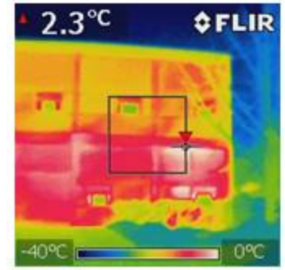
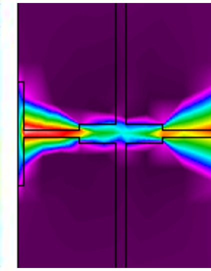
CAE 331/513
Building Science
Fall 2017



October 19, 2017
Refrigeration cycles (part 2)

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Illinois Institute of Technology
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Schedule updates

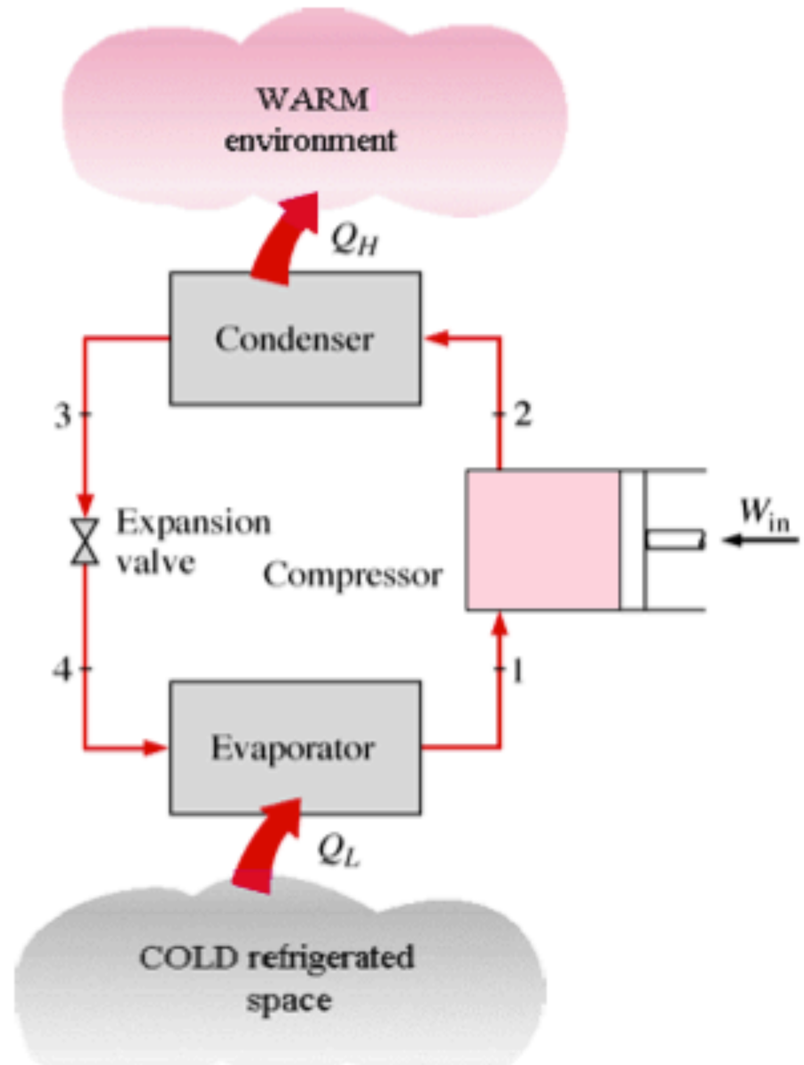
- Tuesday October 24
  - Campus HVAC tour with Brian Bozell, IIT Facilities
- Thursday October 26
  - Exam #2
  - 1:00 pm to 4:00 pm (you will be given up to 2 hours)
  - **IMIPORTANT: New classroom – Life Sciences Room 152**

Graduate student projects

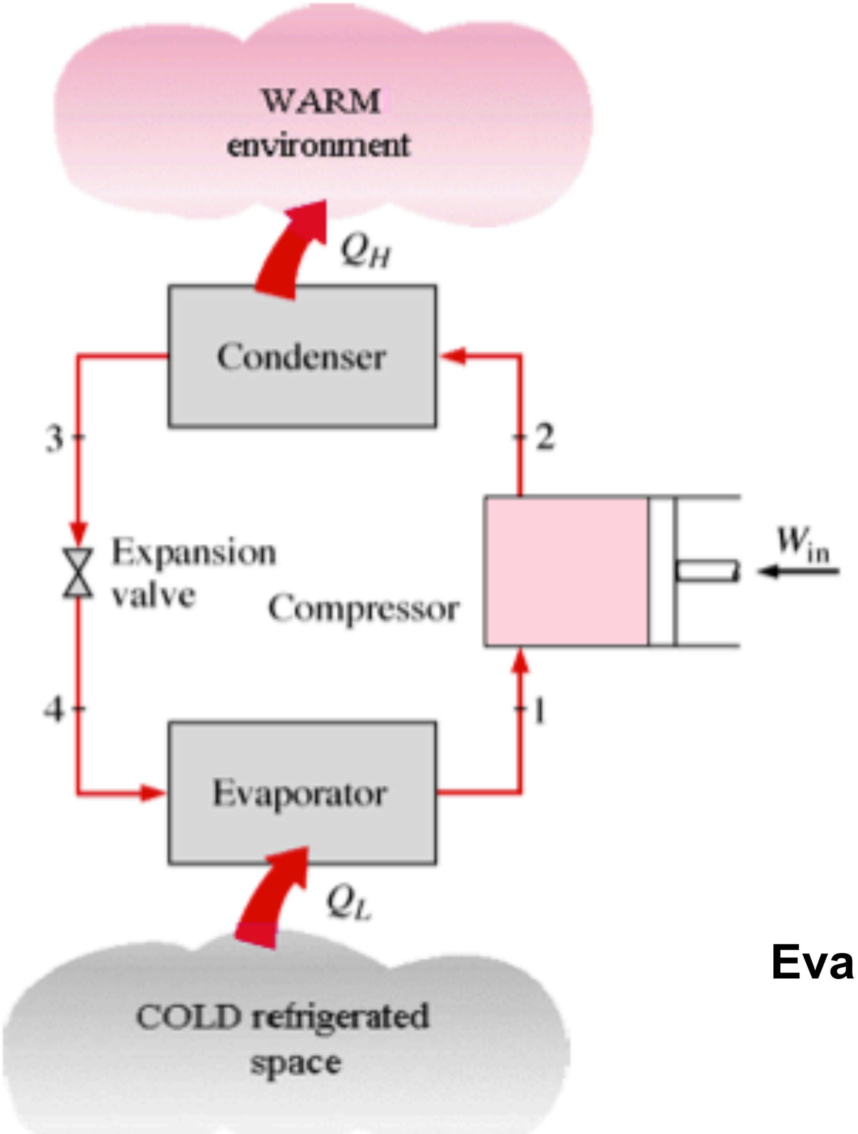
Student	Major	Project topic
Arias Solorzano, Sergio	CM	Construction costs of green buildings
Chen, Lingzhou	ARCE	Solar assisted absorption cooling
Cuevas Castillo, Leire Andrea	MAE	
Geng, Mina	ARCH	Vegetative facades
Horin, Brett Andrew	ARCE	Statistical approach to ECMs
Killarney, Sean Joseph	ARCE	HVAC energy recovery
Kim, Yohan	ARCH	Energy impacts of ETFE façade material
Kotur, Ajay Ashok	ARCE	
Martinez Jimenez, Pau	MAE	Smart windows OR integrated wind turb.
Mounier, Anna Lisa Marie	ARCE	Façade design and energy use
Sok, Pauline Socheat	ARCE	Water-cooled façade system
Wright, Eric	ARCE	Energy impacts of tankless water heaters
Zhu, Tianxing	ARCE	Lighting technologies and net energy use
Cornelius, John A	ARCE	ETFE OR radiant heating/cooling systems
Gavhane, Viraj Vilas	ITO	

Last time

- Finished psychrometric examples
- Heating systems
- Refrigeration cycles
  - Vapor compression
  - Absorption
  - Expansion

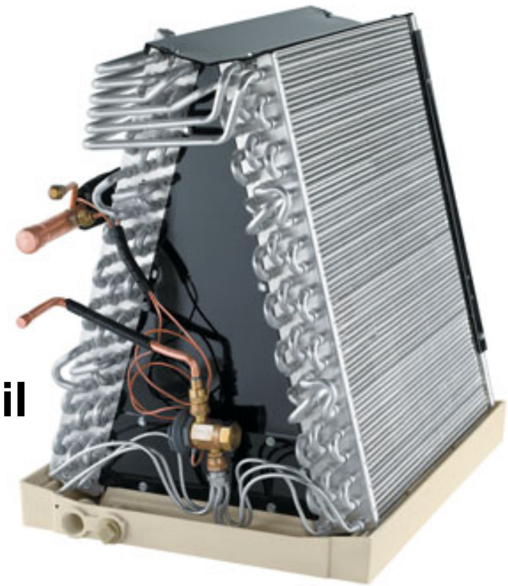


Ideal single-stage vapor compression cycle

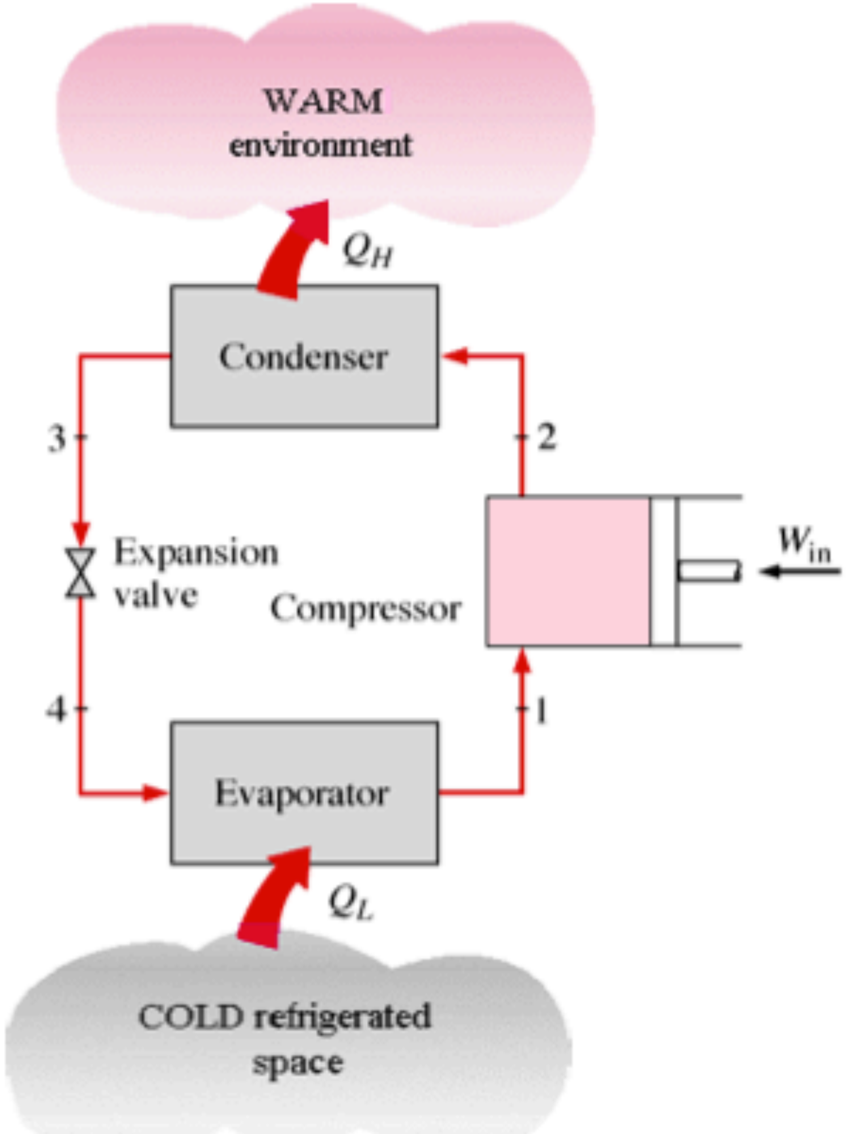


Expansion valve
(creates the high P restriction)

Evaporator coil



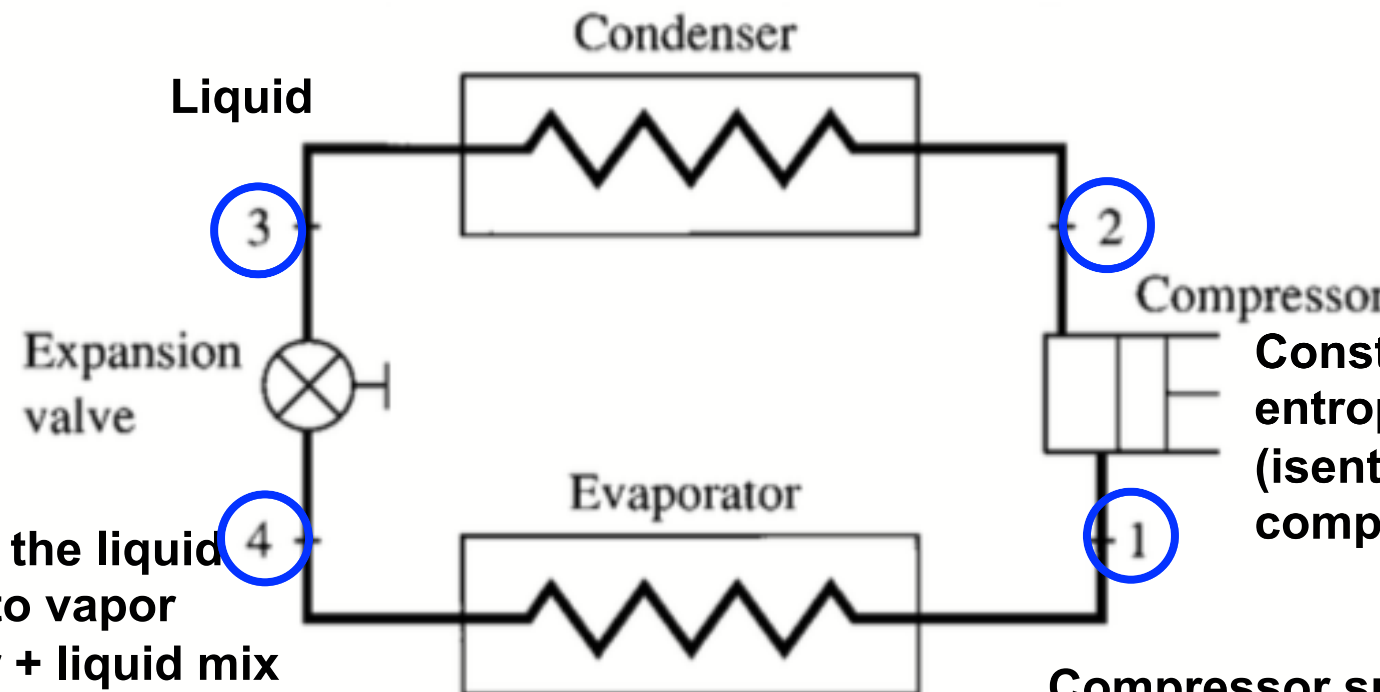
Ideal single-stage vapor compression cycle



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**

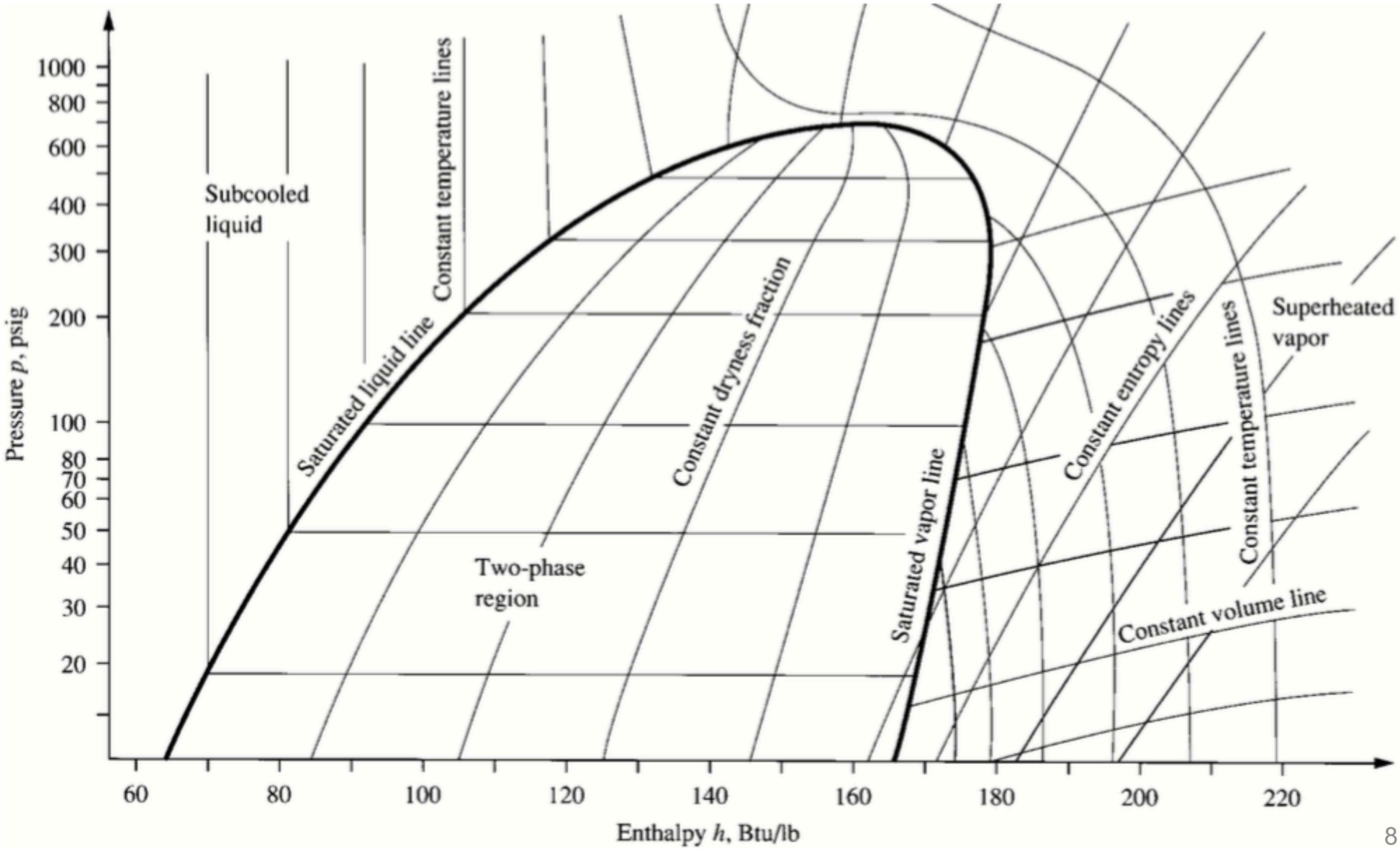
Rest of liquid evaporates at evaporating temperature

Compressor suction

- **“suction pressure”**

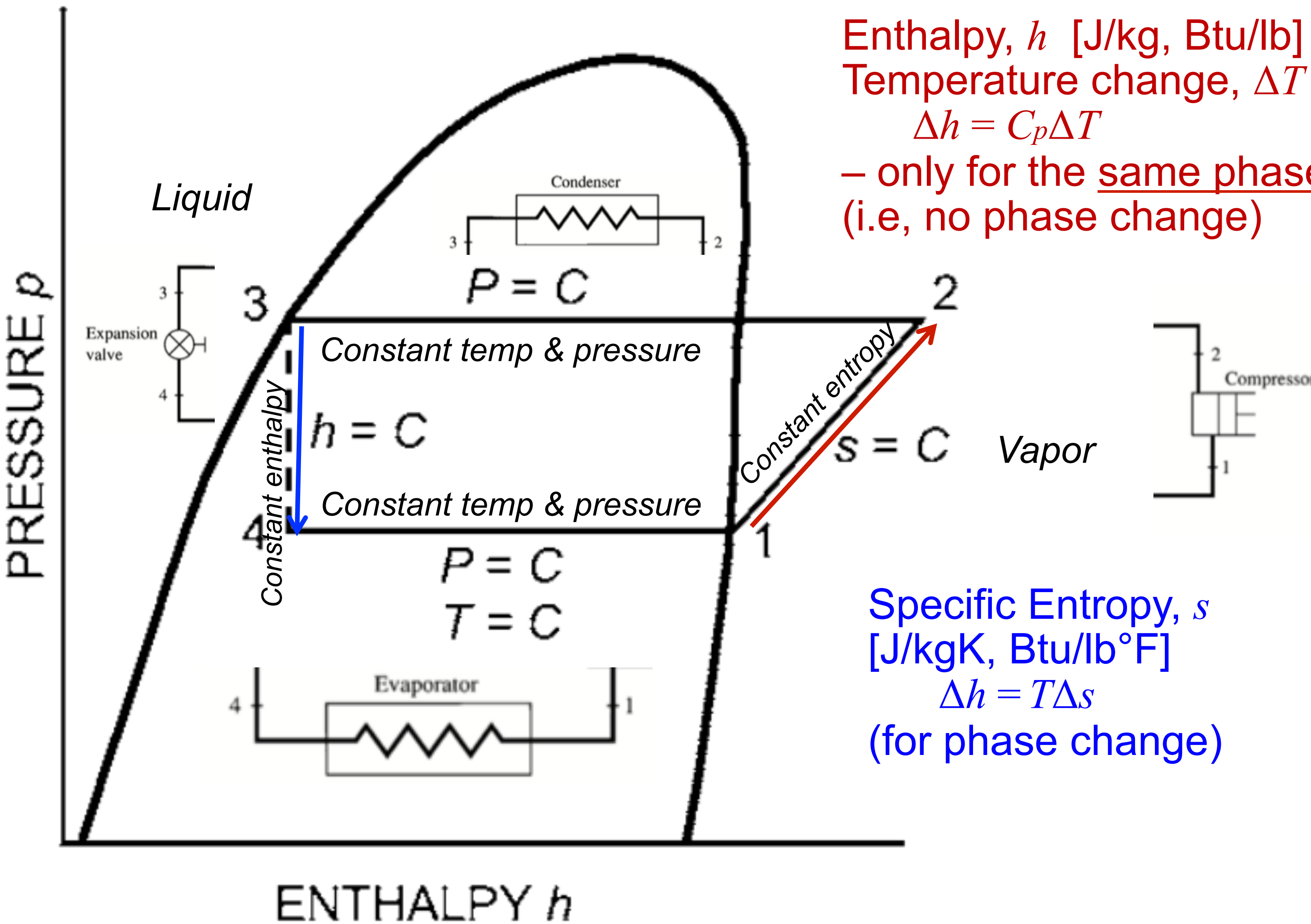
Ideal single-stage vapor compression cycle

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

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

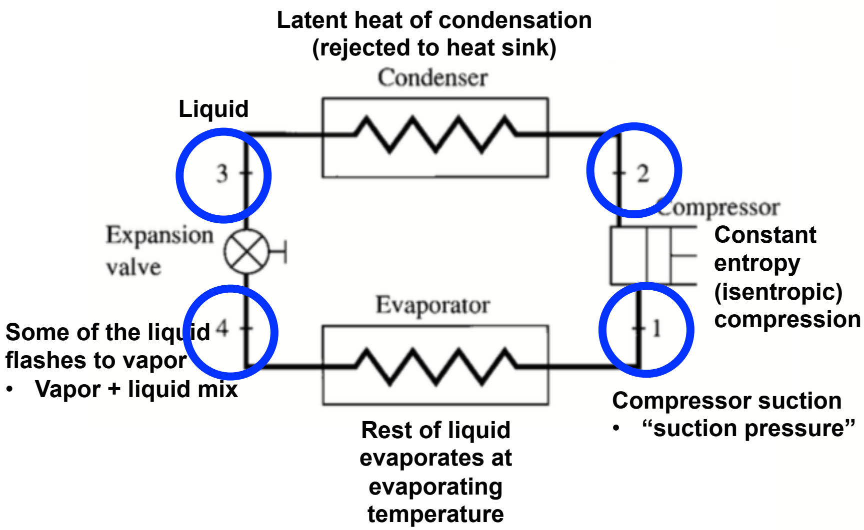
– only for the <u>same phase</u>
(i.e, no phase change)

Specific Entropy, s
[J/kgK, Btu/lb°F]

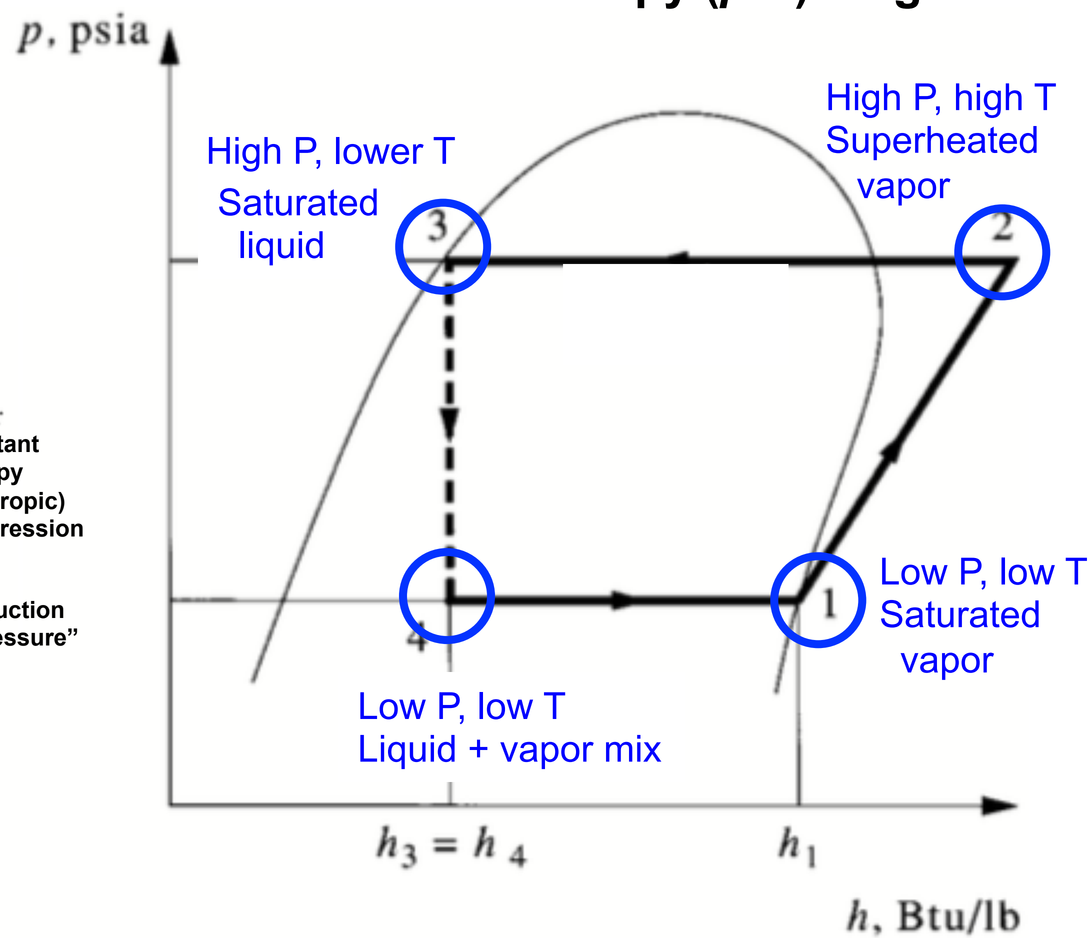
$$\Delta h = T \Delta s$$

(for phase change)

Ideal single-stage vapor compression cycle

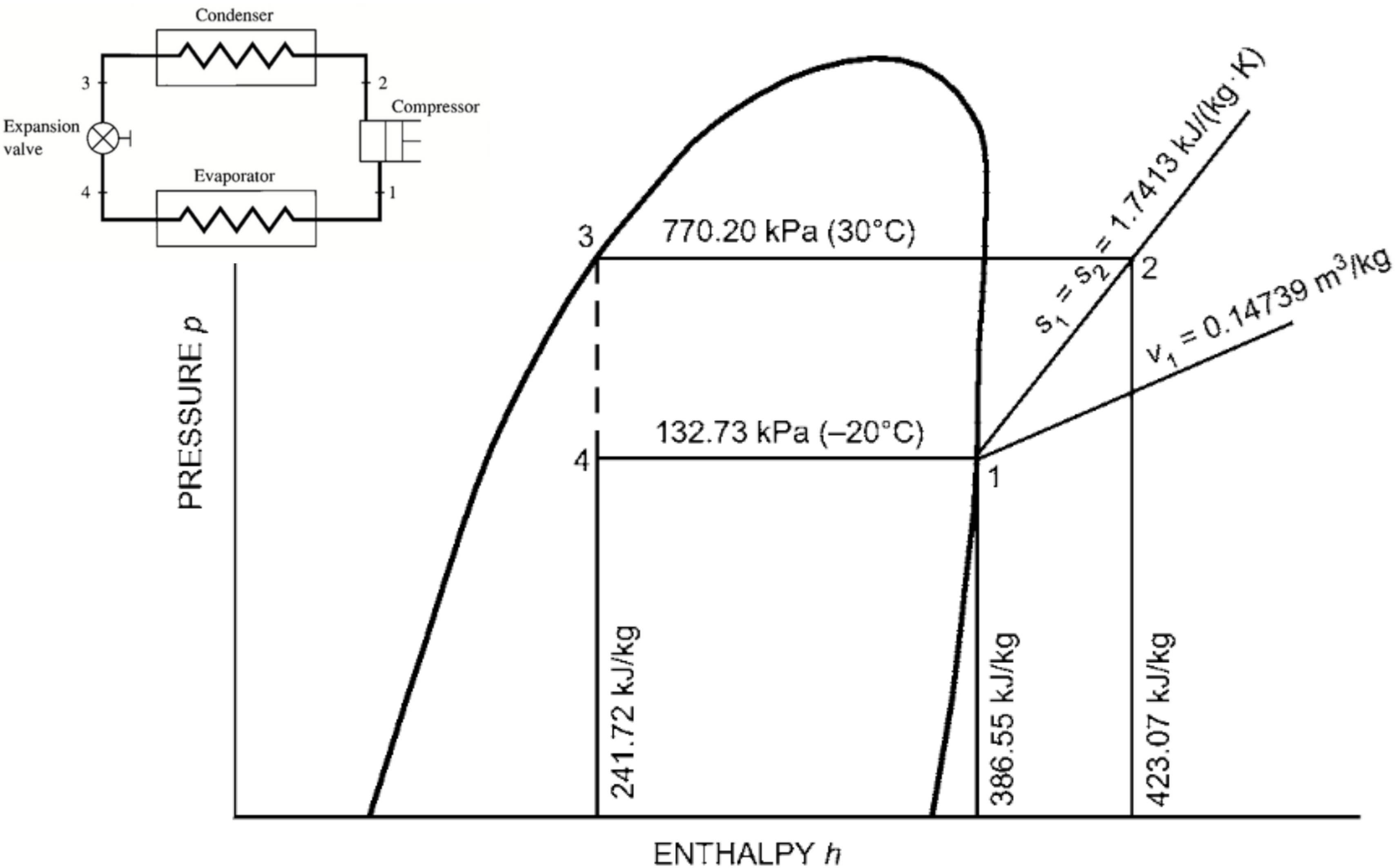


Pressure-enthalpy (*p-h*) diagram



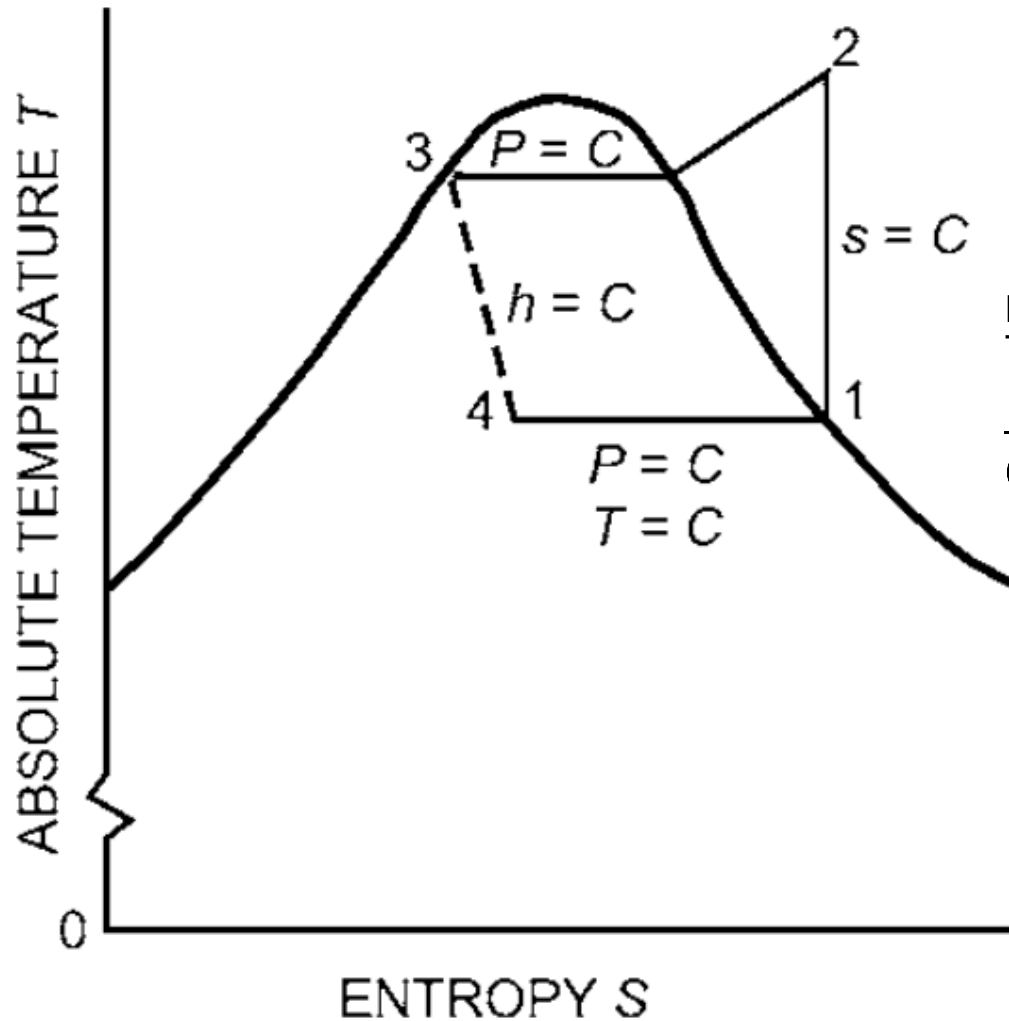
Ideal single-stage vapor compression cycle

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

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

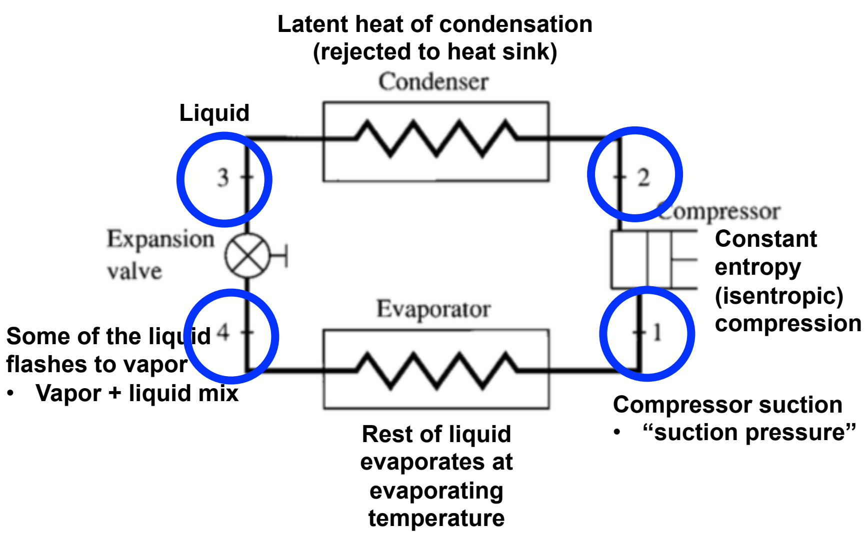
– only for the <u>same phase</u>
(i.e, no phase change)

Specific Entropy, s
[J/kgK, Btu/lb°F]

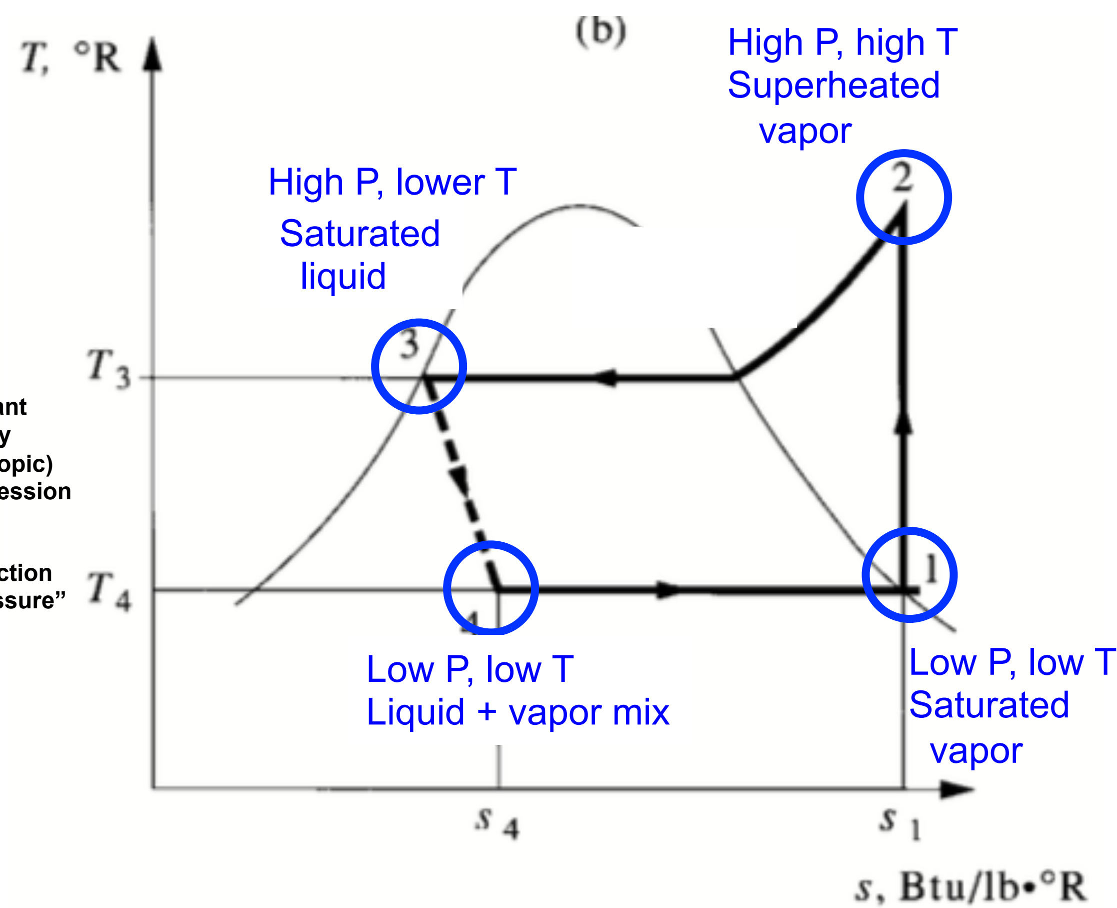
$$\Delta h = T\Delta s$$

(for phase change)

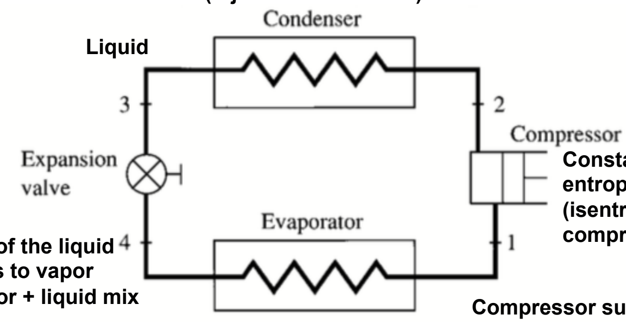
Ideal single-stage vapor compression cycle



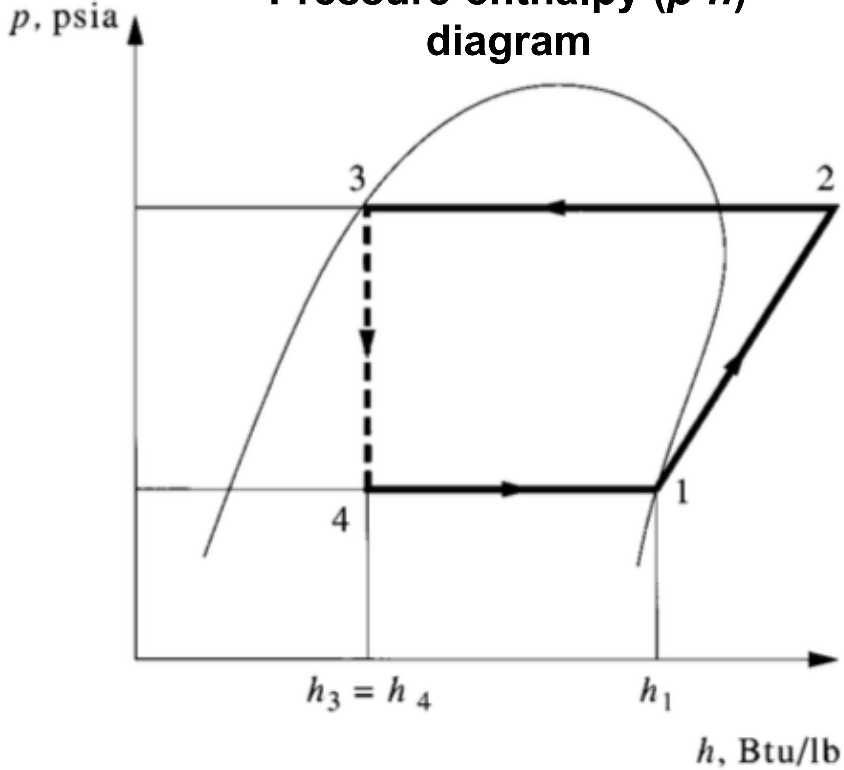
Temperature-entropy (*T-s*) diagram



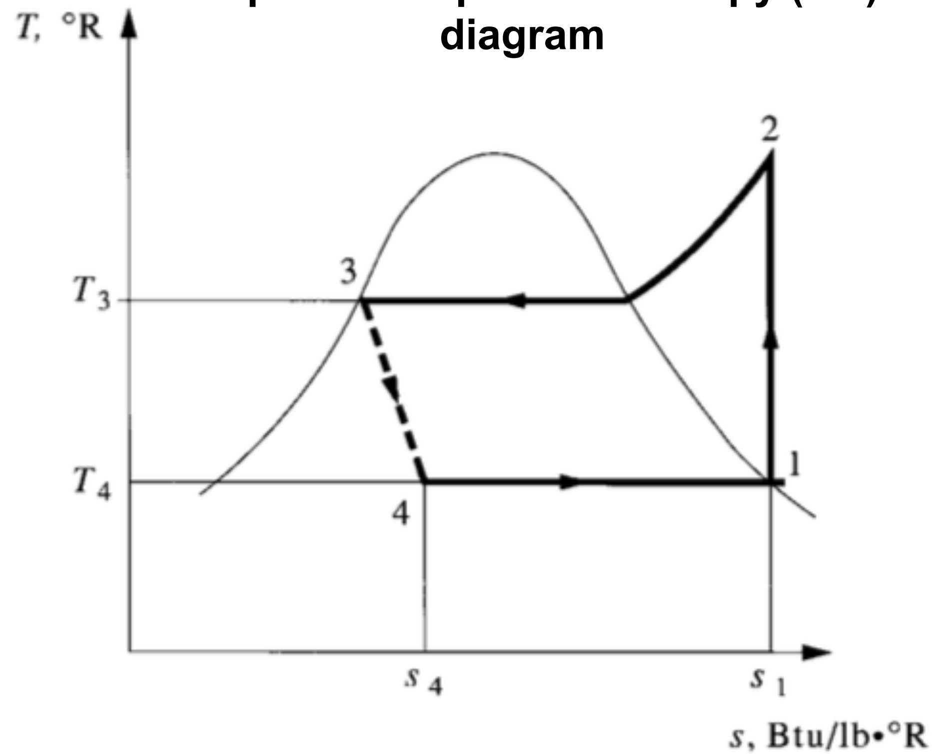
Ideal single-stage vapor compression cycle



Pressure-enthalpy (*p-h*) diagram



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



What makes a good refrigerant?

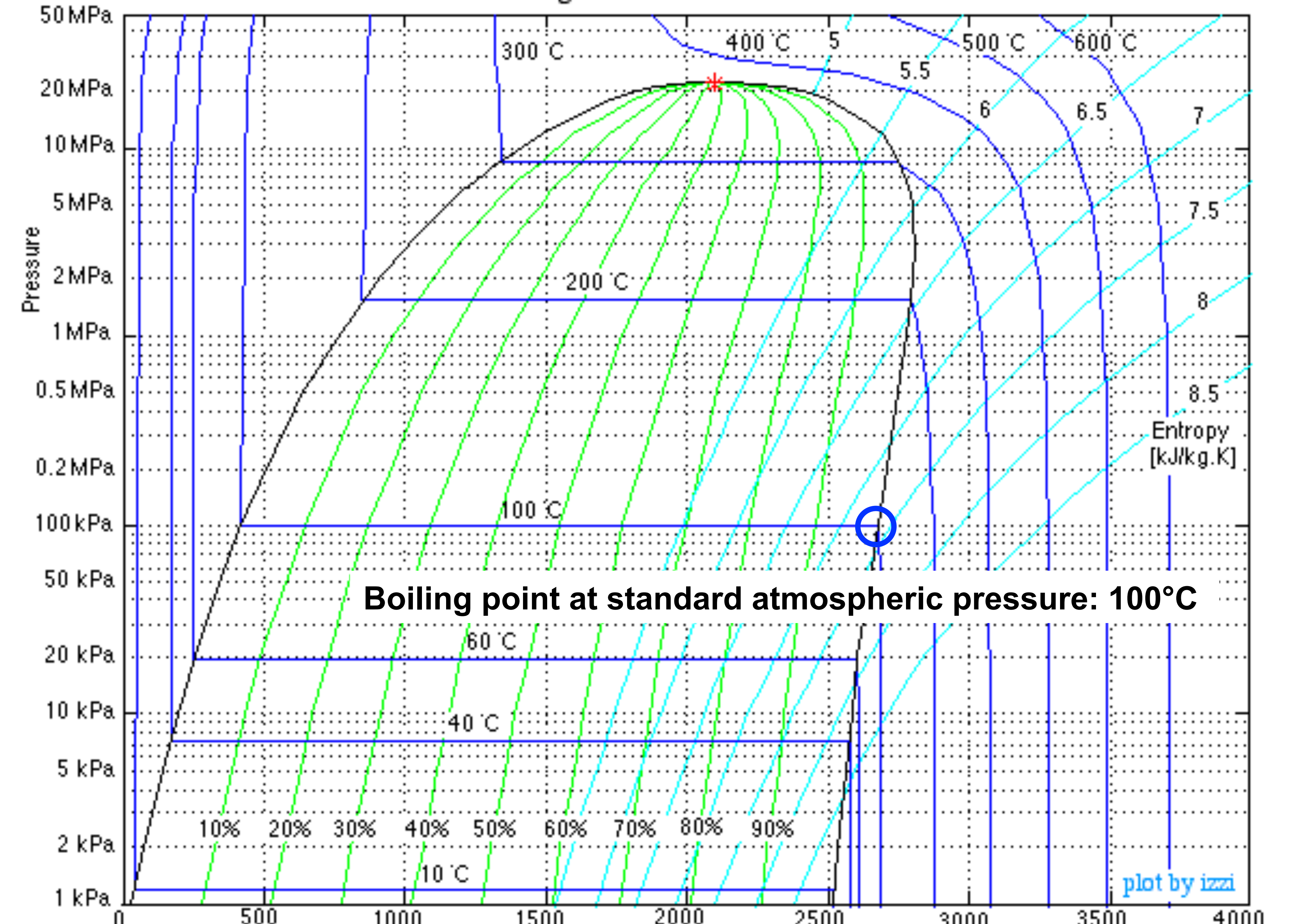
- The goal is to find a fluid that absorbs heat at a low temperature and low pressure and releases heat at a higher temperature and pressure
  - Most refrigerants will undergo phase changes during heat absorption (i.e., evaporation) and heat release (i.e., condensation)
- You want a refrigerant that:
  - Has an evaporating pressure 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 inert (avoids corrosion)
  - Has a high thermal conductivity (increases heat transfer efficiency in heat exchangers)
  - Has a high refrigeration capacity (i.e., a high latent heat of vaporization and specific volume at the suction pressure)

What makes a good refrigerant?

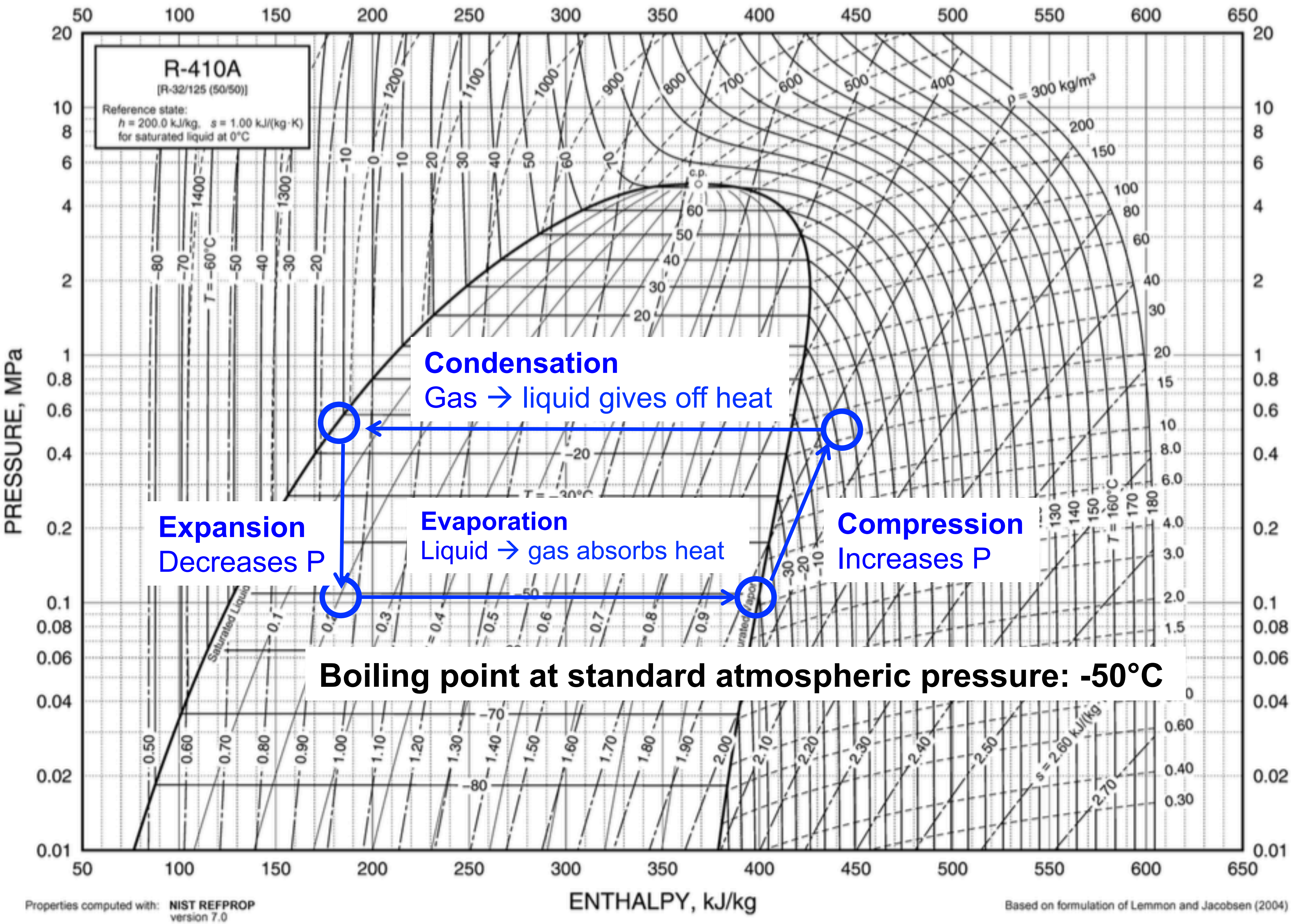
- In the past, we have used ammonia, sulfur dioxide, methyl chloride, and others
  - All are quite toxic

- 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 (which are being phased out once again for global warming potentials)
  - Boiling point = -55°F
  - Liquid heat capacity = 1.8 kJ/kgK @ STP
  - Gas heat capacity = 0.84 kJ/kgK @ STP



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



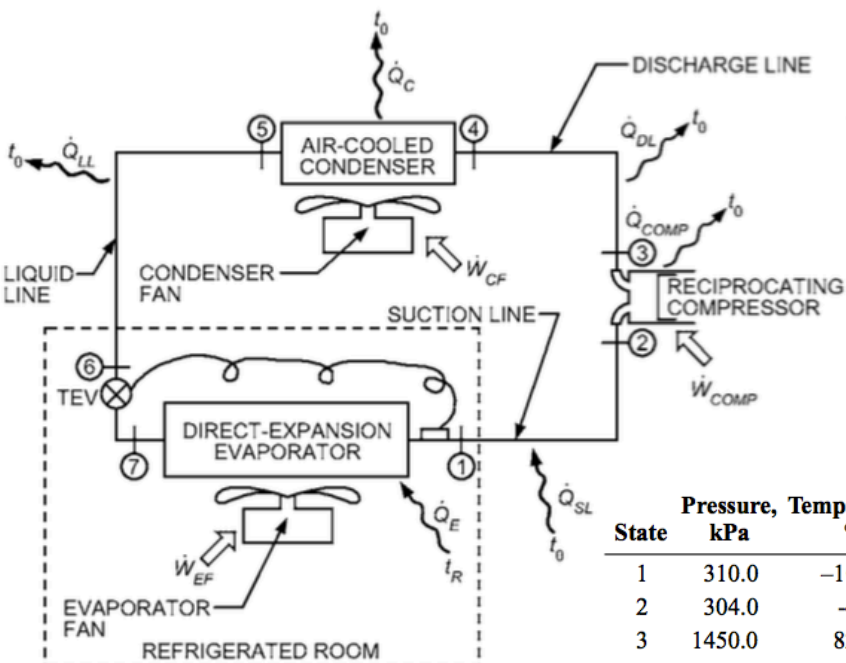
***p-h* diagram for R-410A**

Fig. 16 Pressure-Enthalpy Diagram for Refrigerant 410A

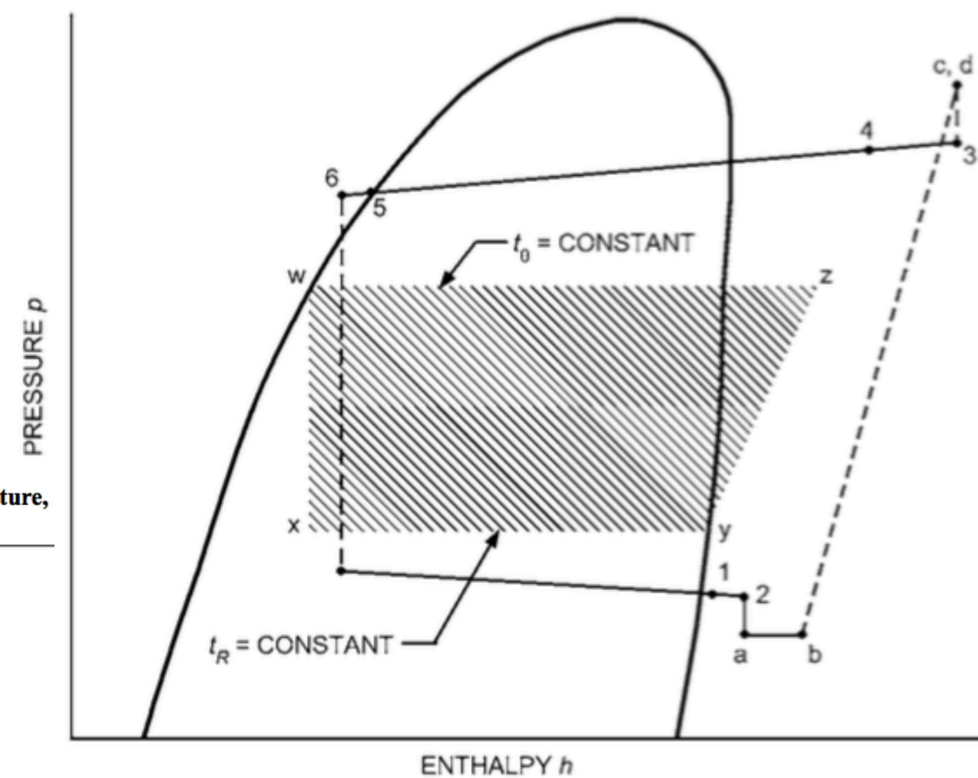
<u>Non</u>-ideal single-stage vapor compression cycle

<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



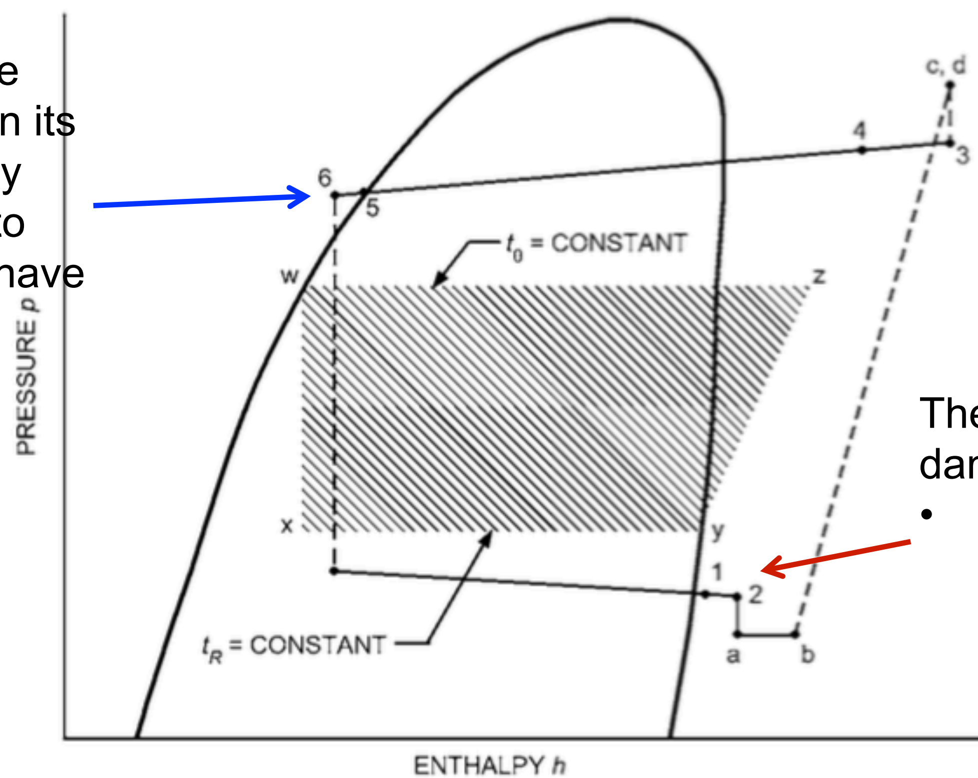
<u>Non</u>-ideal single-stage vapor compression cycle

<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

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

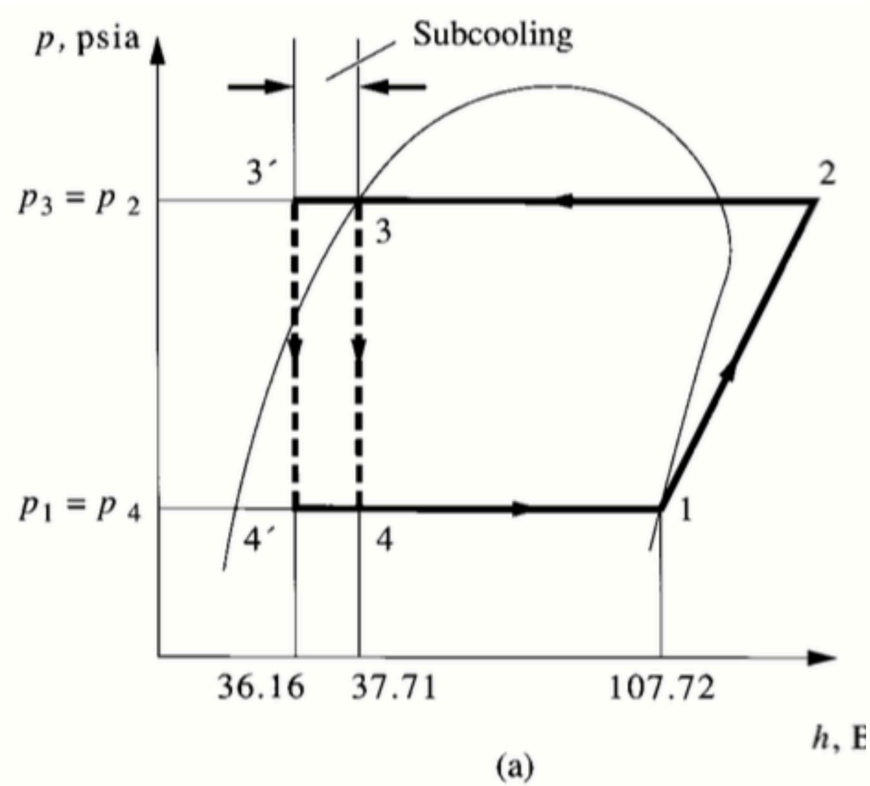
- You "**subcool**" to ensure that you have only liquid

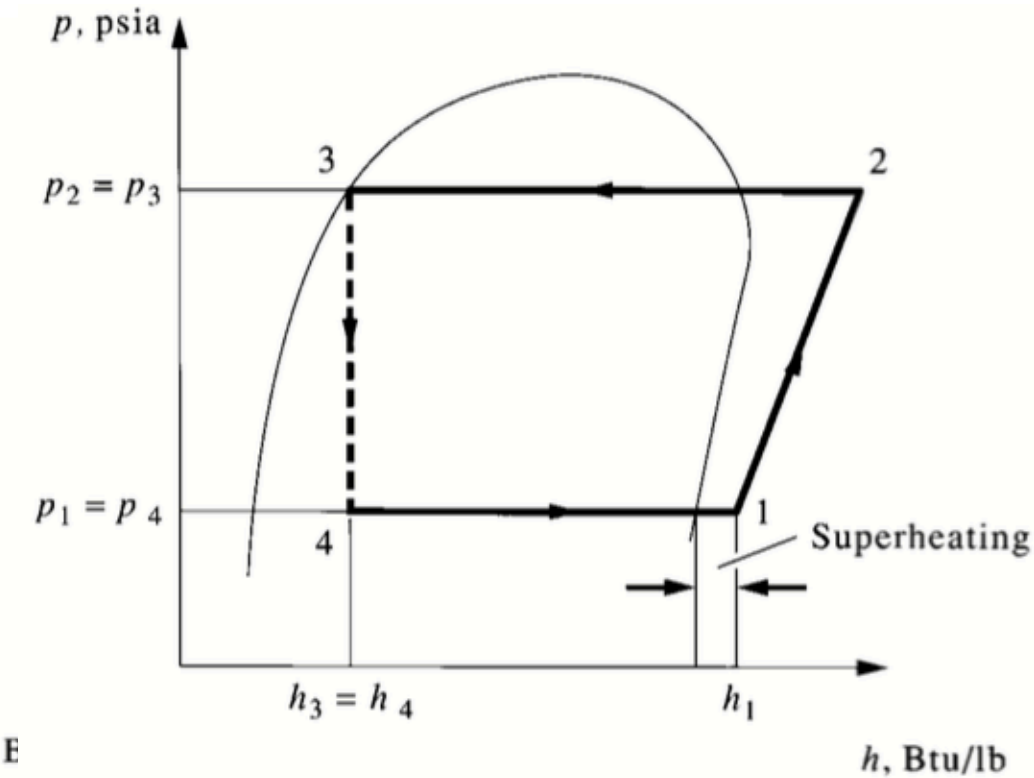


The compressor will be damaged if liquid enters

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

Non-ideal single-stage vapor compression cycle





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

Joke courtesy of Jeff Siegel, University of Toronto

Coefficient of performance (COP)

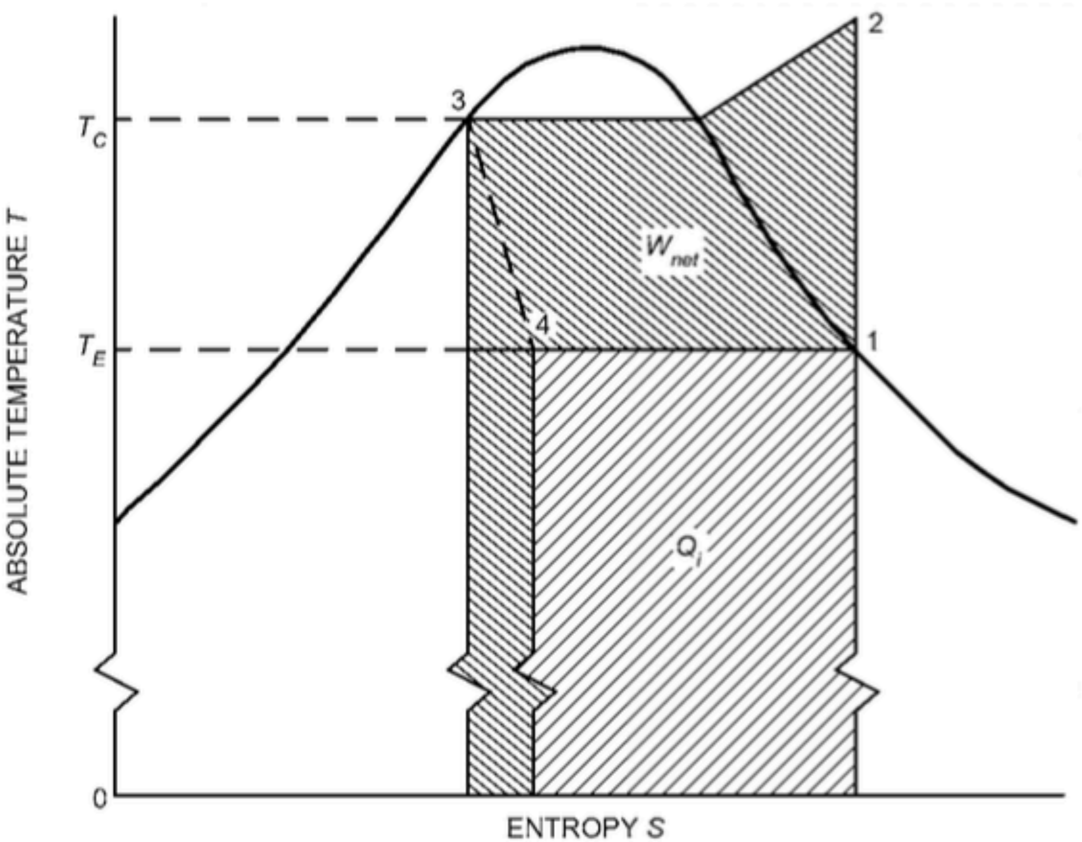
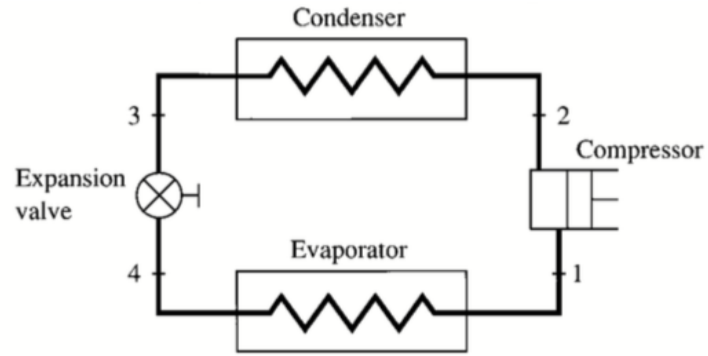


Fig. 10 Areas on *T*- *s* Diagram Representing Refrigerating Effect and Work Supplied for Theoretical Single-Stage Cycle

For an <u>ideal</u> refrigeration cycle:

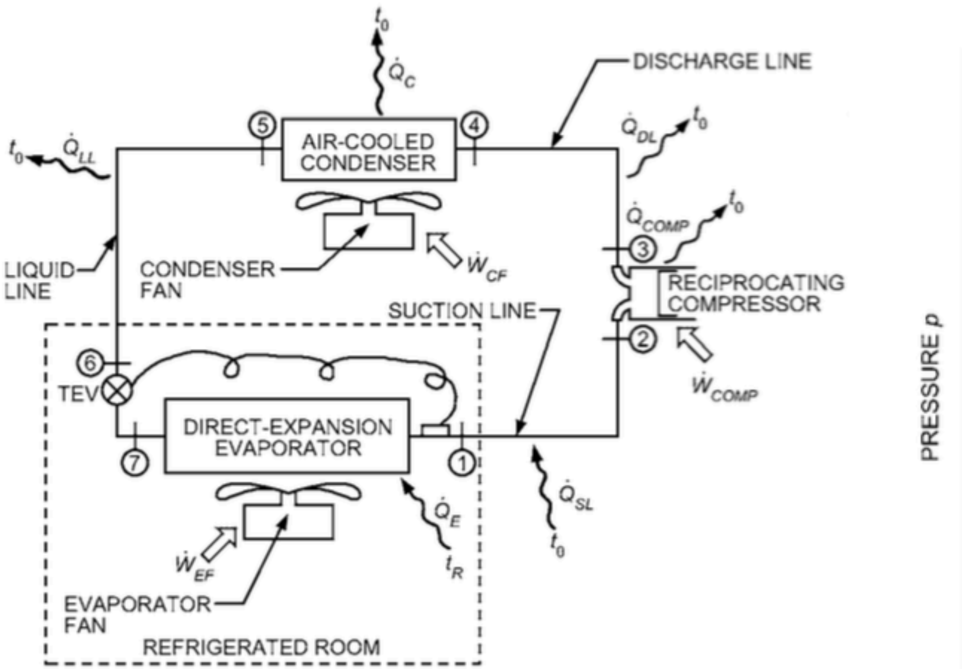
$$COP = \frac{Q_{cool}}{W_{elec}} = \frac{h_1 - h_4}{h_2 - h_1}$$

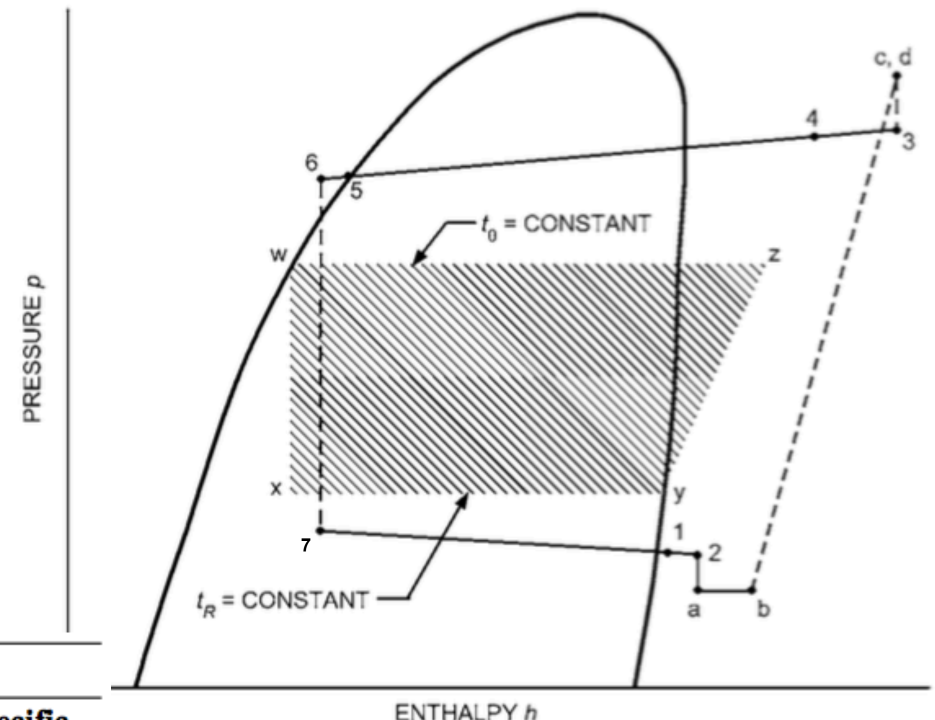


What is the efficiency of a typical residential AC unit?

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

COP example calculation





	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

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

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

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)

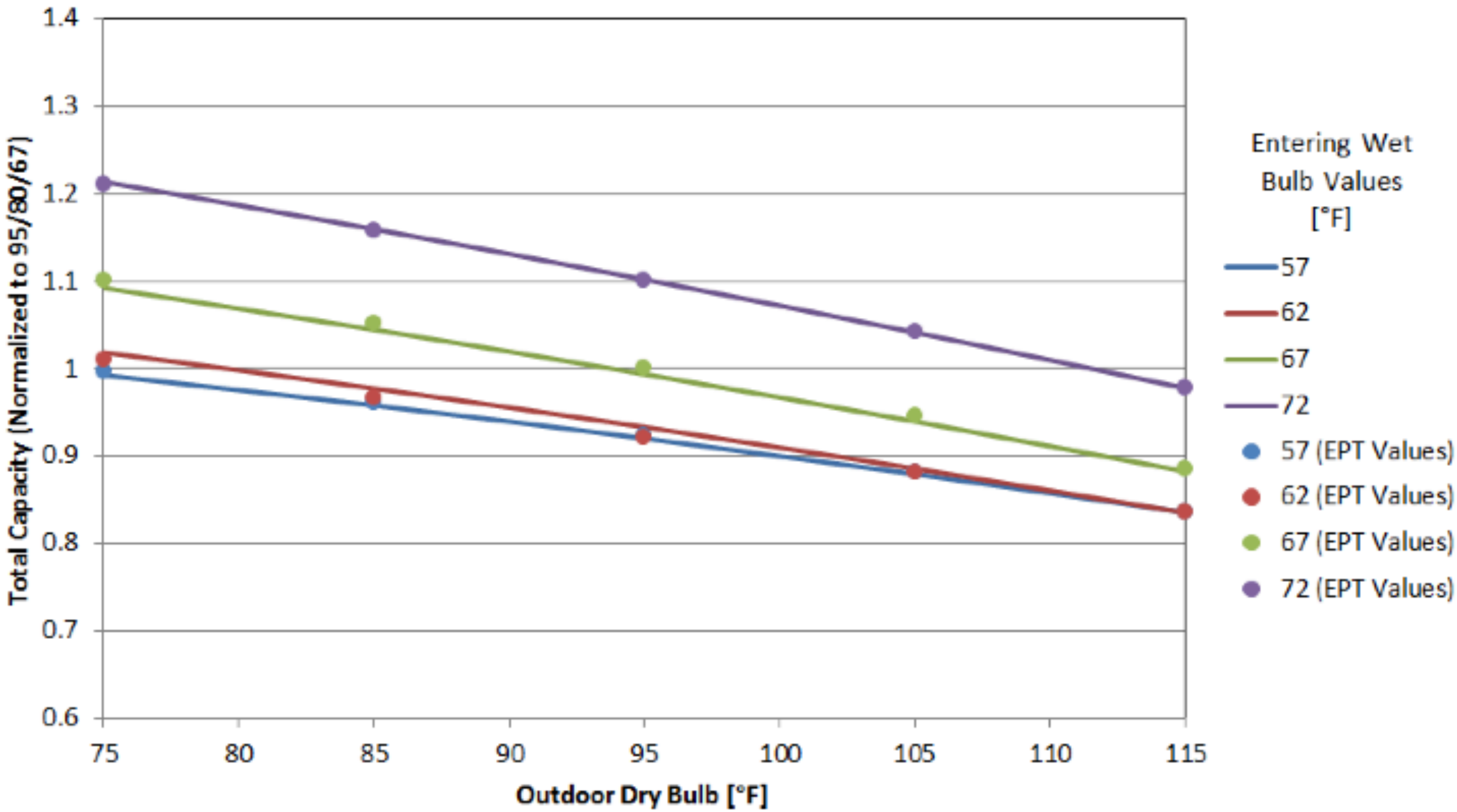
Evaporator Air		Condenser Air °F (°C)								
		75 (23.9)			95 (35)			105 (40.6)		
cfm	EWB °F (°C)	Capacity kBtu/h Total[1]	Capacity kBtu/h Sens[1,2]	Total Sys kW[3]	Capacity kBtu/h Total[1]	Capacity kBtu/h Sens[2]	Total Sys kW[3]	Capacity kBtu/h Total[1]	Capacity kBtu/h Sens[2]	Total Sys kW[3]
875	72 (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:

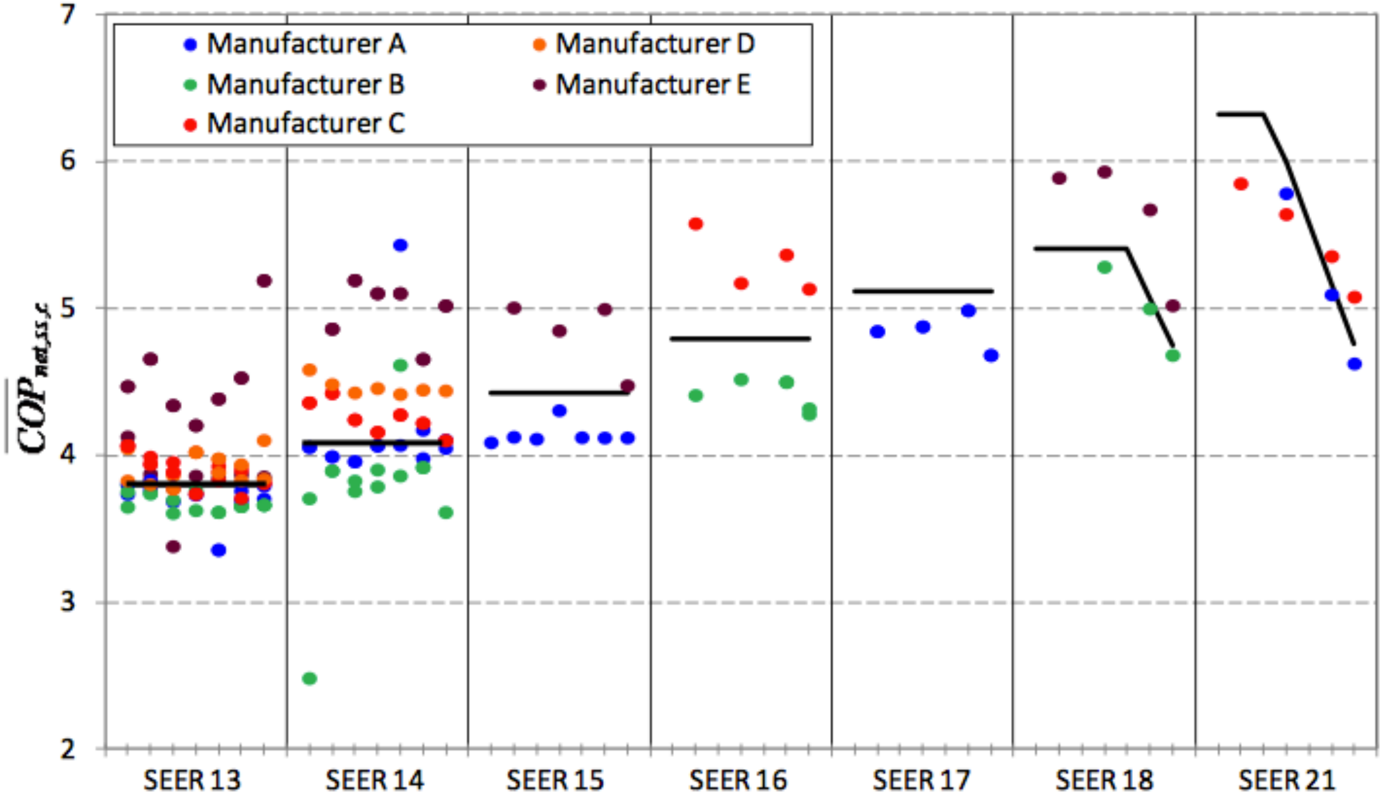
$$COP = \frac{8.5\ [\mathrm{kW}]}{2.48\ [\mathrm{kW}]} = 3.43 \qquad EER = \frac{29.0\ [\mathrm{kBtu/hr}]}{2.48\ [\mathrm{kW}]} = 11.7$$

$$EER = COP \times 3.41$$

- 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:

$$\mathrm{P}_{elec} = \frac{Q_{cooling,load}}{COP}$$

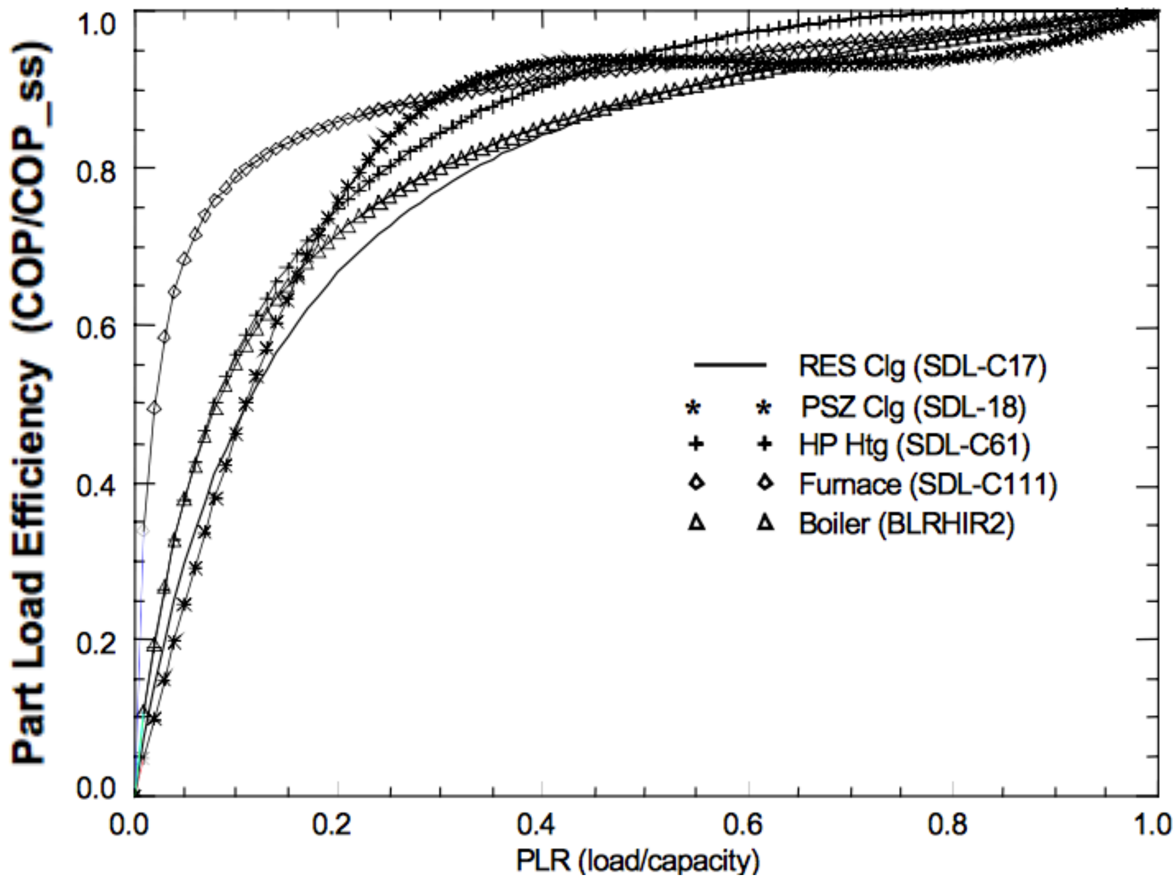
- If you multiply by the number of hours and sum over a period of operating time, you can estimate energy consumption:

$$E = \sum \mathrm{P}_{elec}\,\Delta t$$

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

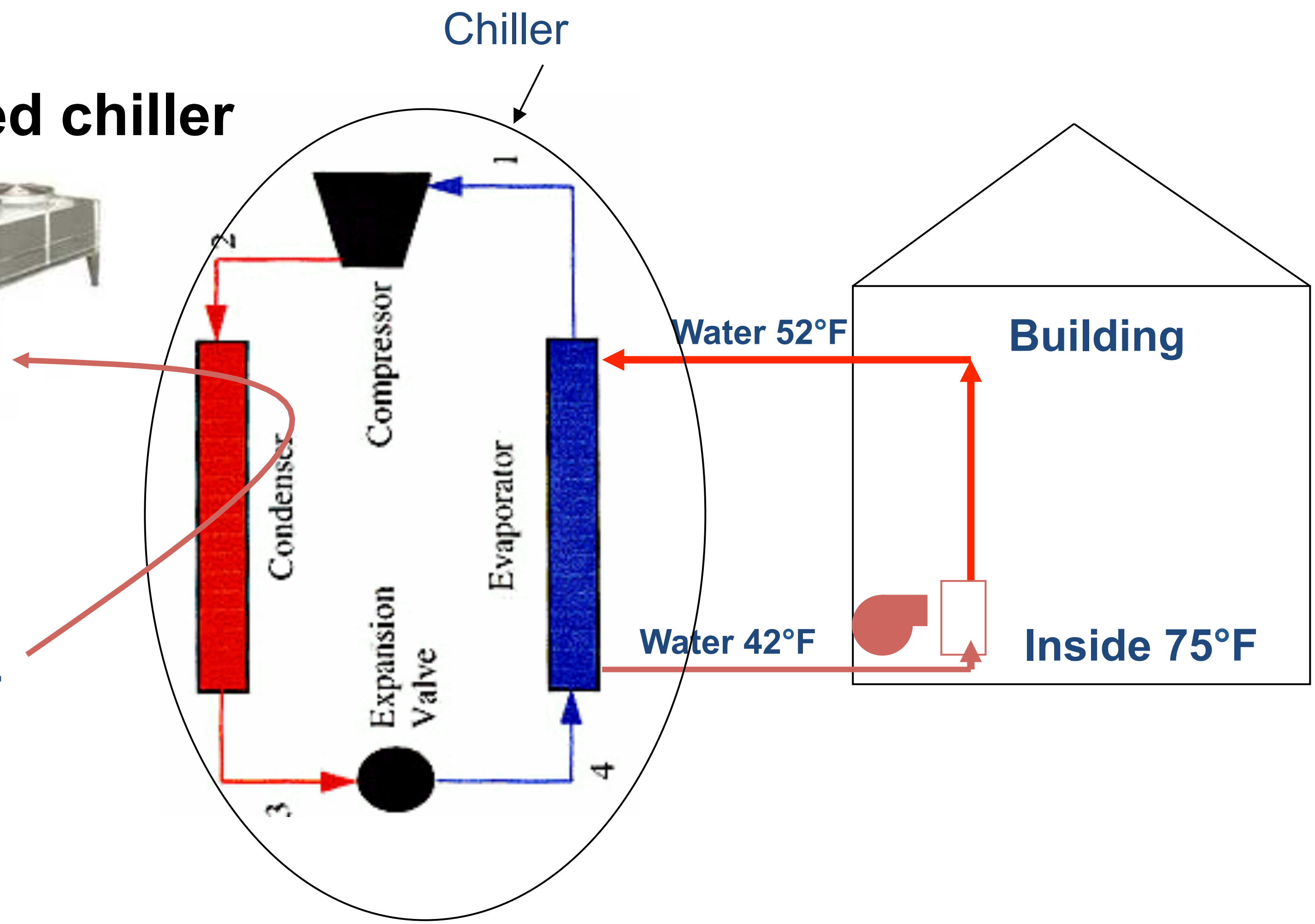
Part-load ratio (PLR)

- Many systems operate at their highest efficiency (highest COP) at design load conditions
  - Maximum load
- But systems don't always operate at peak load conditions
  - "Part-load" conditions are common
- The "part-load ratio" quantifies COP at part-load conditions



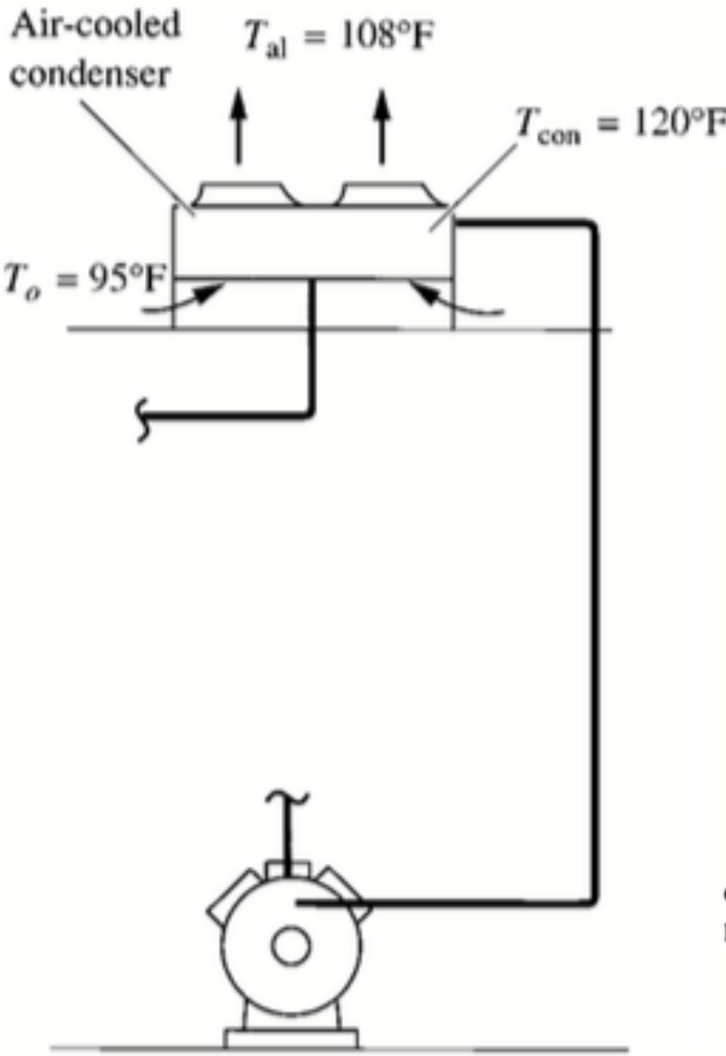
Air-cooled chillers

- Chillers use vapor compression or absorption systems to produce chilled water for cooling spaces

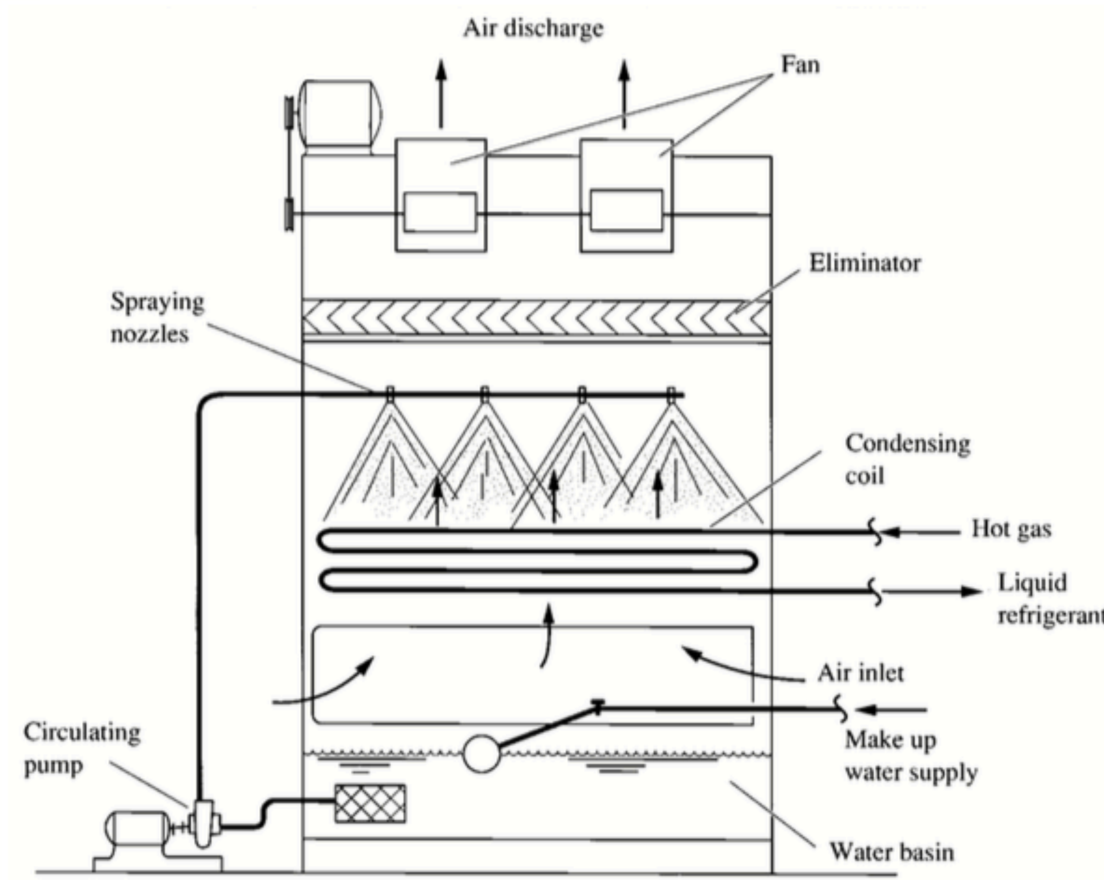


Air-cooled and evaporative condensers

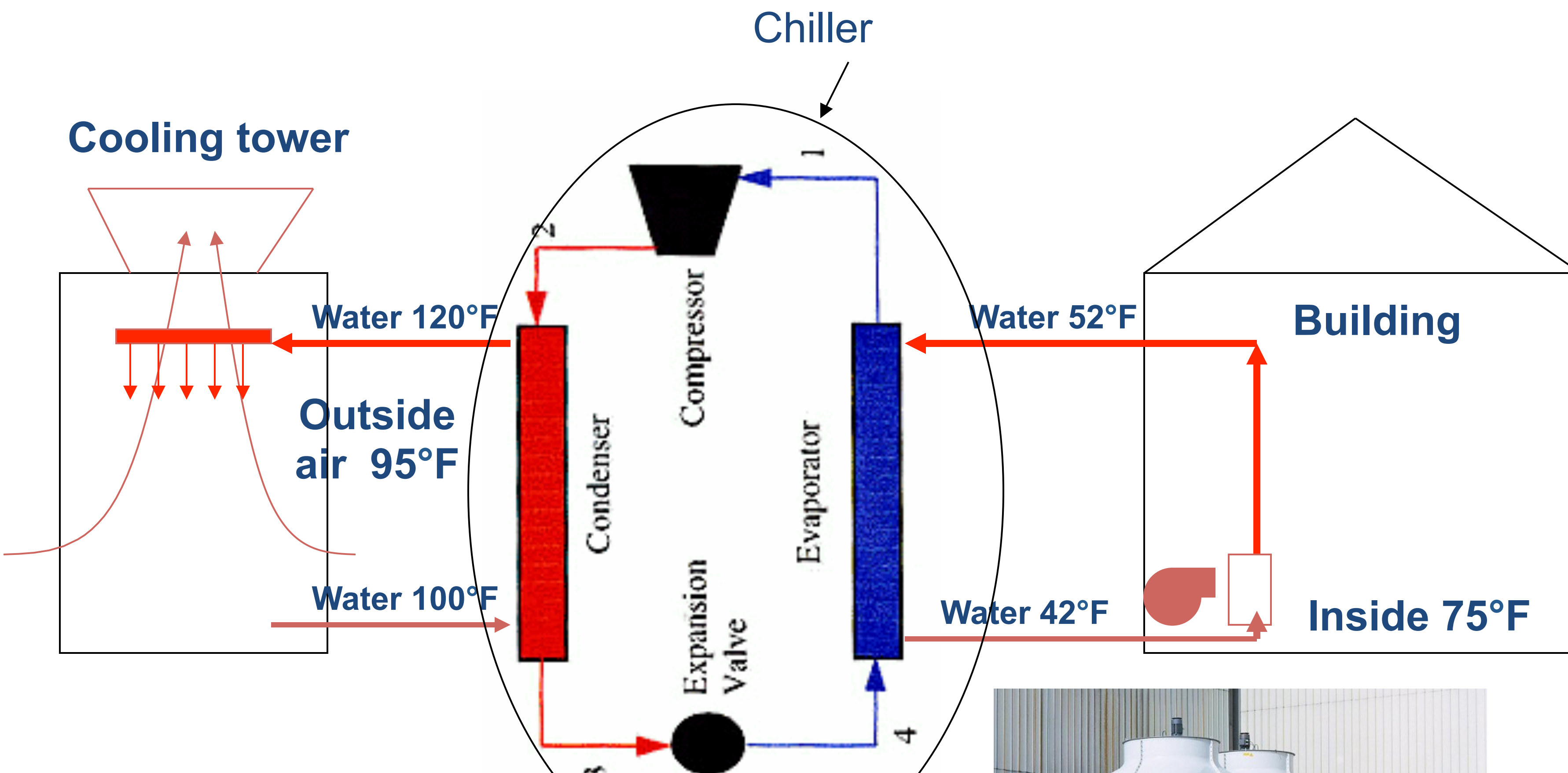
Air-cooled condenser



Evaporative condenser

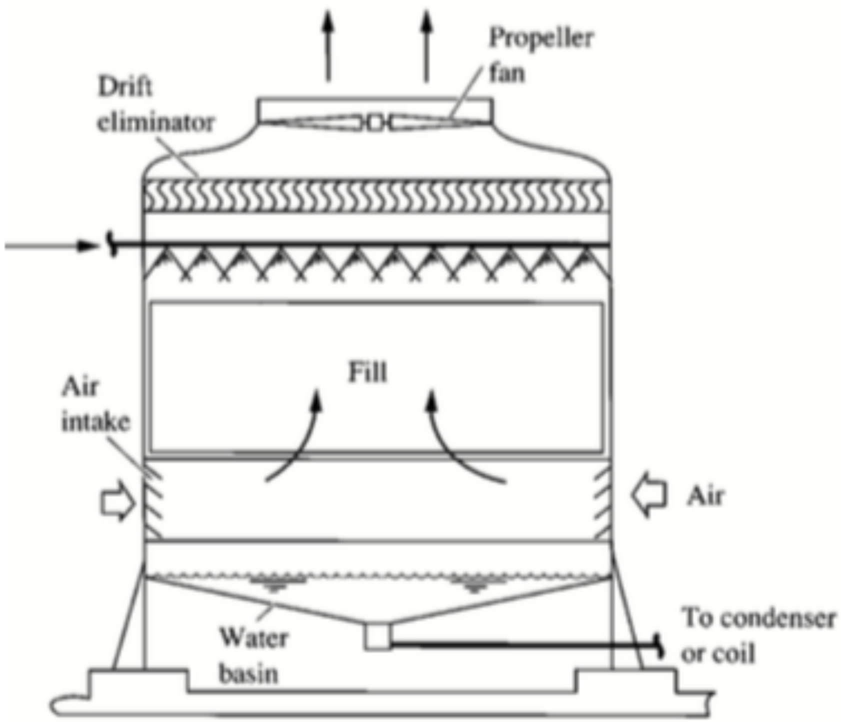


Water-cooled chillers (i.e., “cooling tower”)

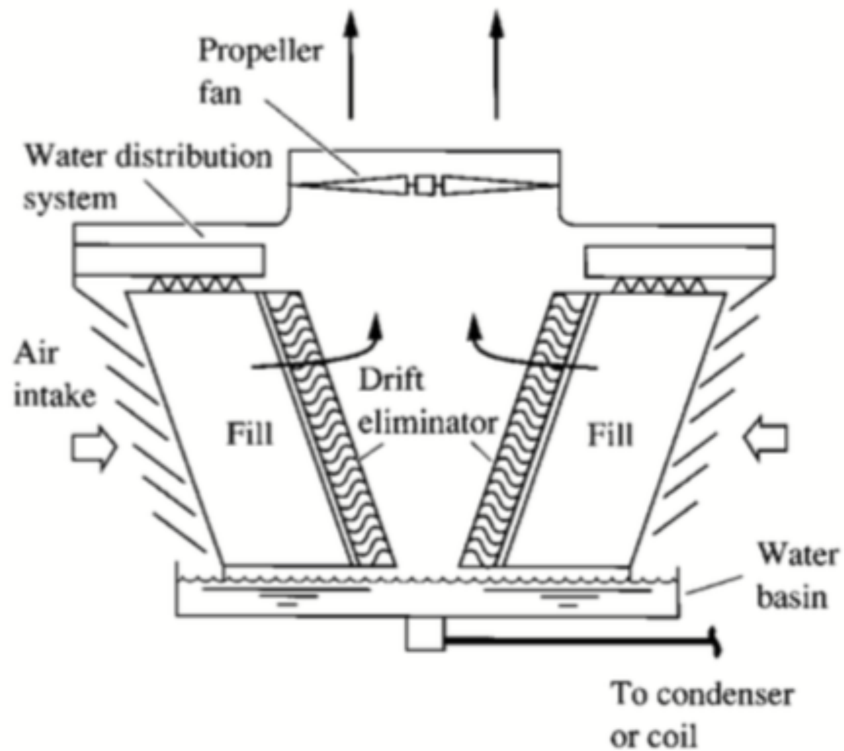


Water-cooled chillers (i.e., “cooling tower”)

Counter-flow induced draft



Cross-flow induced draft



Air vs. water cooled chillers

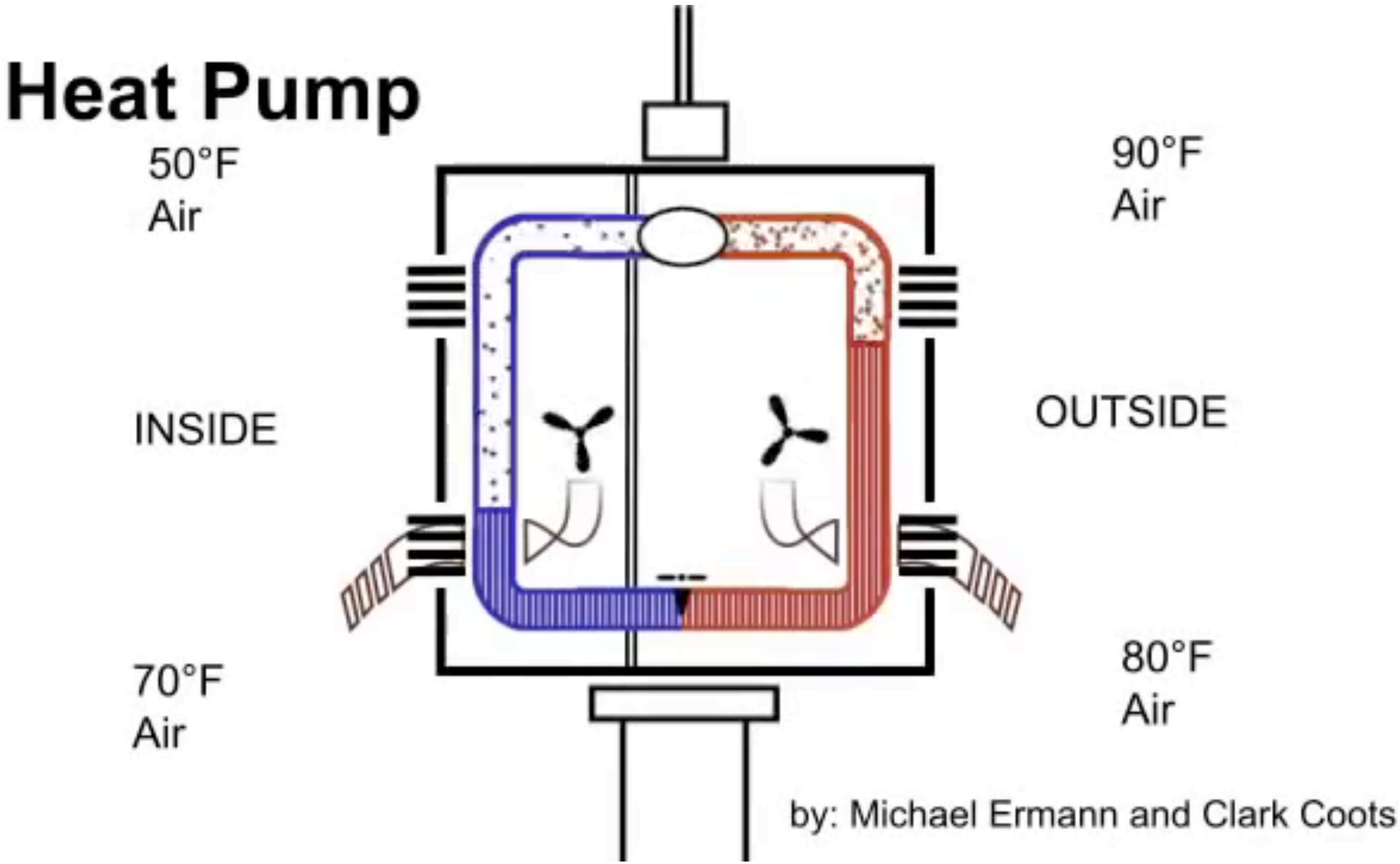
TABLE 10.3 Comparison of Various Heat Rejection Systems at Summer Design Conditions

	Water-cooled condenser	Water-cooled condenser and cooling tower	Air-cooled condenser	Evaporative condenser
Condensing temperature, °F	95	102	120	100
Cooling air volume flow rate, cfm/ton*			600–1200	Smaller than air-cooled condenser
Cooling water, gpm/ton*	3	3		1.6–2
Makeup water, gal/(h·ton)*		2.4		2.4
Maintenance			Periodic cleaning of coil when outdoor air is not clean	Monthly inspection and cleaning of coil
Initial cost (refrigeration plant)	Depending on initial cost on water intake	Lower than air-cooled condenser	Higher	Higher
Energy consumption (refrigeration plant)	Lower	Lower than air-cooled condenser	Higher at design load	Lower
Condensing heat used for winter heating or equipment itself used for evaporative cooling	Easier	Best applied	Between water-cooled and evaporative condenser	Difficult
Application	Large	Medium and large	Medium and small size, or where water is scarce	Medium and large

Comparison is based on outdoor 95°F dry-bulb, 78°F wet-bulb; lake, river, or seawater temperature = 78°F.
*Ton refrigeration capacity at the evaporator.

HEAT PUMPS

Air- and ground-source heat pumps

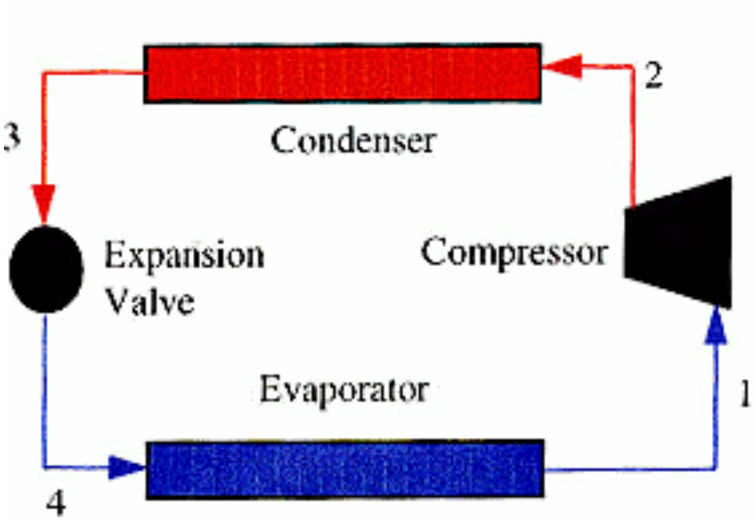


https://www.youtube.com/watch?v=NyNeh7wPQQk

Heat pumps

Cooling

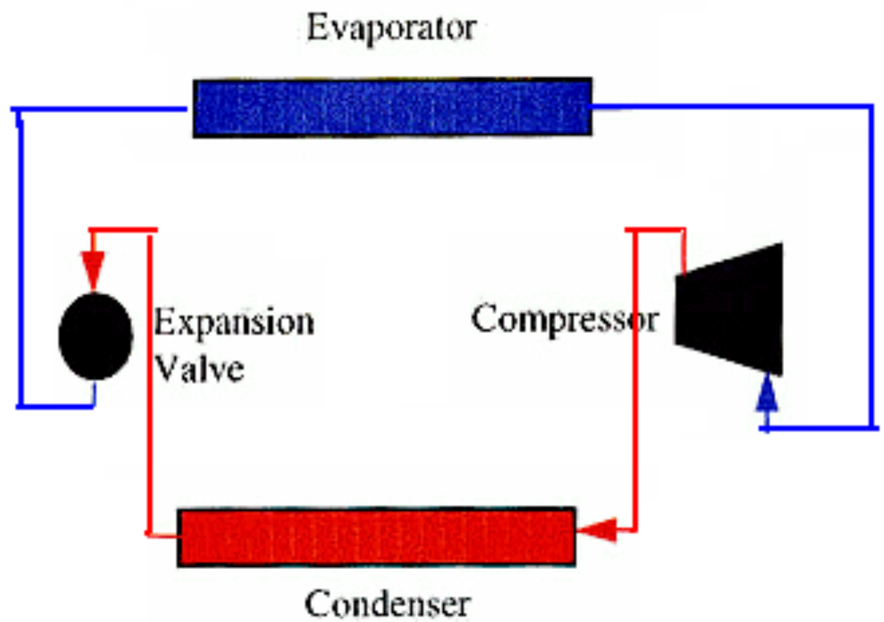
Outside 95°F



Inside 75°F

Heating

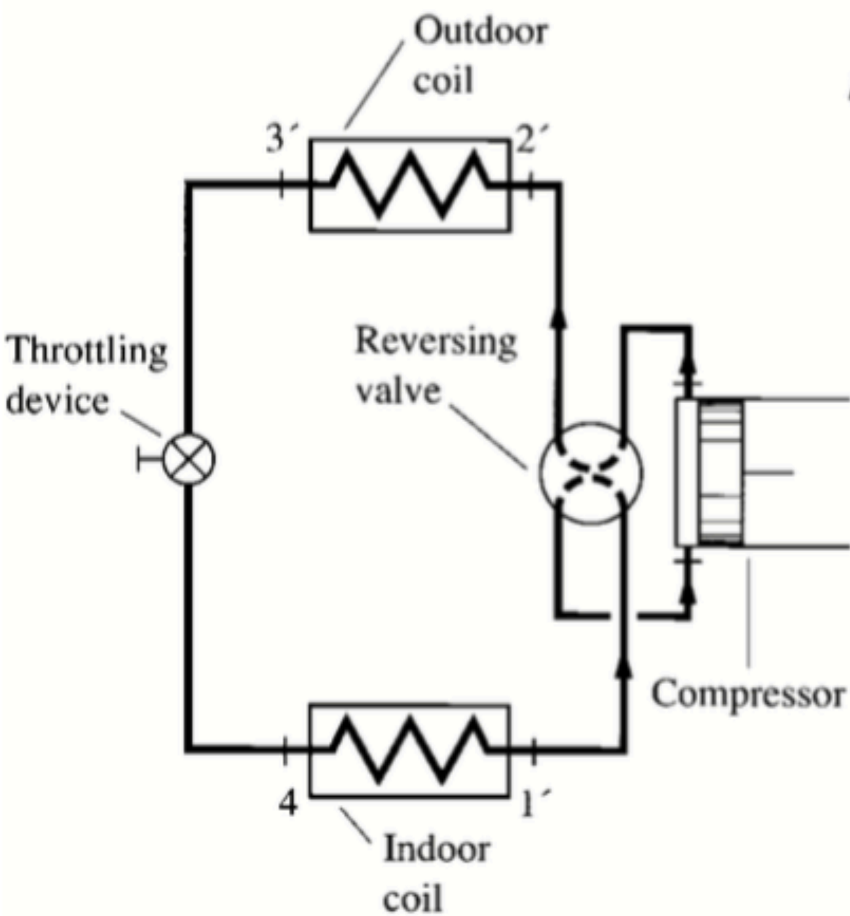
Outside 45°F



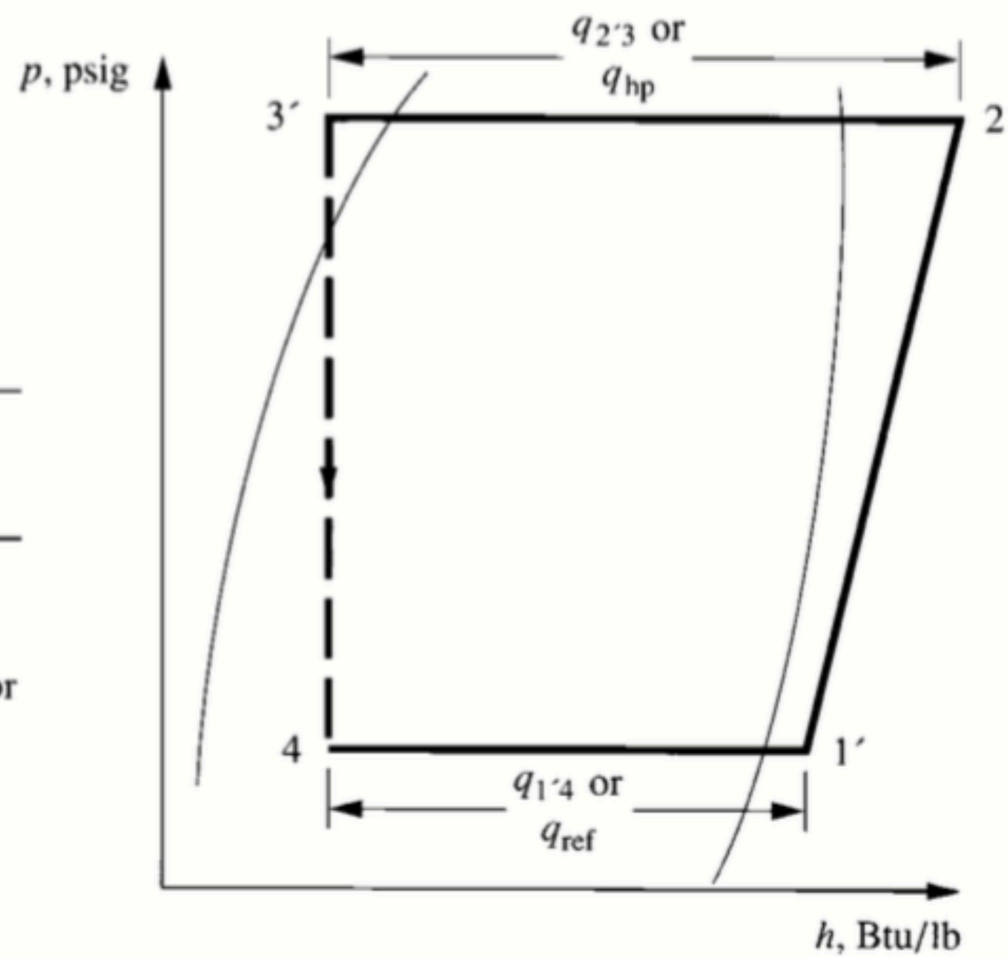
Inside 75°F

Air-conditioner run in reverse

Heat pumps

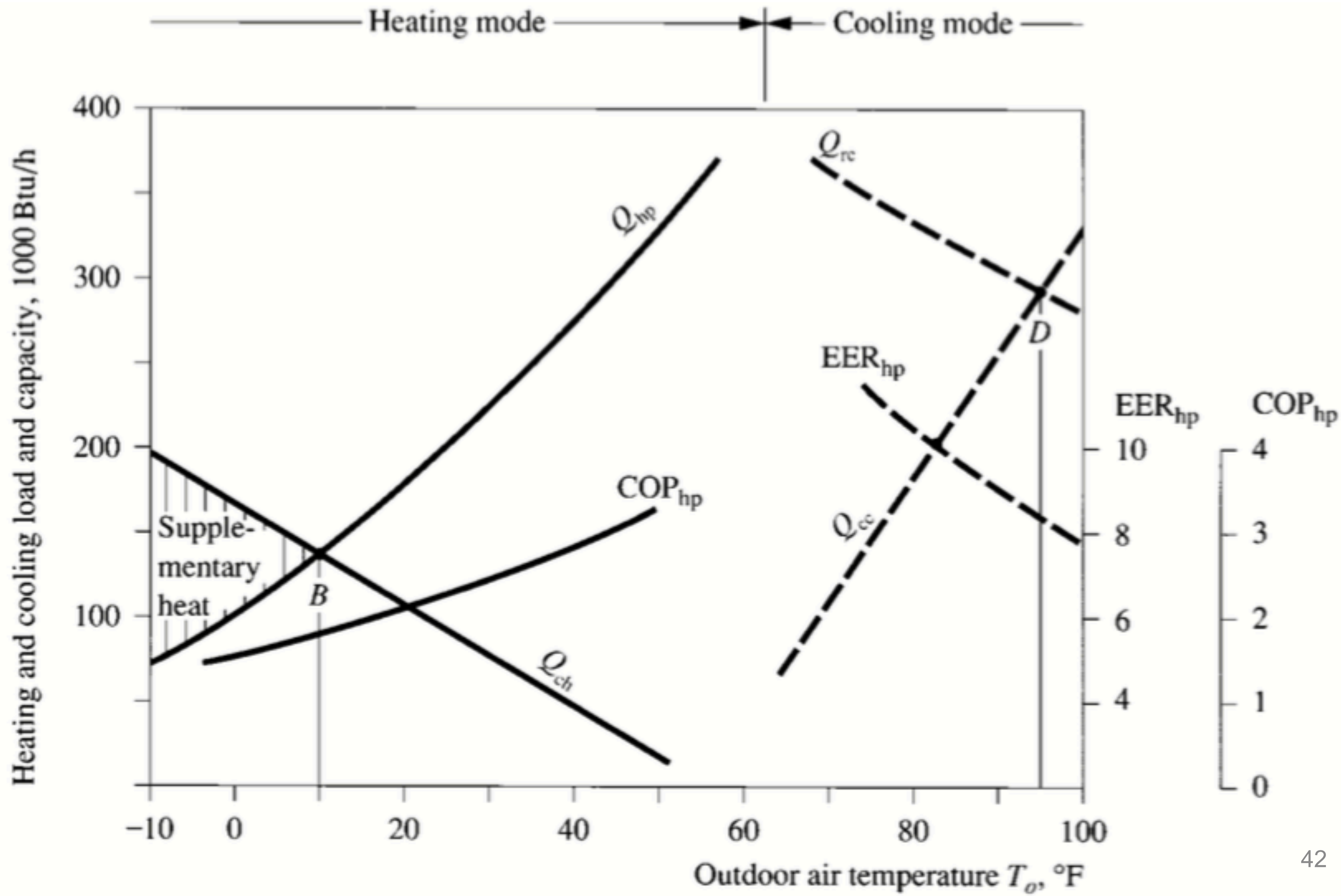


Outdoor coil
3′
2′
Throttling device
Reversing valve
Compressor
4
1′
Indoor coil



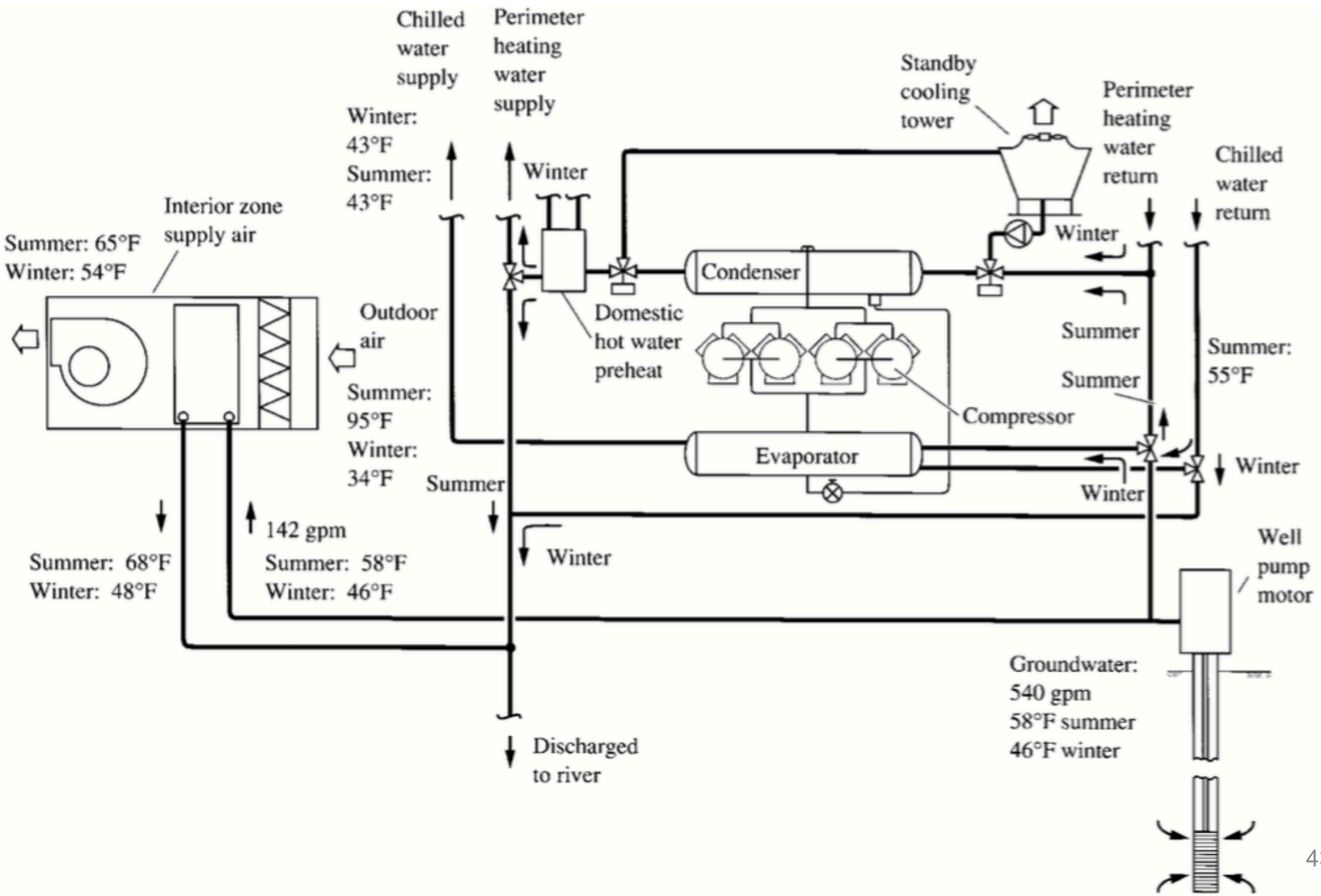
p, psig
$q_{2'3}$ or q_{hp}
3′
2′
4
1′
$q_{1'4}$ or q_{ref}
h, Btu/lb

Heat pumps

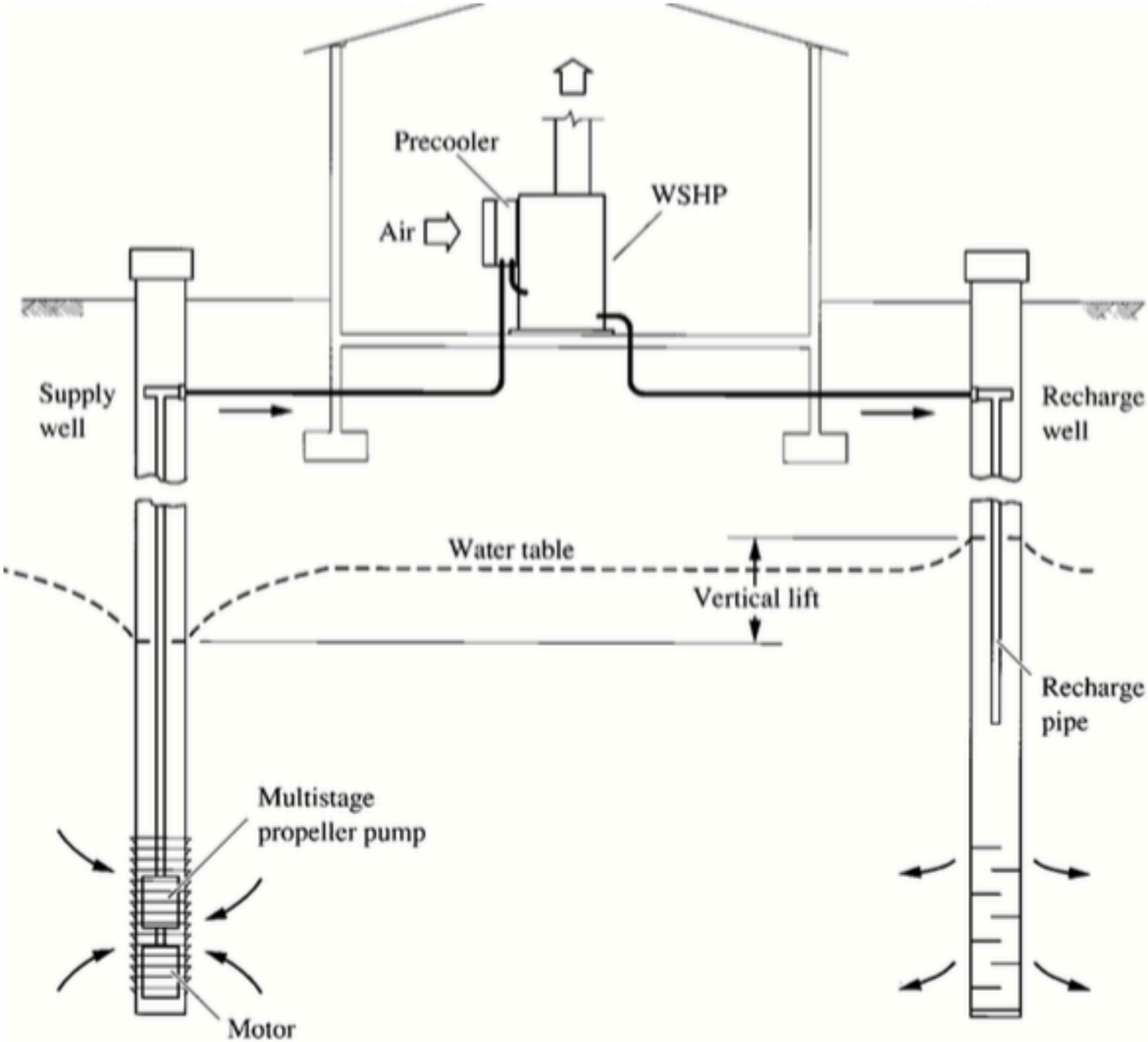


Heating mode
Cooling mode
400
300
200
100
Heating and cooling load and capacity, 1000 Btu/h
Q_{hp}
Q_{rc}
D
EER_{hp}
COP_{hp}
Supple-
mentary
heat
B
Q_{ch}
Q_{cc}
EER_{hp}
10
8
6
4
COP_{hp}
4
3
2
1
0
−10
0
20
40
60
80
100
Outdoor air temperature T_o, °F

Ground source heat pumps



Ground source heat pumps



Ground coupled heat pumps