	1.96	28.59	20.05	2.43	27.04	19.44	2.71
	63 (17)	29.35	20.58	1.96	26.66	19.40	2.43	25.19	18.78	2.70
	62 (17)	28.82	25.13	1.95	26.24	23.94	2.43	24.86	23.29	2.70
	57 (14)	28.00	28.00	1.95	25.89	25.89	2.43	24.74	24.74	2.70
1000	72 (22)	34.88	18.05	2.01	31.66	16.90	2.48	29.96	16.30	2.76
	67 (19)	31.98	22.49	2.01	29.00	21.31	2.48	27.40	20.68	2.75
	63 (17)	29.88	21.78	2.00	27.07	20.58	2.48	25.55	19.95	2.75
	62 (17)	29.44	26.90	2.00	26.81	26.81	2.48	25.62	25.62	2.75
	57 (14)	29.10	29.10	2.00	26.85	26.85	2.48	25.62	25.62	2.75
1125	72 (22)	35.27	18.78	2.06	17.61	17.61	2.53	30.22	17.07	2.81
	67 (19)	32.36	23.68	2.05	22.50	22.50	2.53	27.66	21.88	2.80
	63 (17)	30.25	22.90	2.05	21.70	21.70	2.52	25.82	21.07	2.80
	62 (17)	30.02	28.49	2.05	27.62	27.62	2.52	26.32	26.32	2.80
	57 (14)	29.99	29.99	2.05	27.62	27.62	2.52	26.32	26.32	2.80

[1] Total and sensible capacities are net capacities. Blower motor heat has been subtracted.

[2] Sensible capacities shown are based on 80°F (27°C) entering air at the indoor coil. For sensible capacities at other than 80°F (27°C), deduct 835 Btu/h (245 W) per 1000 cfm (480 L/S) of indoor coil air for each degree below 80°F (27°C), or add 835 Btu/h (245 W) per 1000 cfm (480 L/s) of indoor coil air per degree above 80°F (27°C).

[3] System kilowatt is the total of indoor and outdoor unit kilowatts.

AC capacity and efficiency changes with outdoor T, indoor T/RH, and airflow rates



EER and SEER

- EER = Energy Efficiency Ratio
  - Same as COP but in mixed units: (Btu/hr)/W
  - Example from previous page:

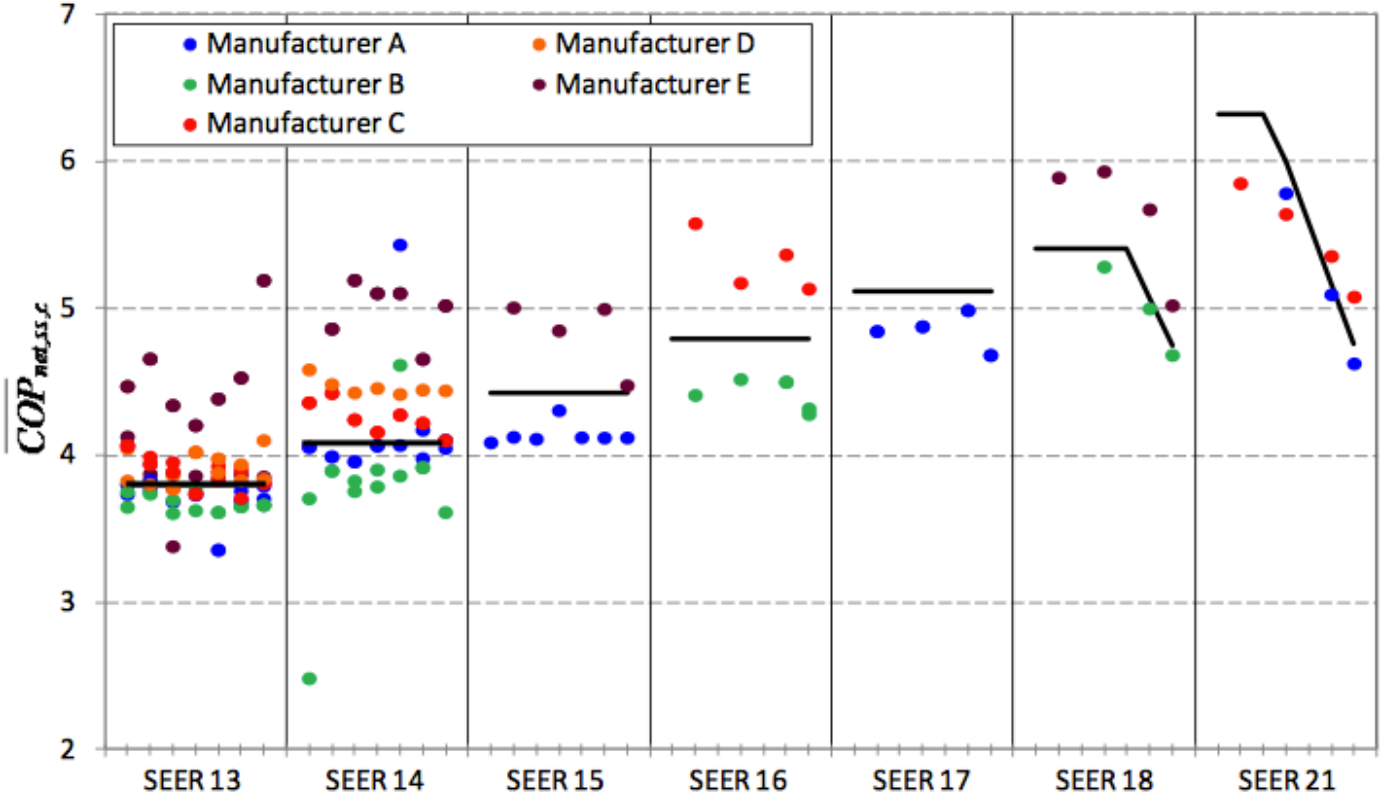
$$COP = \frac{8.5\ [\text{kW}]}{2.48\ [\text{kW}]} = 3.43 \qquad EER = \frac{29.0\ [\text{kBtu/hr}]}{2.48\ [\text{kW}]} = 11.7$$

$$EER = COP \times 3.41$$

- SEER = Seasonal Energy Efficiency Ratio, units: [Btu/Wh]
  - Cooling output during a typical cooling season divided by the total electric energy input during the same period
  - Represents expected performance over a range of conditions

$$EER \approx -0.02 \times SEER^2 + 1.12 \times SEER$$

EER and SEER



- AC units must be 14 SEER (or 12.2 EER) beginning on January 1, 2015 if installed in southeastern region of the US

Using COP to estimate power draw and energy consumption

- If you know the cooling load and you know the COP, you can estimate the instantaneous electric power draw required to meet the load:

$$P_{elec} = \frac{Q_{cooling,load}}{COP}$$

- If you multiply by the number of hours and sum over a period of operating time, you can estimate energy consumption:

$$E = \sum P_{elec}\,\Delta t$$

- You can also split data into bins if COP/EER changes with varying conditions