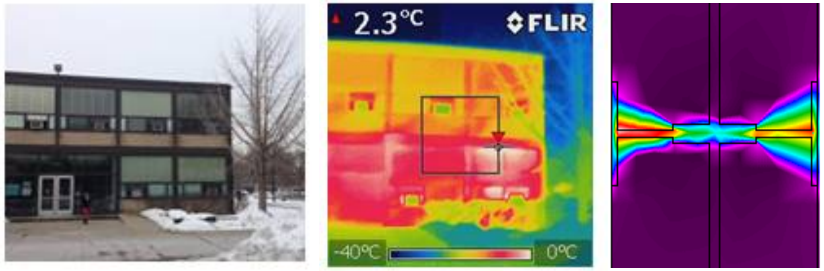
CAE 331/513
Building Science
Fall 2019



October 17, 2019
Introduction to HVAC systems: Part 2 (Systems)

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Last time

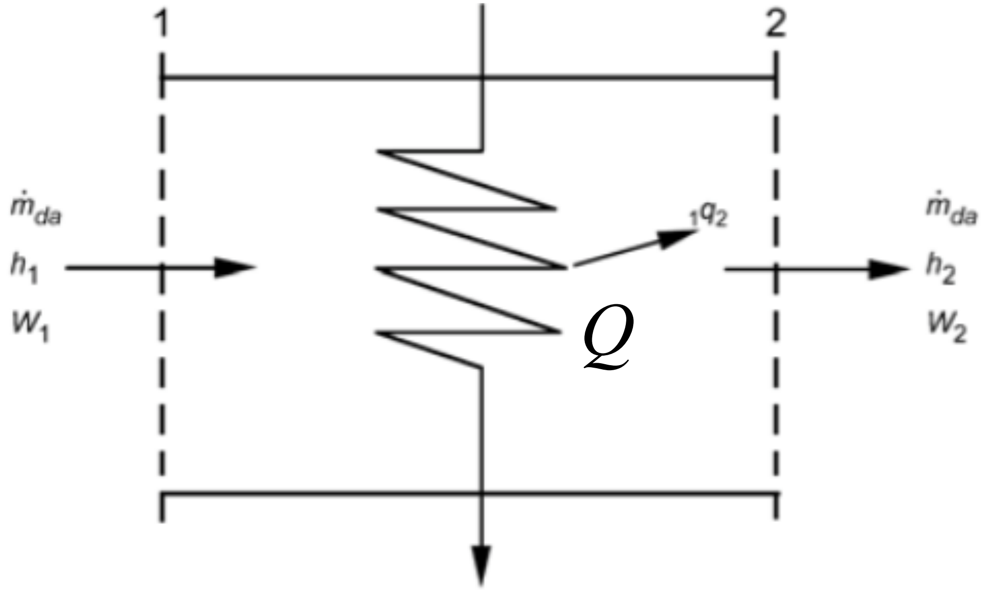
- Energy and mass balances on psychrometric processes
  - Heating
  - Cooling and dehumidification
  - Mixing
  - Humidifying
  - Heating and humidifying
  - Space heat and moisture gains

PSYCHROMETRIC PROCESSES

Using energy and mass balance equations

Energy/mass balances for psychrometric processes

Heating air



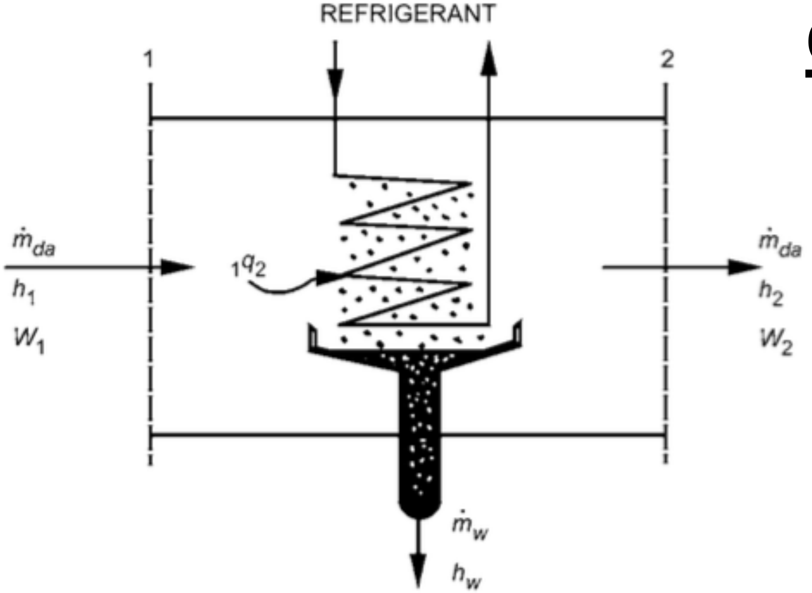
Energy balance: $\dot{m}_{da,1}h_1 + Q_{1\to 2} = \dot{m}_{da,2}h_2$

Mass balance on air: $\dot{m}_{da,1} = \dot{m}_{da,2} = \dot{m}_{da}$

Mass balance on water vapor: $\dot{m}_{da,1}W_1 = \dot{m}_{da,2}W_2$

Therefore: $Q_{1\to 2} = \dot{m}_{da}(h_2 - h_1)$

Energy/mass balances for psychrometric processes



Cooling and dehumidifying

*Note that h_w = h_g for steam/vapor and h_w = h_f for water

Energy balance: $\dot{m}_{da,1}h_1 + Q_{1\rightarrow 2} = \dot{m}_{da,2}h_2 + \dot{m}_w h_{w,2}$

Mass balance on air: $\dot{m}_{da,1} = \dot{m}_{da,2} = \dot{m}_{da}$

Mass balance on water vapor: $\dot{m}_{da,1}W_1 = \dot{m}_{da,2}W_2 + \dot{m}_w$

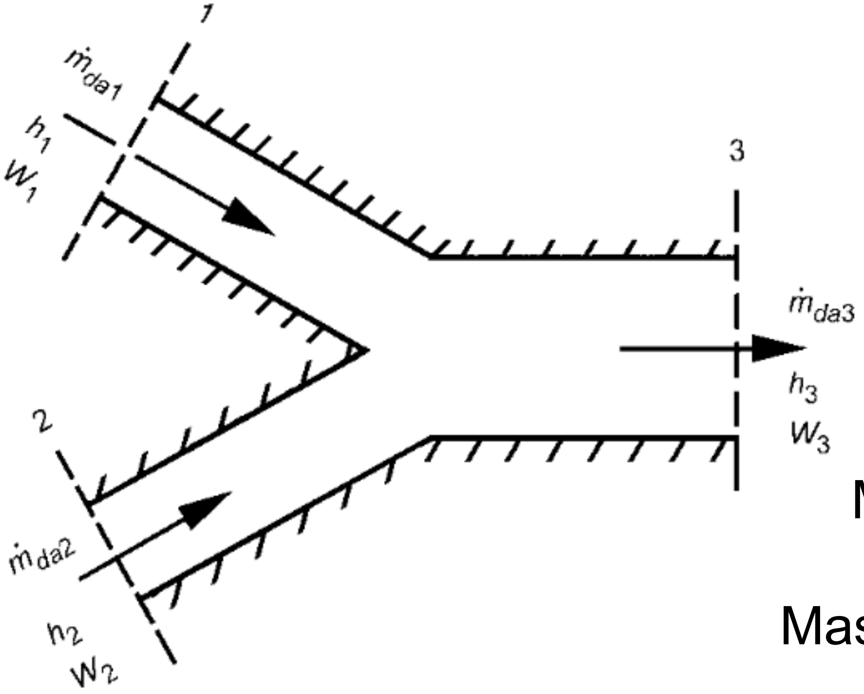
Therefore: $\dot{m}_w = \dot{m}_{da}(W_1 - W_2)$

And: $Q_{1\rightarrow 2} = \dot{m}_{da}[(h_2 - h_1) - (W_2 - W_1)h_{w,2}]$

(Q is negative for cooling)

Energy/mass balances for psychrometric processes

- **Mixing**: Often in HVAC systems we mix airstreams adiabatically
  - **Adiabatically** = Without the addition or extraction of heat
  - e.g. outdoor air mixed with a portion of return/recirculated air



Energy: $\dot{m}_{da,1}h_1 + \dot{m}_{da,2}h_2 = \dot{m}_{da,3}h_3$

Mass (air): $\dot{m}_{da,1} + \dot{m}_{da,2} = \dot{m}_{da,3}$

Mass (water): $\dot{m}_{da,1}W_1 + \dot{m}_{da,2}W_2 = \dot{m}_{da,3}W_3$

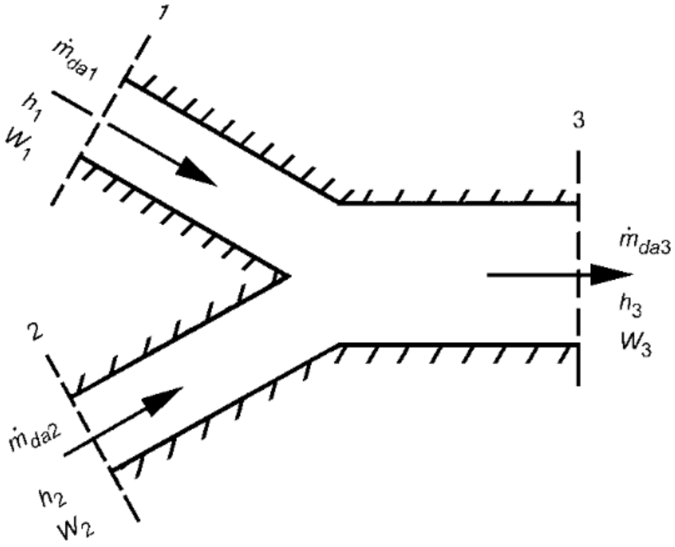
Energy/mass balances for psychrometric processes

- **Mixing**: For most parameters, the outlet conditions end up being the weighted averages of the input conditions based on their mass flow rates
  - Dry bulb temperature
  - Humidity ratio
  - Enthalpy
  - (not RH!)

$$T_3 = \frac{\dot{m}_{da1}T_1 + \dot{m}_{da2}T_2}{\dot{m}_{da1} + \dot{m}_{da2}}$$

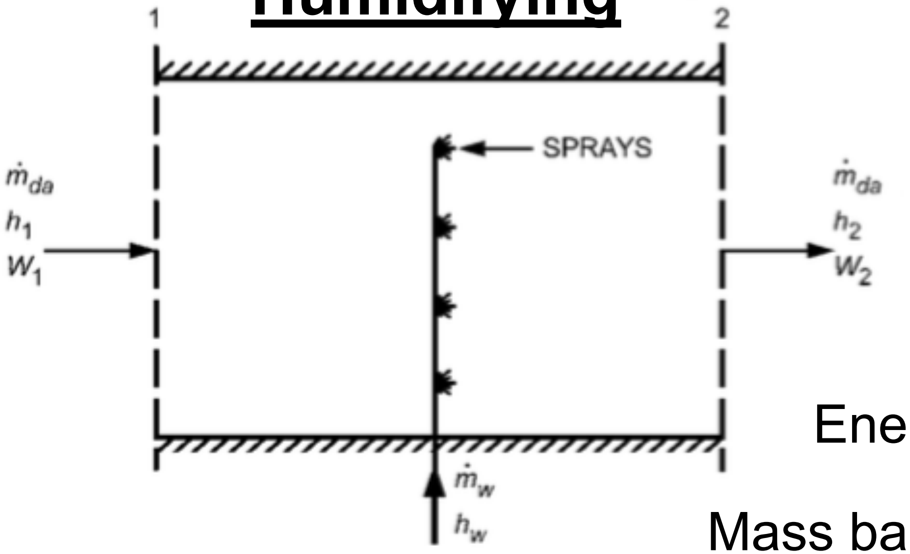
$$W_3 = \frac{\dot{m}_{da1}W_1 + \dot{m}_{da2}W_2}{\dot{m}_{da1} + \dot{m}_{da2}}$$

$$h_3 = \frac{\dot{m}_{da1}h_1 + \dot{m}_{da2}h_2}{\dot{m}_{da1} + \dot{m}_{da2}}$$



Energy/mass balances for psychrometric processes

Humidifying



Energy balance: $\dot{m}_{da,1}h_1 + \dot{m}_w h_w = \dot{m}_{da,2}h_2$

Mass balance on air: $\dot{m}_{da,1} = \dot{m}_{da,2} = \dot{m}_{da}$

Mass balance on water vapor: $\dot{m}_{da,1}W_1 + \dot{m}_w = \dot{m}_{da,2}W_2$

Therefore: $\dot{m}_w = \dot{m}_{da}(W_2 - W_1)$

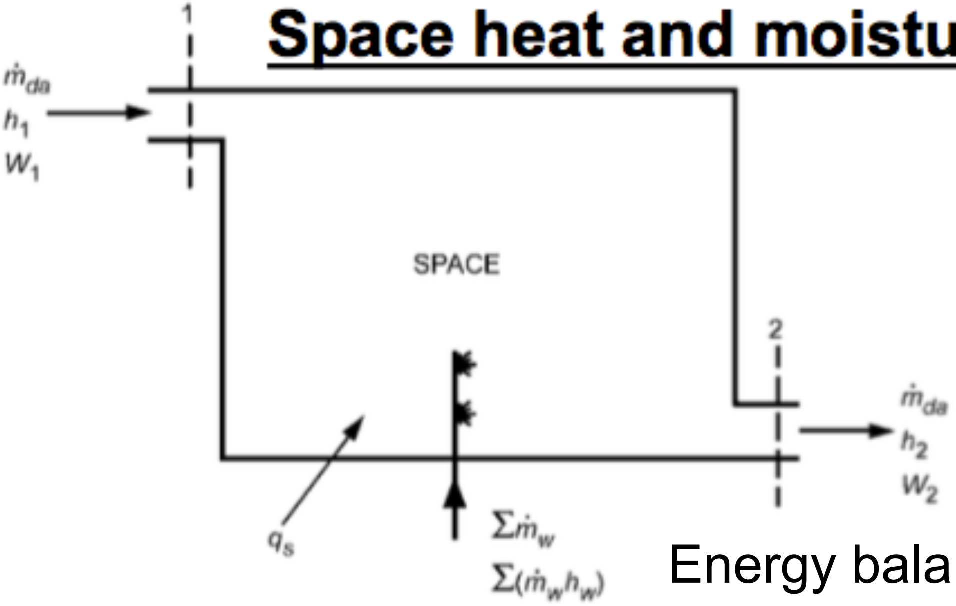
And: $\dot{m}_w h_w = \dot{m}_{da}(h_2 - h_1)$

And: $\dfrac{h_2 - h_1}{W_2 - W_1} = \dfrac{\Delta h}{\Delta W} = h_w$

*Note that h_w = h_g for steam/vapor and h_w = h_f for water

Energy/mass balances for psychrometric processes

Space heat and moisture gains



Energy balance: $\dot{m}_{da}h_1 + Q_{gains} + \sum \dot{m}_w h_w = \dot{m}_{da}h_2$

Mass balance on water vapor: $\dot{m}_{da}W_1 + \sum \dot{m}_w = \dot{m}_{da}W_2$

Therefore: $\sum \dot{m}_w = \dot{m}_{da}(W_2 - W_1)$

Therefore: $\sum \dot{m}_w h_w + Q_{gains} = \dot{m}_{da}(h_2 - h_1)$

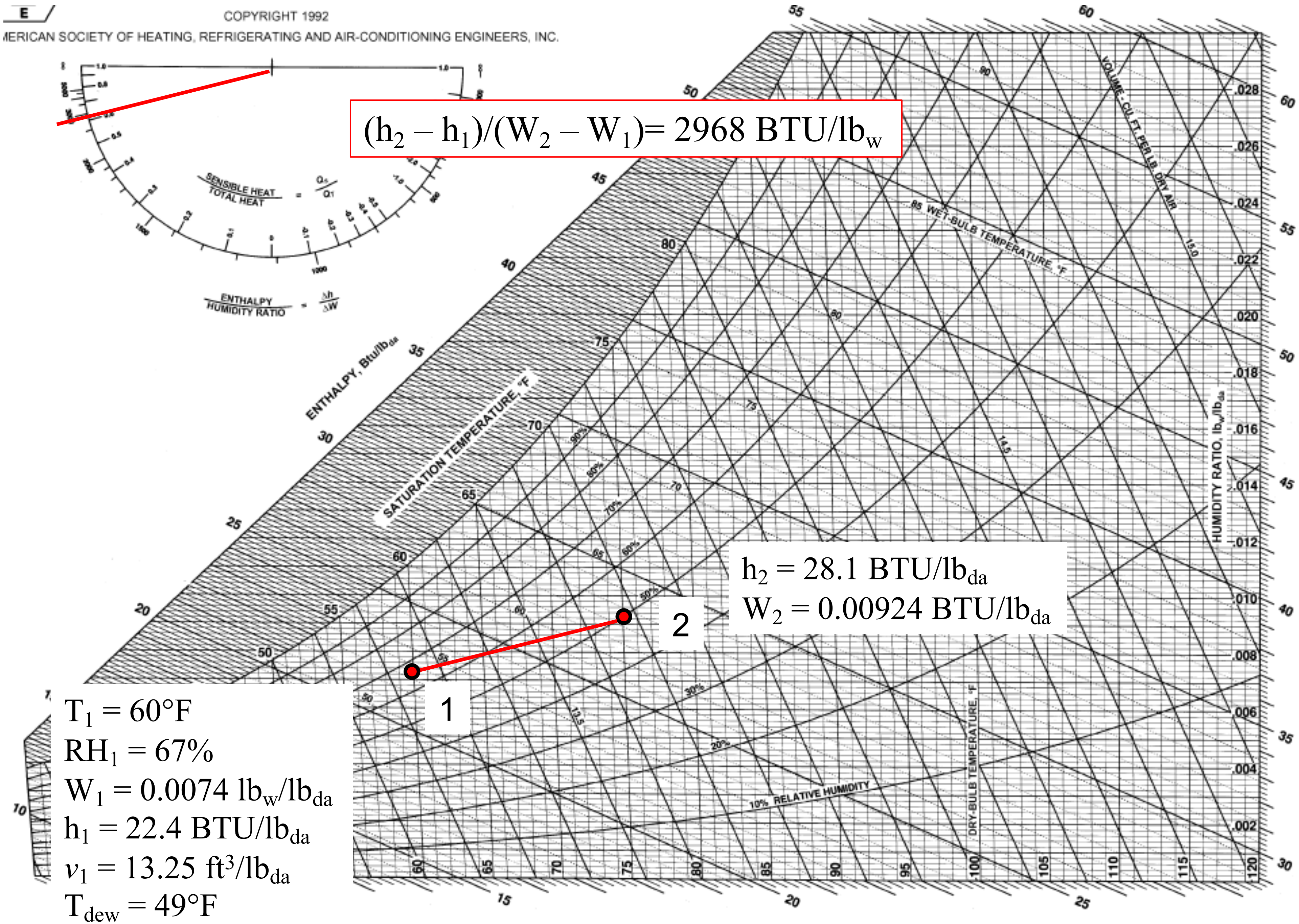
And: $$\frac{\Delta h}{\Delta W} = \frac{\sum \dot{m}_w h_w + Q_{gains}}{\sum \dot{m}_w}$$

*Note that h_w = h_g for steam/vapor and h_w = h_f for water

Example 7: Space conditioning – cooling (IP)

- The air in a restaurant is to be maintained at 75°F dry-bulb temperature and 50% RH. The load calculations for the restaurant estimate the rate of sensible heat gain to be 178,000 BTU/h. The rate of moisture gain is estimated to be 95 lb_w/h with an average enthalpy of moisture (h_w) of 1095 BTU/lb_w. The supply air temperature is to be 60°F. Assume standard atmospheric pressure.

- Determine the following:
  a) The required dew-point temperature of the supply air
  b) The required volumetric flow rate of supply air (in CFM)



$(h_2 - h_1)/(W_2 - W_1) = 2968$ BTU/lb_w

$h_2 = 28.1$ BTU/lb_{da}

$W_2 = 0.00924$ BTU/lb_{da}

$T_1 = 60°F$

$RH_1 = 67\%$

$W_1 = 0.0074\ lb_w/lb_{da}$

$h_1 = 22.4$ BTU/lb_{da}

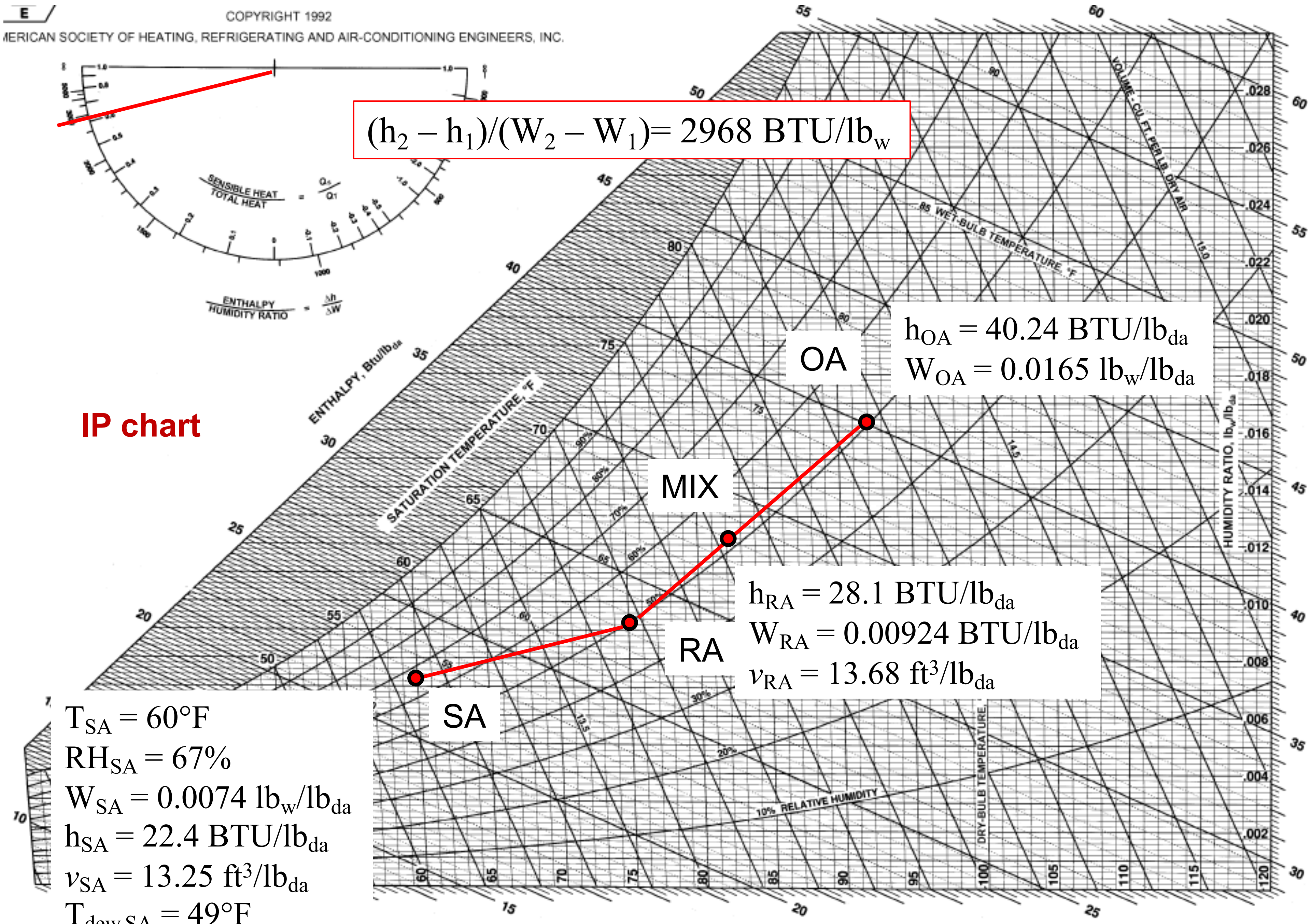
$v_1 = 13.25\ ft^3/lb_{da}$

$T_{dew} = 49°F$

Example 8: Single-zone space conditioning (IP)

- Assume the restaurant from the previous example is to be served by an air handling unit that mixes outdoor air with recirculated air, then passes the air over a cooling coil to the space. Outside air conditions are 92°F dry bulb and 77°F wet bulb temperatures. The rate of exhaust from the restaurant is 4500 CFM.

- Determine the following:
  a) The mass flow rate of recirculated air
  b) The thermodynamic state of the moist air entering the cooling coil
  c) The refrigeration capacity required



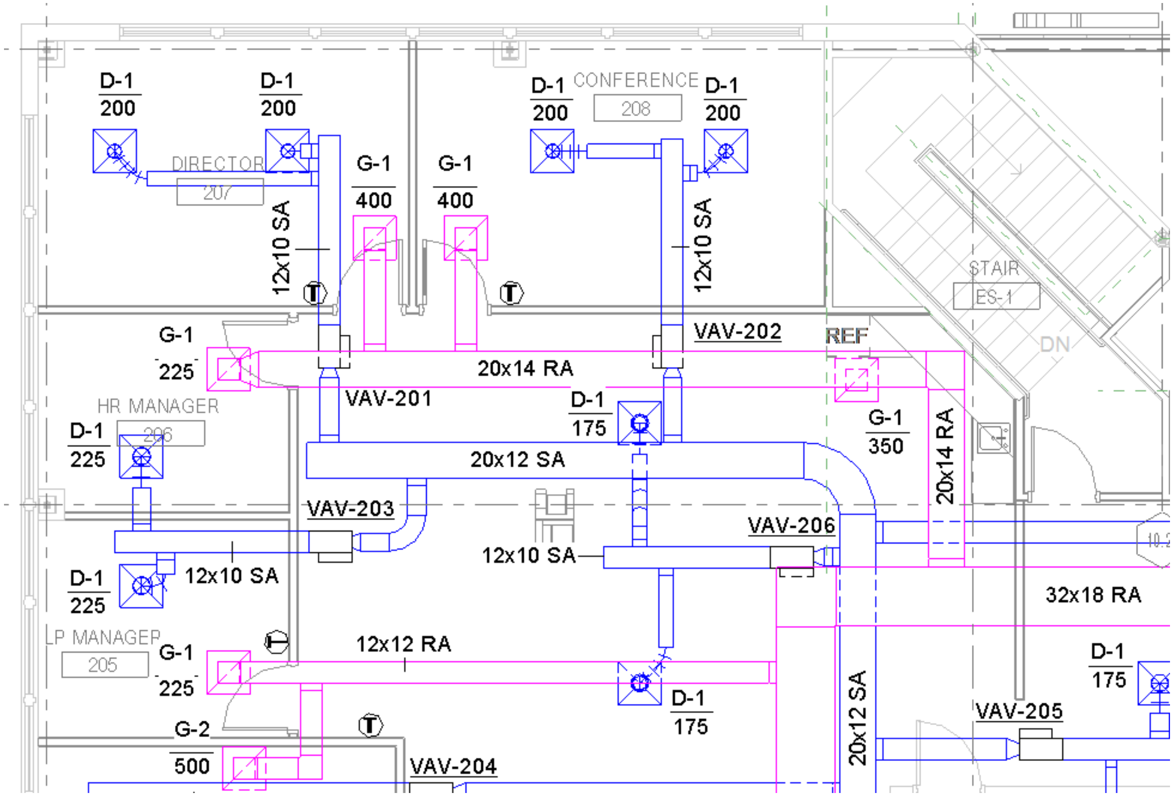
$(h_2 - h_1)/(W_2 - W_1) = 2968\ \text{BTU/lb}_w$

$h_{OA} = 40.24\ \text{BTU/lb}_{da}$
$W_{OA} = 0.0165\ \text{lb}_w/\text{lb}_{da}$

IP chart

$h_{RA} = 28.1\ \text{BTU/lb}_{da}$
$W_{RA} = 0.00924\ \text{BTU/lb}_{da}$
$v_{RA} = 13.68\ \text{ft}^3/\text{lb}_{da}$

$T_{SA} = 60°\text{F}$
$RH_{SA} = 67\%$
$W_{SA} = 0.0074\ \text{lb}_w/\text{lb}_{da}$
$h_{SA} = 22.4\ \text{BTU/lb}_{da}$
$v_{SA} = 13.25\ \text{ft}^3/\text{lb}_{da}$
$T_{dew,SA} = 49°\text{F}$



OVERVIEW OF HVAC SYSTEMS

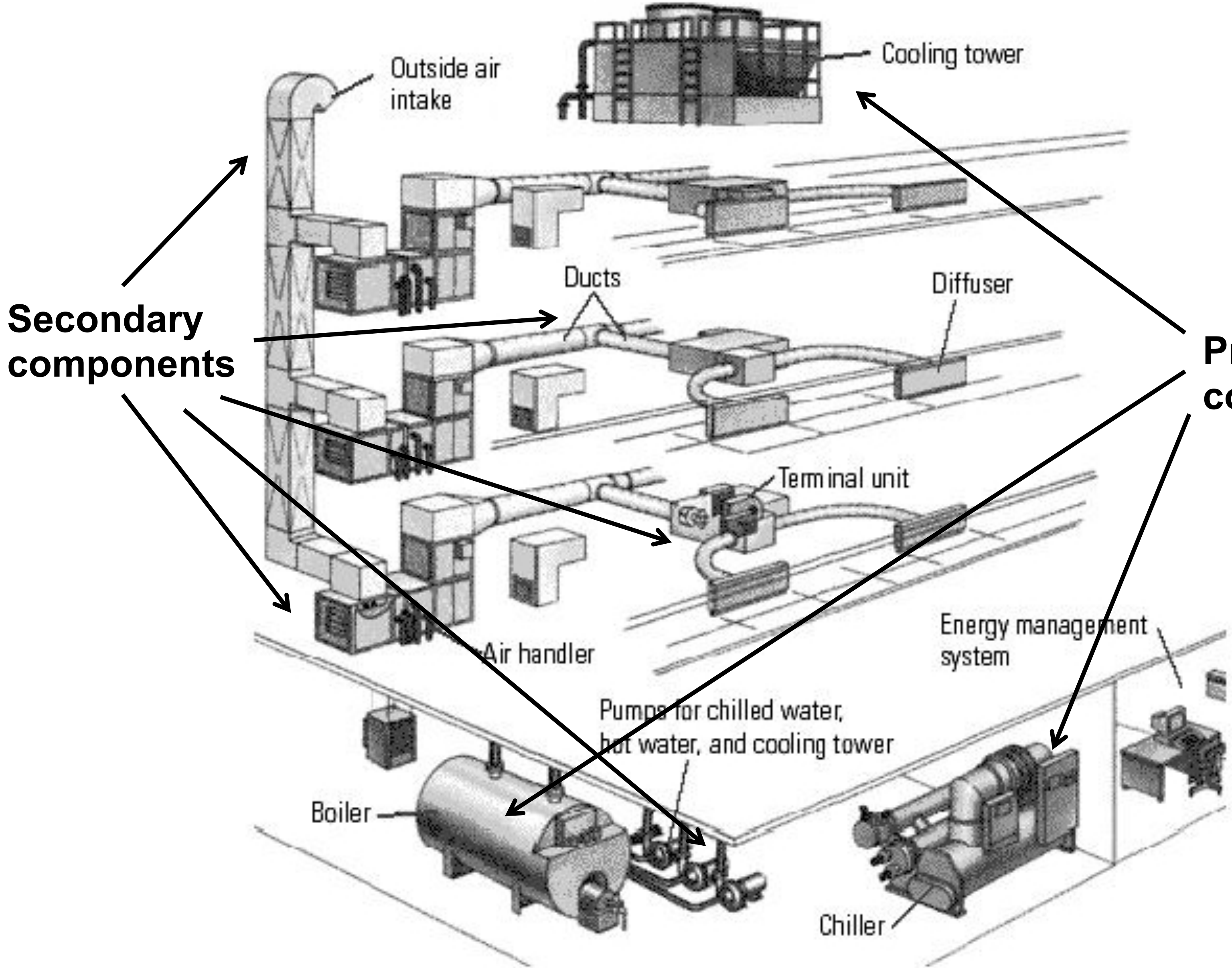
What do they look like and what are common processes?

HVAC systems overview: Recap

- Primary mechanical systems
  - Vapor compression systems (i.e., chillers and condenser units)
    - Electrically driven
    - Thermally driven
  - Cooling towers
  - Evaporative coolers

- Secondary mechanical systems
  - Distribution systems (both air and water)

Typical components of an HVAC system: Recap



Primary components

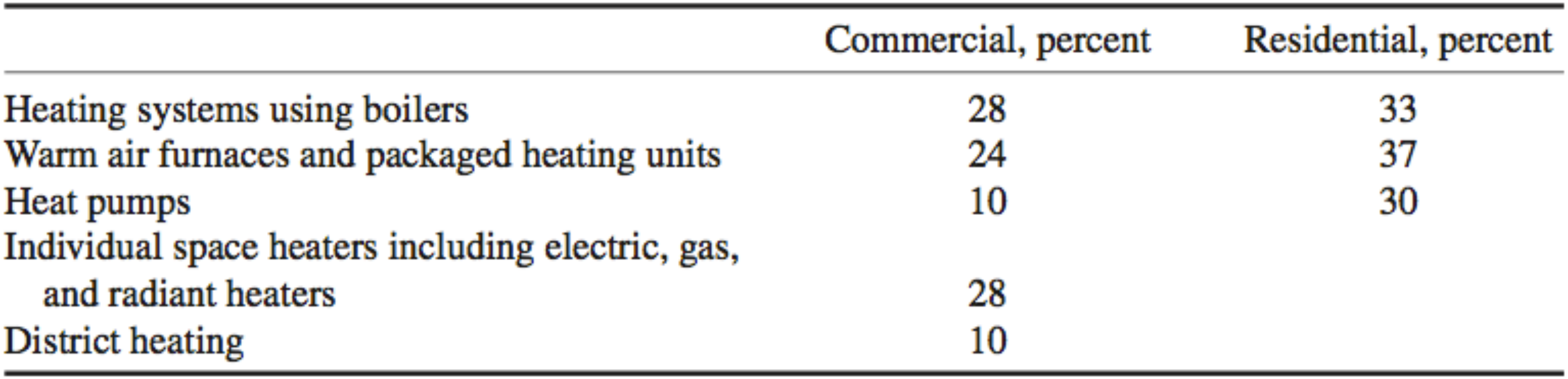
- How do they work?

HEATING SYSTEMS

Heating systems

- Heating systems are relatively straightforward
  - They add energy to heat a medium (e.g., air or water)

- Heating systems vary by building type:



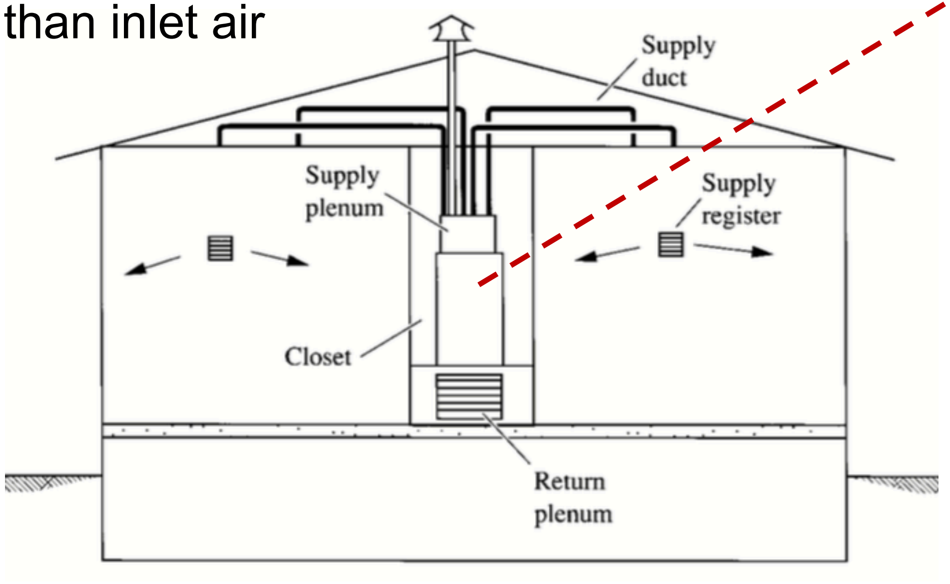
	Commercial, percent	Residential, percent
Heating systems using boilers	28	33
Warm air furnaces and packaged heating units	24	37
Heat pumps	10	30
Individual space heaters including electric, gas, and radiant heaters	28	
District heating	10	

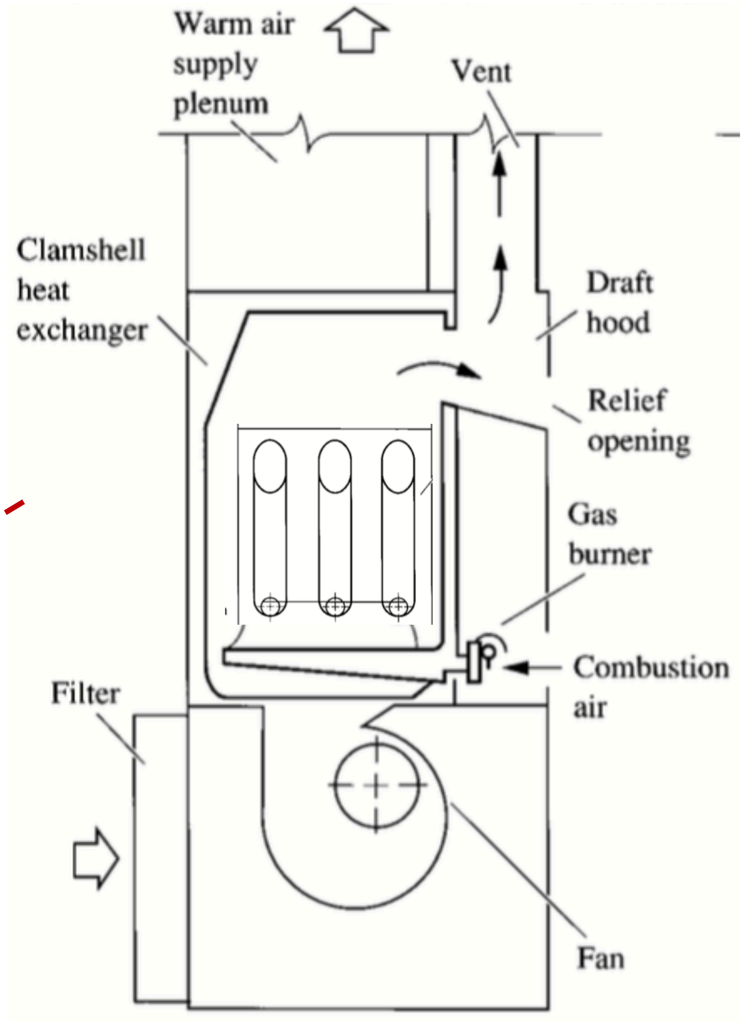
Wang Chapter 8

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





Wang Chapter 8

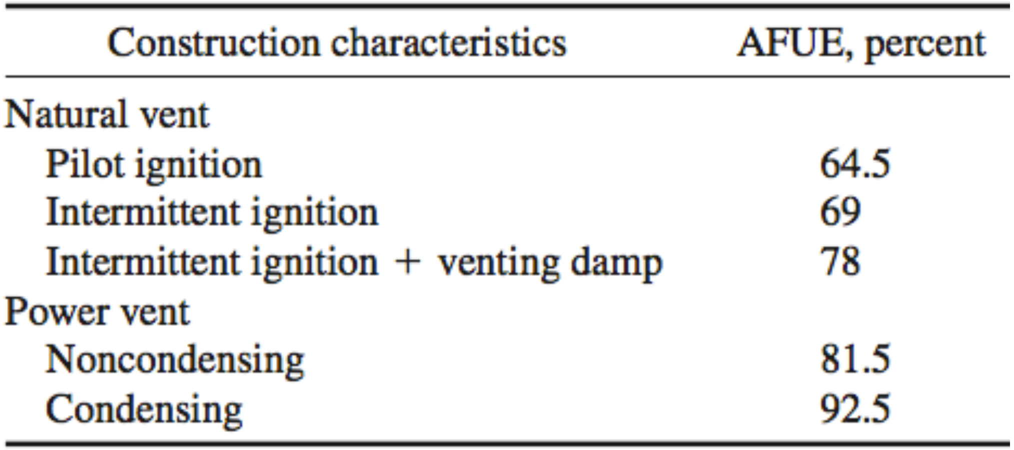
Heating systems: Warm air furnaces

- **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

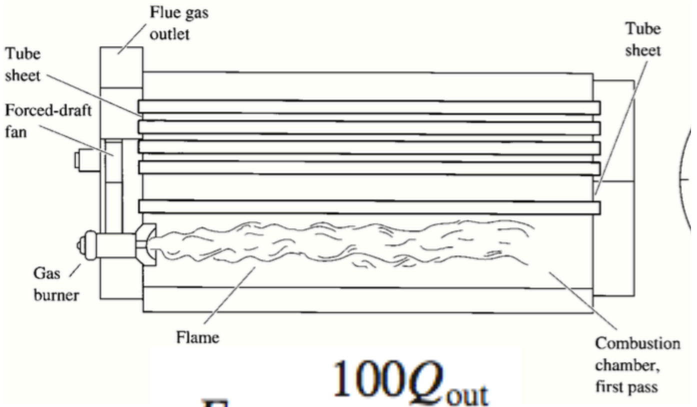
Hot water boiler

- 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 kBTU/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



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

COOLING SYSTEMS

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 or ground 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

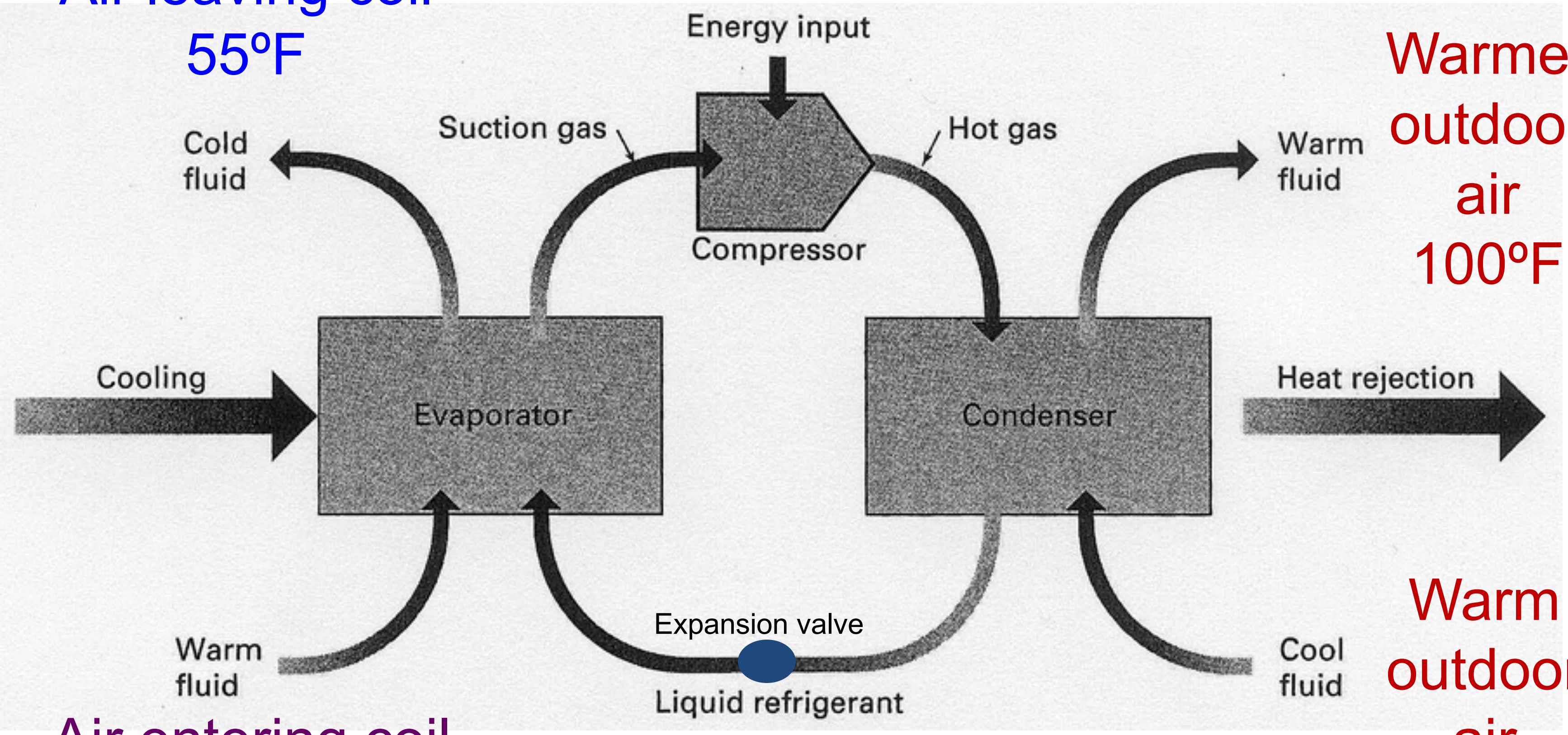
Fundamentals of vapor compression systems

Heat of Vaporization

by: Michael Ermann and Clark Coots

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

Typical vapor compression cycle: Air-conditioning unit



Air leaving coil
55ºF

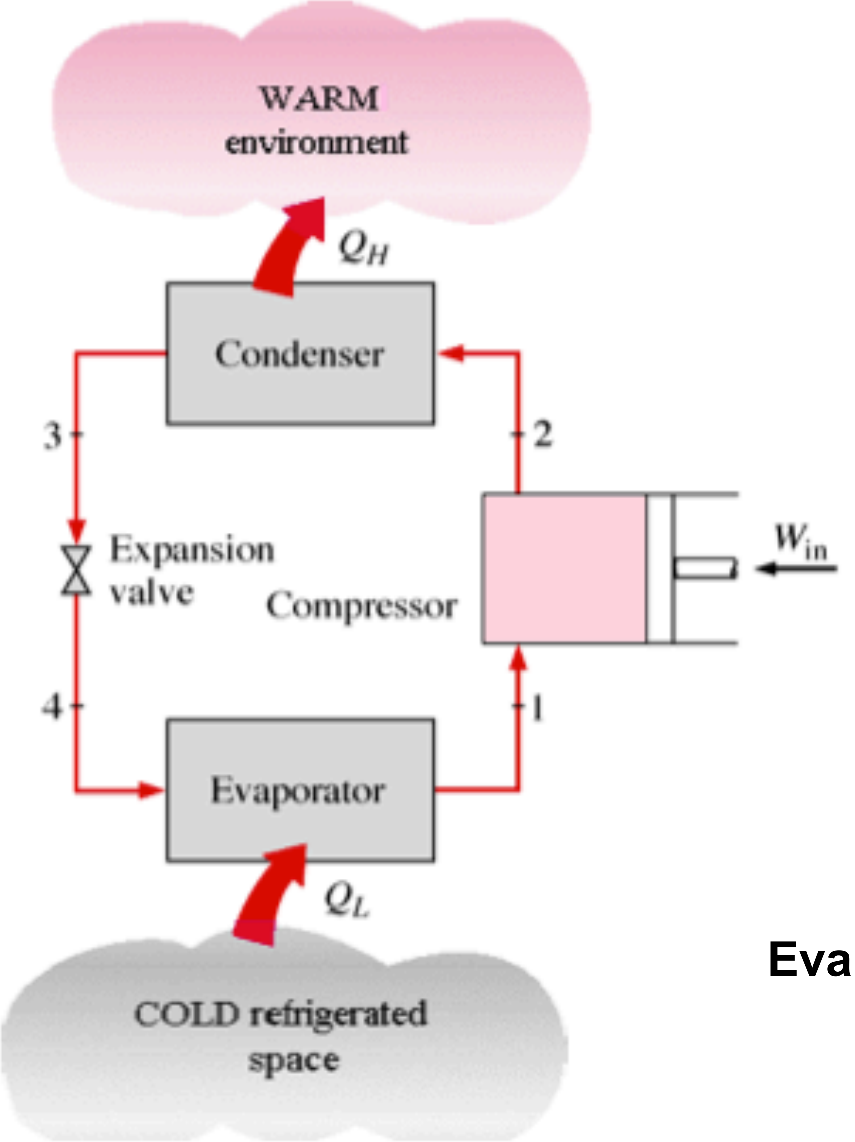
Warmer
outdoor
air
100ºF

Warm
outdoor
air
90ºF

Air entering coil
75ºF

Changing refrigerant
T and P

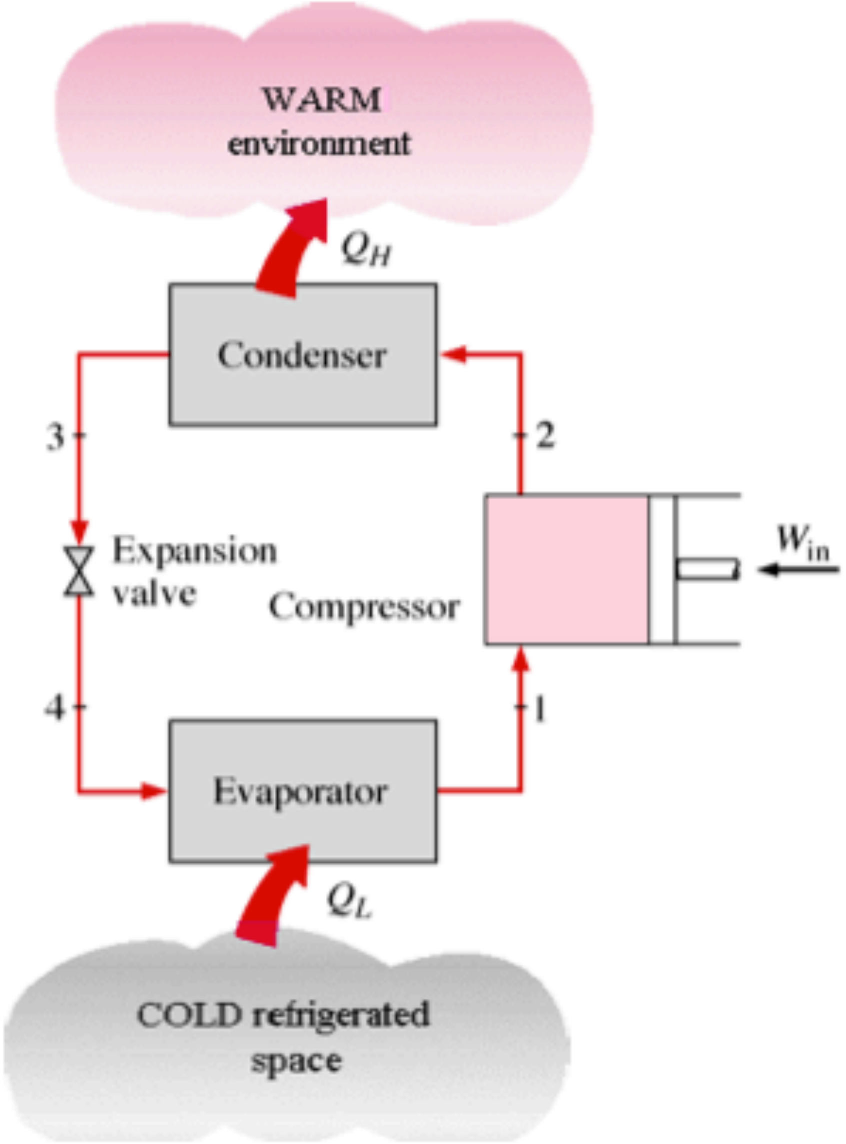
Ideal single-stage vapor compression cycle



Expansion valve
(creates the high P restriction)

Evaporator coil

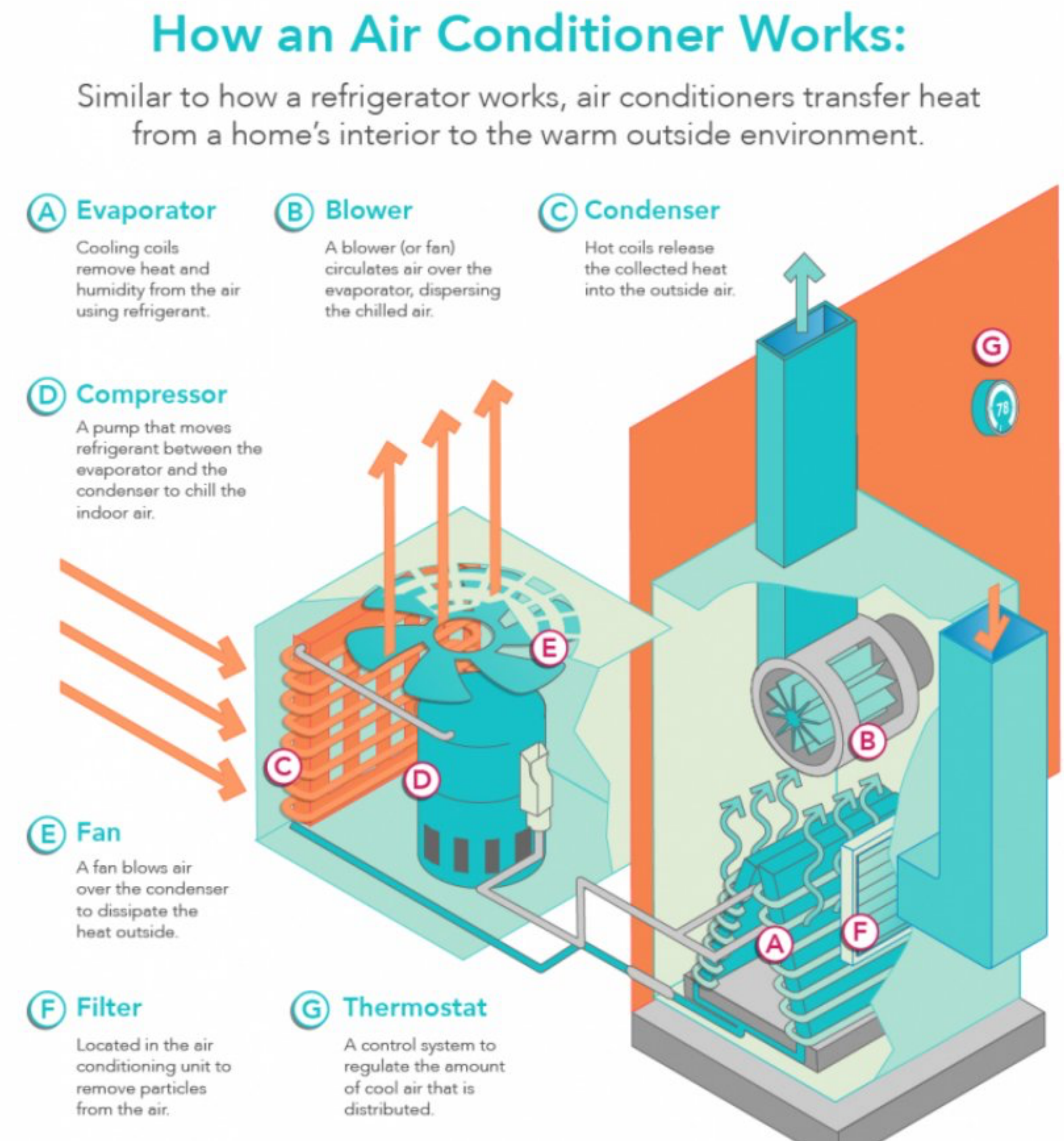
Ideal single-stage vapor compression cycle



Condenser coil

Compressor

Typical central residential system



How an Air Conditioner Works:

Similar to how a refrigerator works, air conditioners transfer heat from a home's interior to the warm outside environment.

Ⓐ Evaporator

Cooling coils remove heat and humidity from the air using refrigerant.

Ⓑ Blower

A blower (or fan) circulates air over the evaporator, dispersing the chilled air.

Ⓒ Condenser

Hot coils release the collected heat into the outside air.

Ⓓ Compressor

A pump that moves refrigerant between the evaporator and the condenser to chill the indoor air.

Ⓔ Fan

A fan blows air over the condenser to dissipate the heat outside.

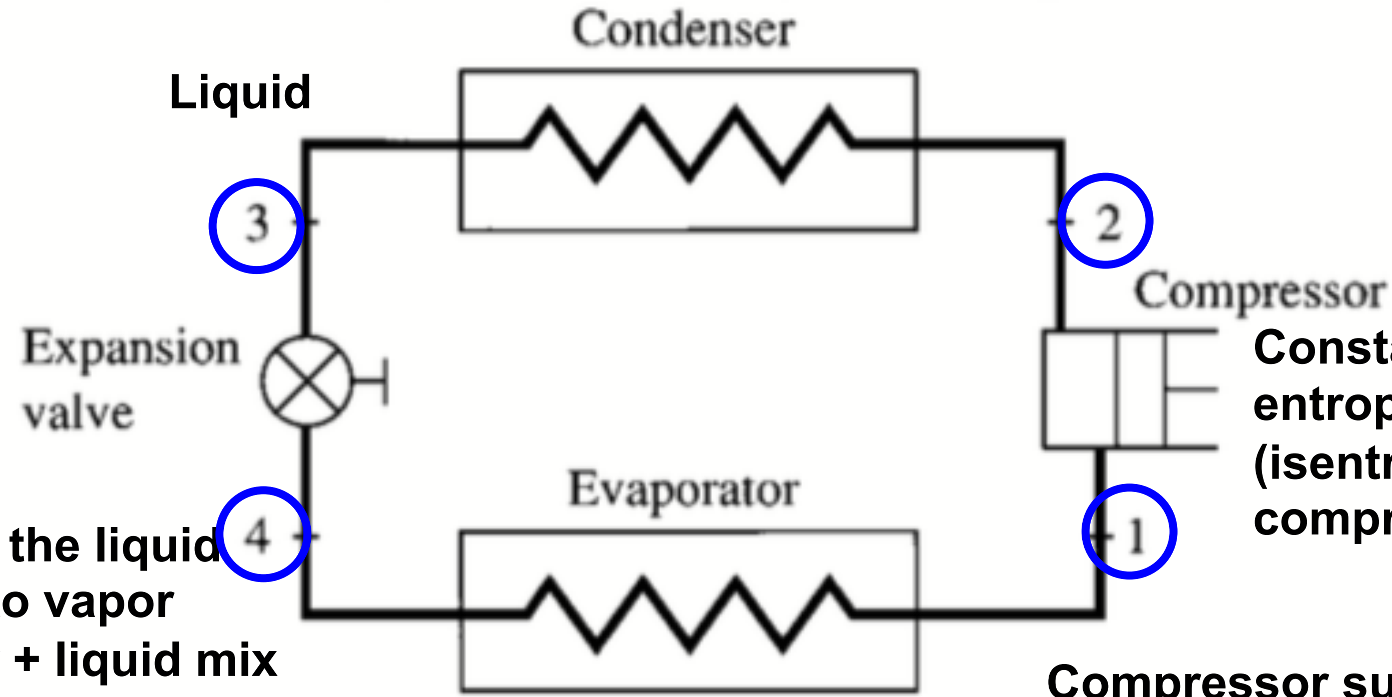
Ⓕ Filter

Located in the air conditioning unit to remove particles from the air.

Ⓖ Thermostat

A control system to regulate the amount of cool air that is distributed.

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”**

Question: What is the COP?

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

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

Equivalent to the efficiency of an air-conditioning unit

Joke courtesy of Jeff Siegel, University of Toronto

What is the efficiency of a typical residential AC unit?

A. 10%

B. 50%

C. 80%

D. 100%

E. 300% ←

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 changes with varying conditions

EER and SEER

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

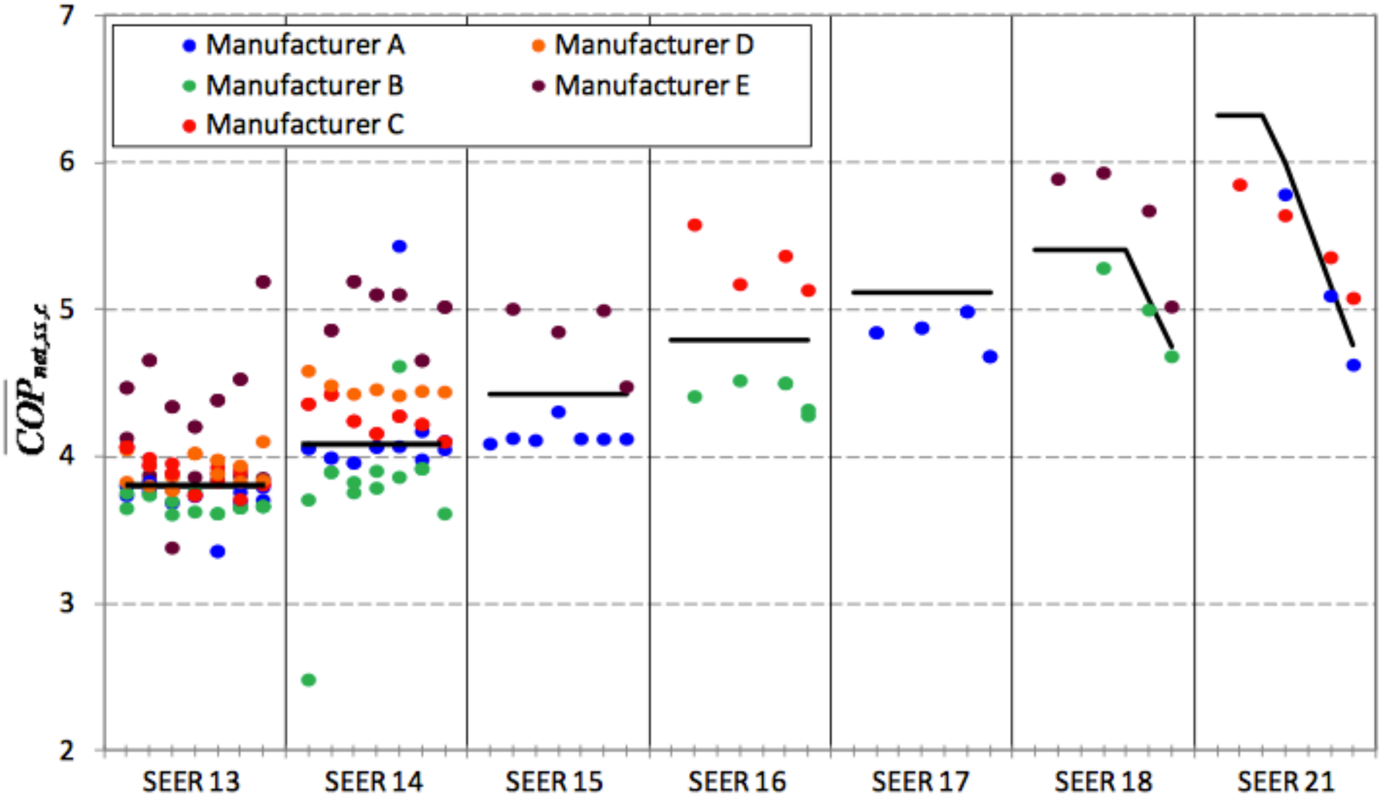
$$COP = \frac{8.5 \text{ [kW]}}{2.48 \text{ [kW]}} = 3.43 \qquad EER = \frac{29.0 \text{ [kBtu/hr]}}{2.48 \text{ [kW]}} = 11.7$$

$$EER = COP \times 3.41$$

- **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



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

What do we need to know about cooling systems?

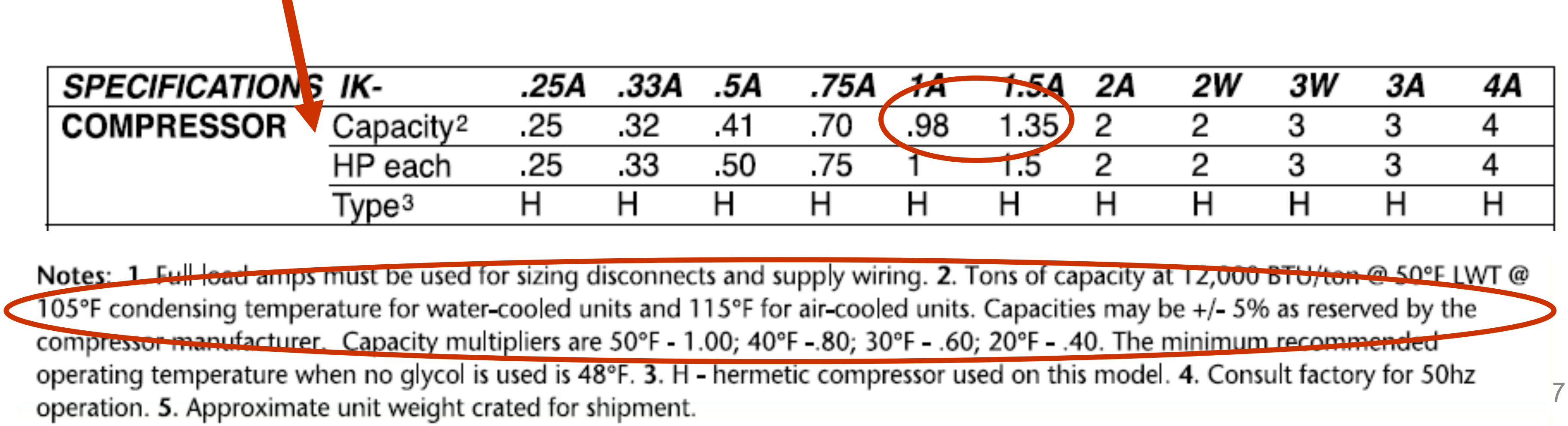
Equipment selection example:

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

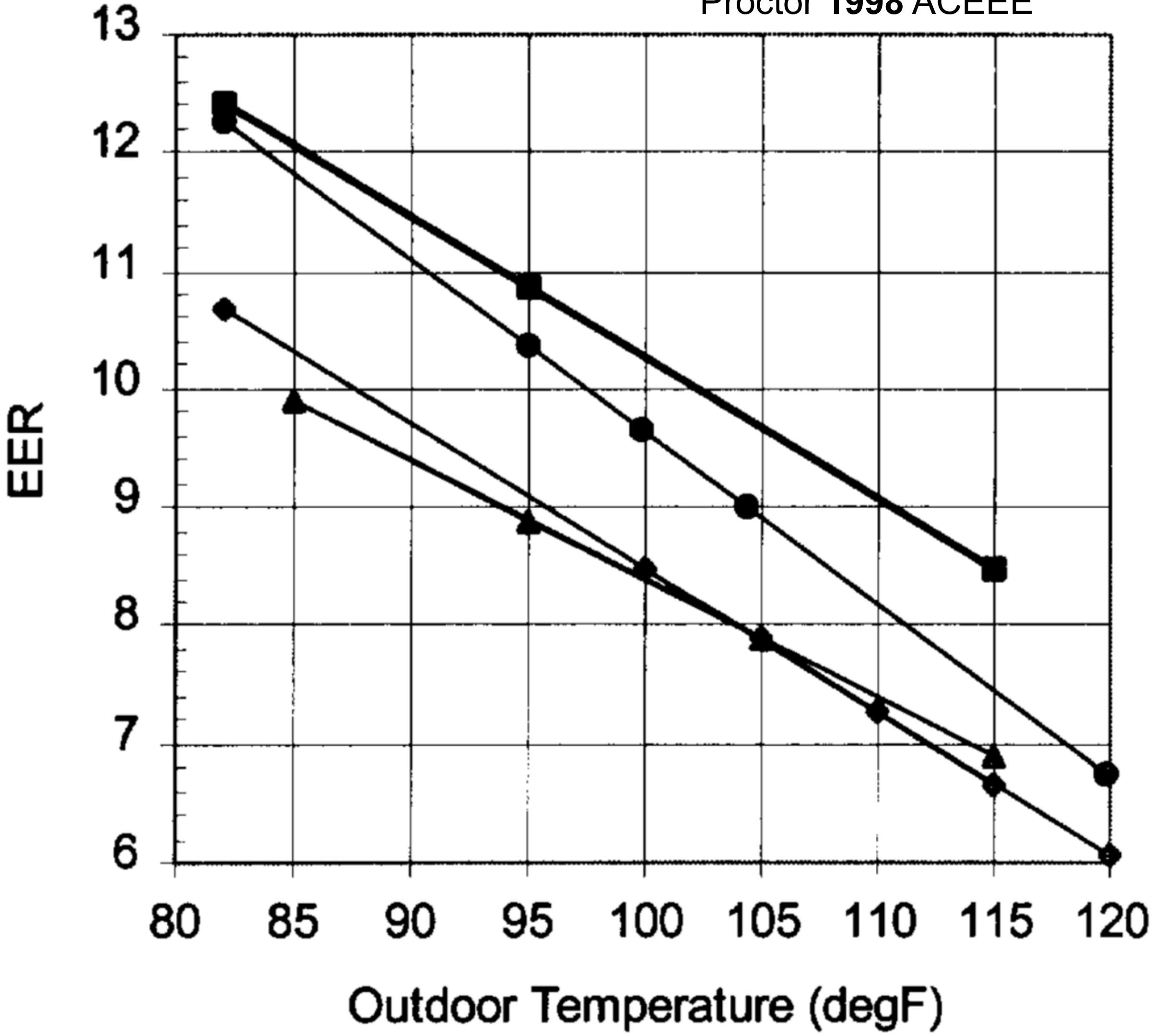


SPECIFICATIONS	IK-	.25A	.33A	.5A	.75A	1A	1.5A	2A	2W	3W	3A	4A
COMPRESSOR	Capacity[2]	.25	.32	.41	.70	.98	1.35	2	2	3	3	4
	HP each	.25	.33	.50	.75	1	1.5	2	2	3	3	4
	Type[3]	H	H	H	H	H	H	H	H	H	H	H

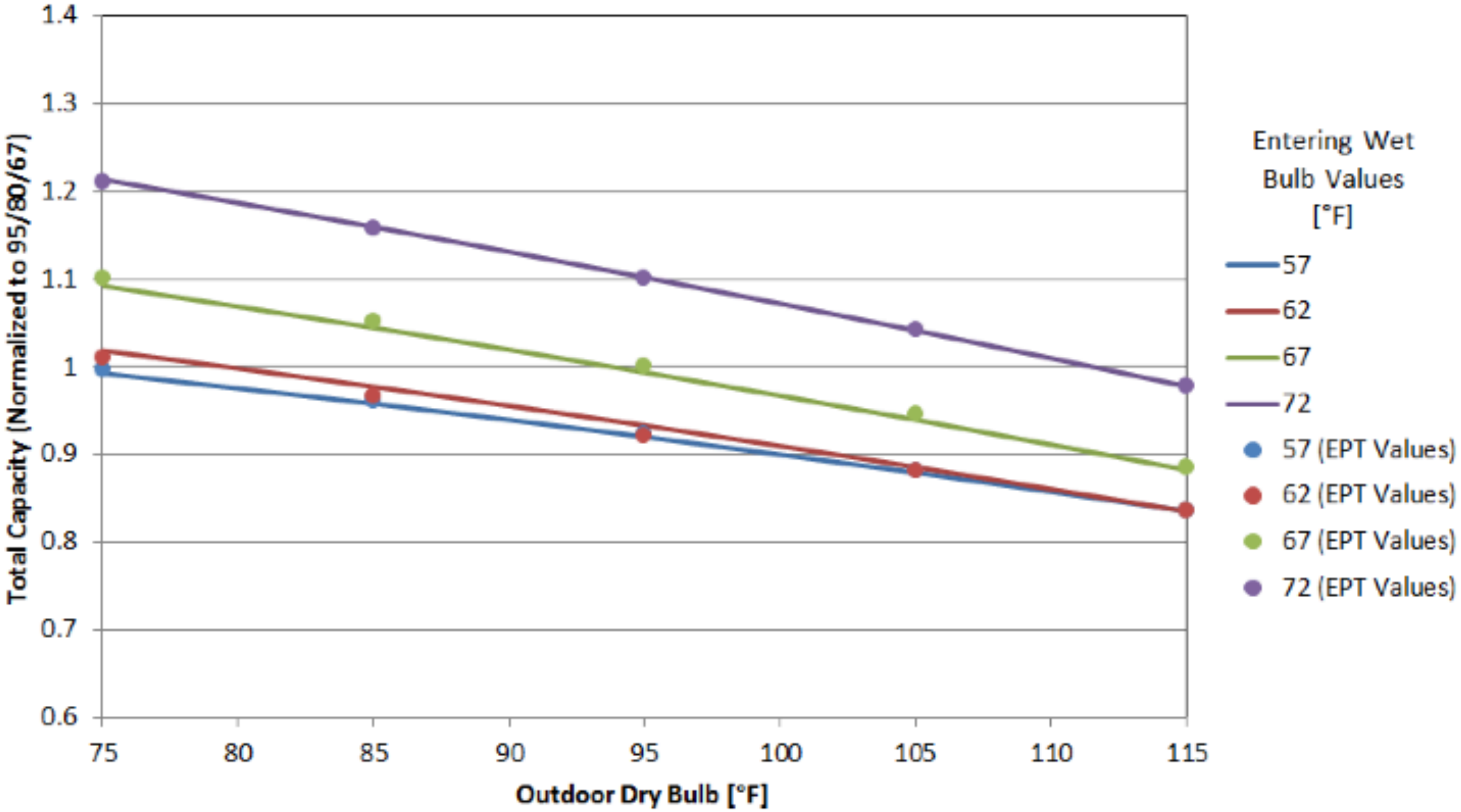
Notes: **1.** Full load amps must be used for sizing disconnects and supply wiring. **2.** Tons of capacity at 12,000 BTU/ton @ 50°F LWT @ 105°F condensing temperature for water-cooled units and 115°F for air-cooled units. Capacities may be +/- 5% as reserved by the compressor manufacturer. Capacity 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

Proctor **1998** ACEEE



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



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

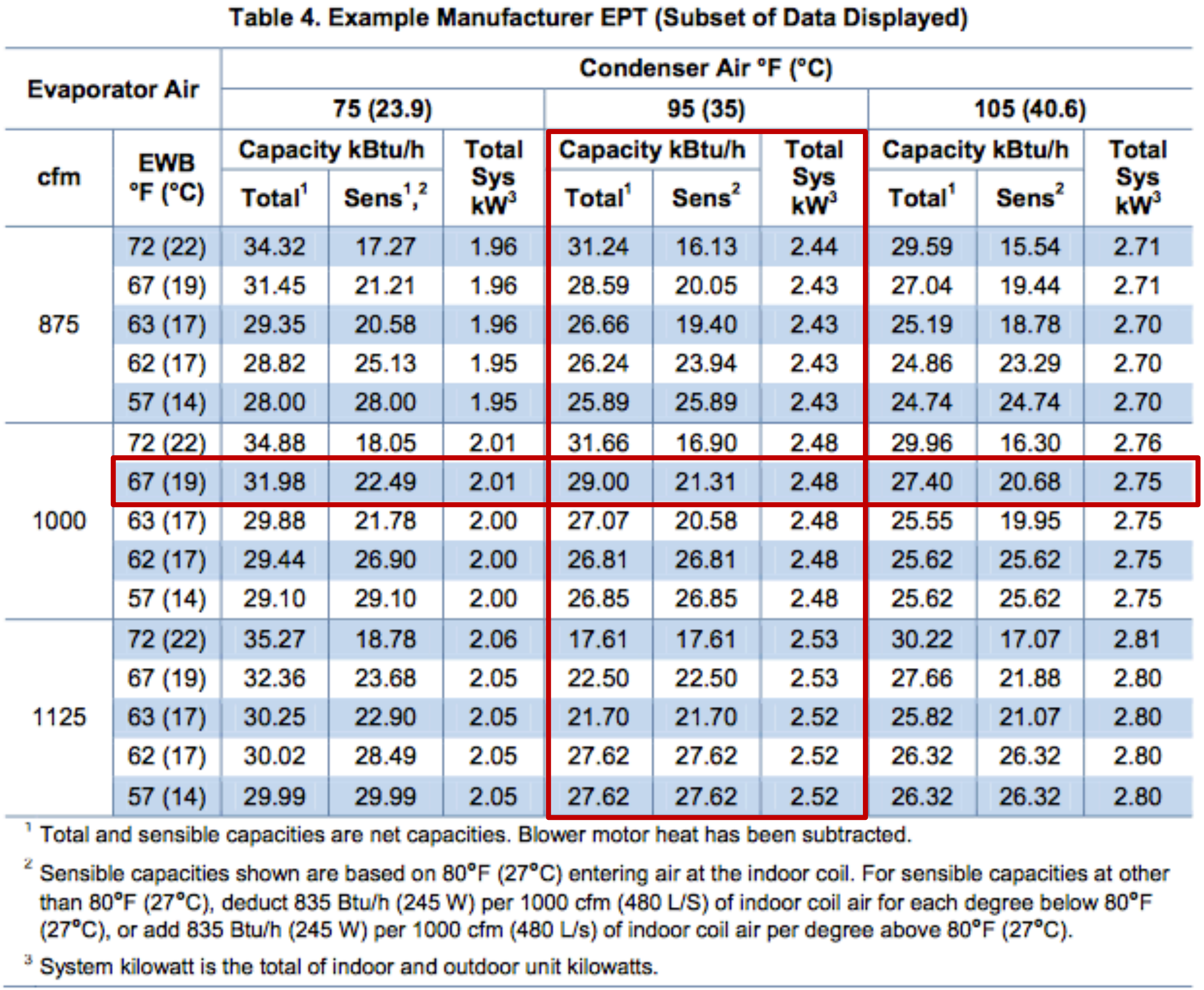


Table 4. Example Manufacturer EPT (Subset of Data Displayed)

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

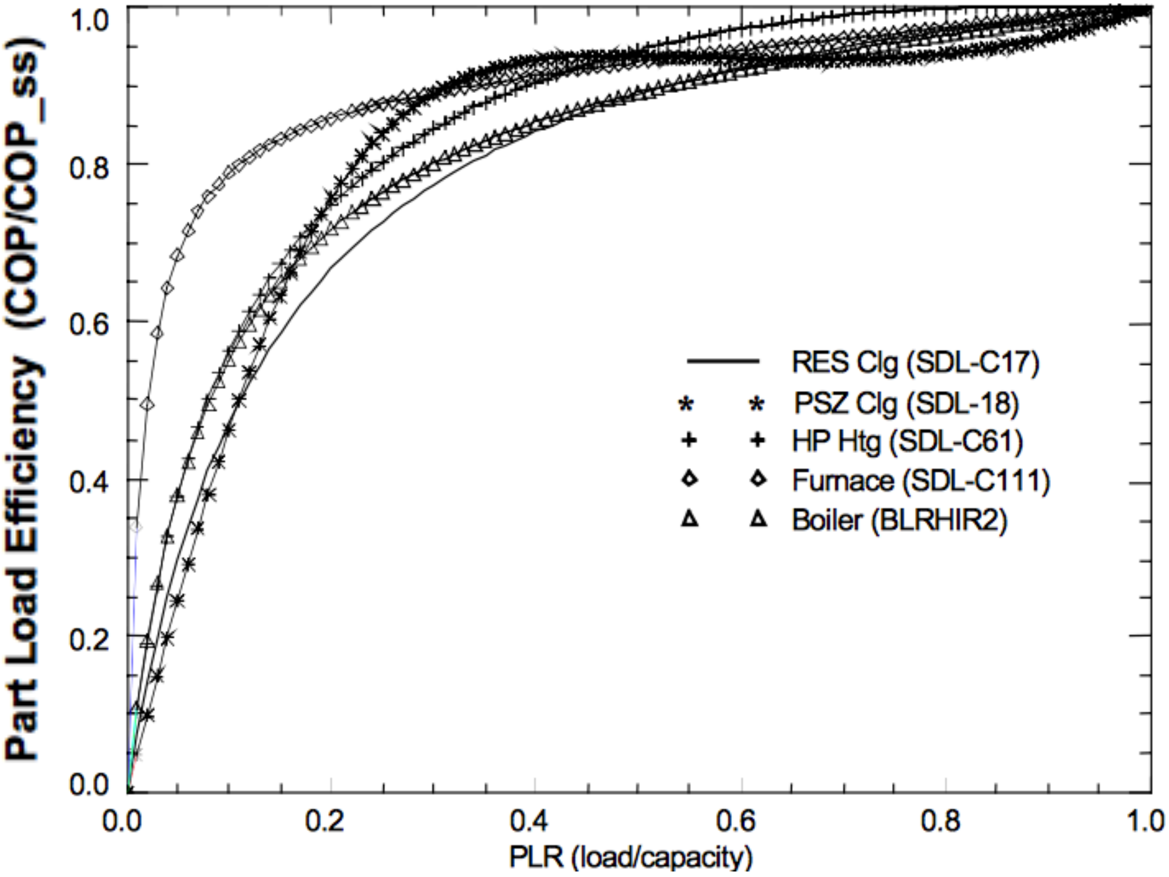
[1] Total and sensible capacities are net capacities. Blower motor heat has been subtracted.

[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.

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



Typical large central commercial system components

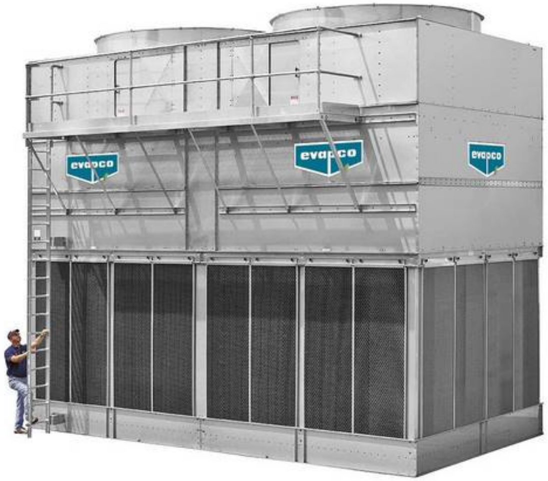
Air cooled chiller

Smaller capacity

Hot water or steam boiler

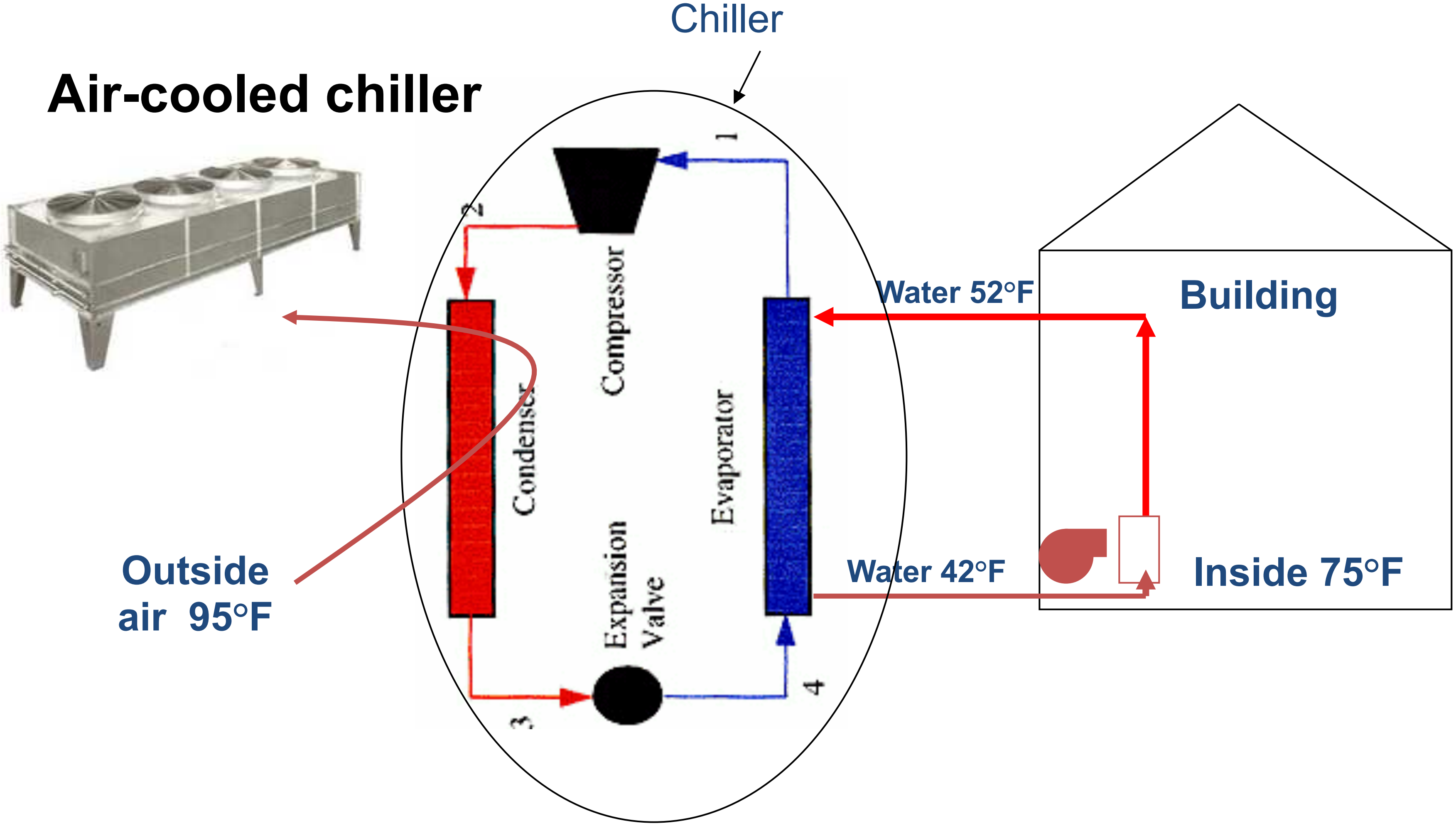
Water-cooled chiller

(w/ cooling tower – larger capacity & more efficient)



Air-cooled chillers

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



Chiller

Air-cooled chiller

Outside air 95°F

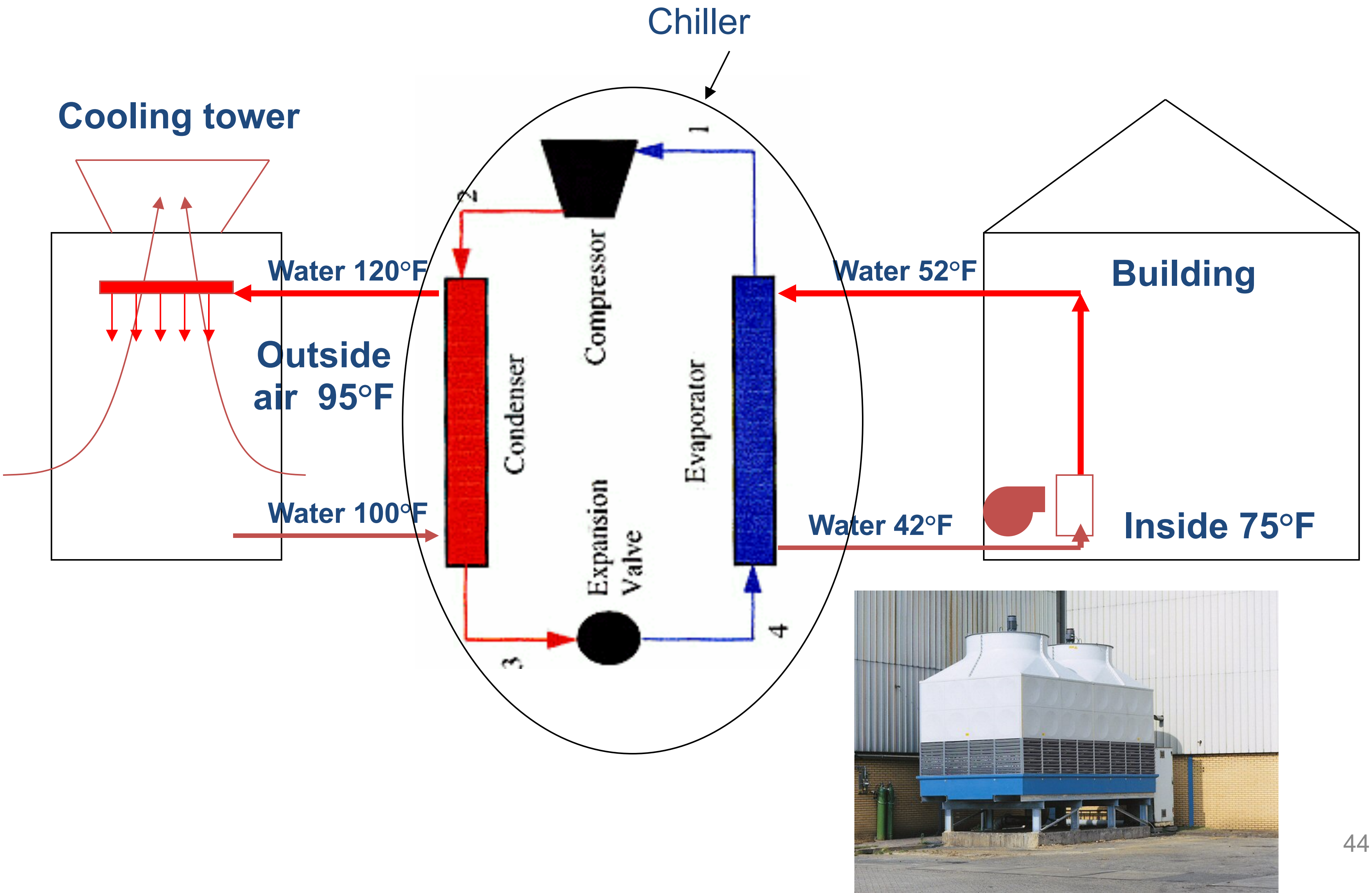
Water 52°F

Water 42°F

Building

Inside 75°F

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



Chiller

Cooling tower

Water 120°F

Outside air 95°F

Water 100°F

Water 52°F

Building

Water 42°F

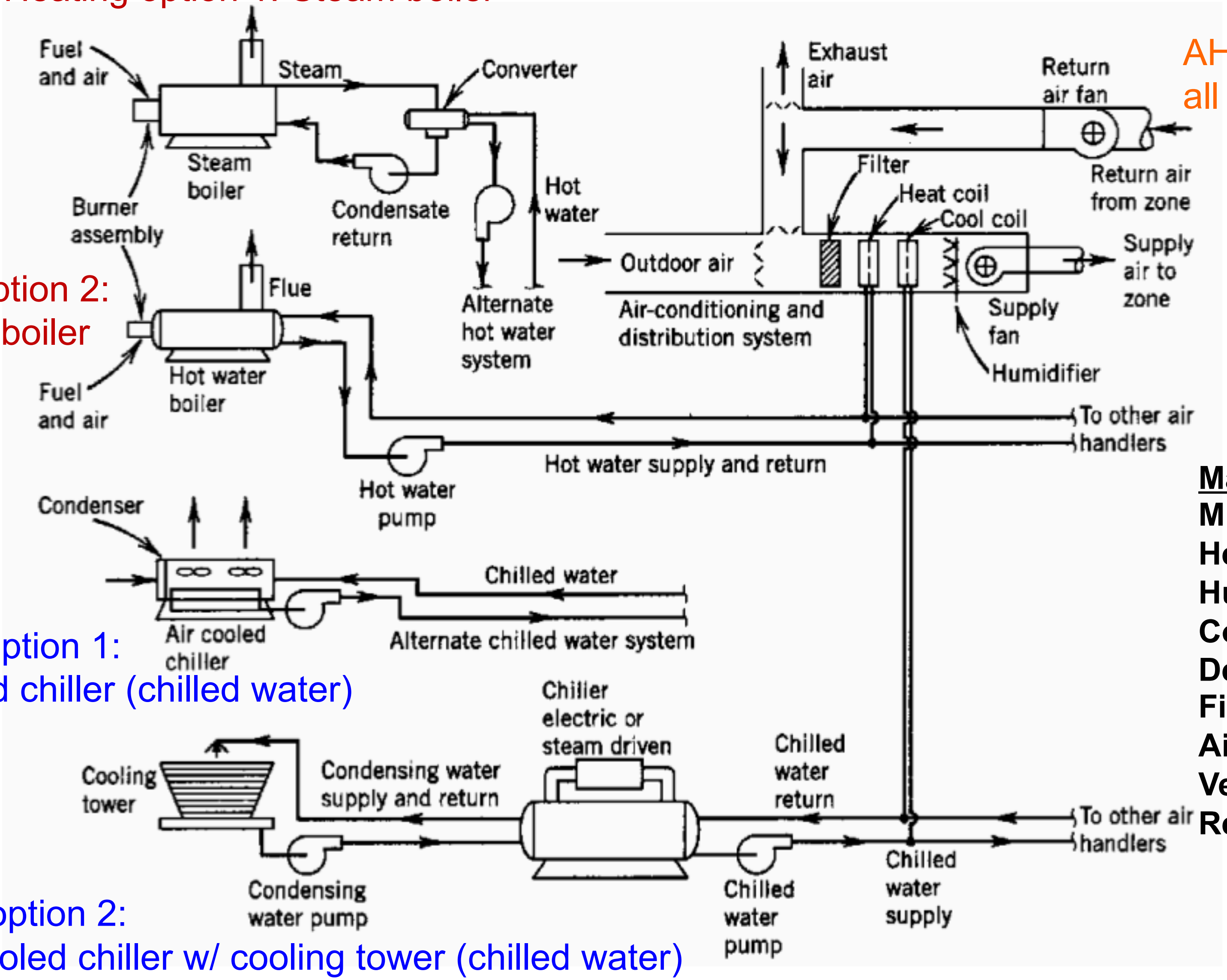
Inside 75°F

Typical large central commercial systems

Heating option 1: Steam boiler

AHU serves all rooms

Heating option 2: Hot water boiler

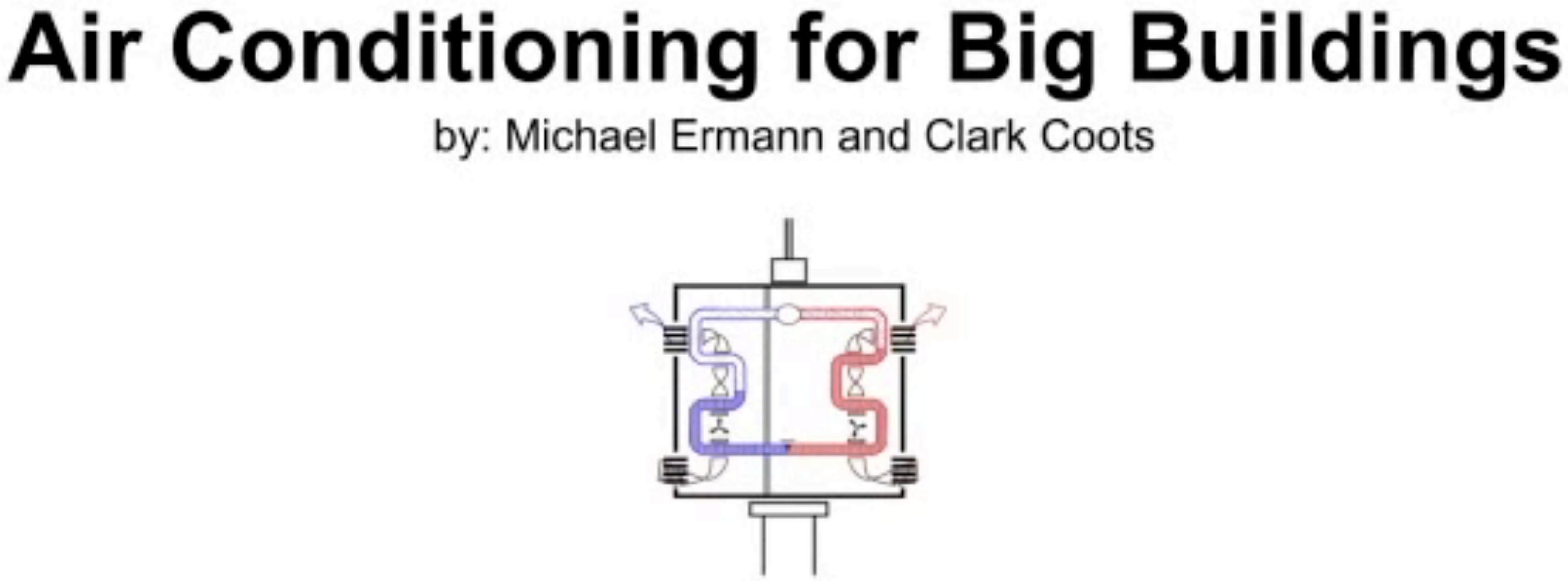


Cooling option 1:
Air cooled chiller (chilled water)

Cooling option 2:
Water cooled chiller w/ cooling tower (chilled water)

Main processes:
Mixing
Heating
Humidification
Cooling
Dehumidification
Filtration
Air distribution
Ventilation
Recirculation

Typical large central commercial systems



Air Conditioning for Big Buildings

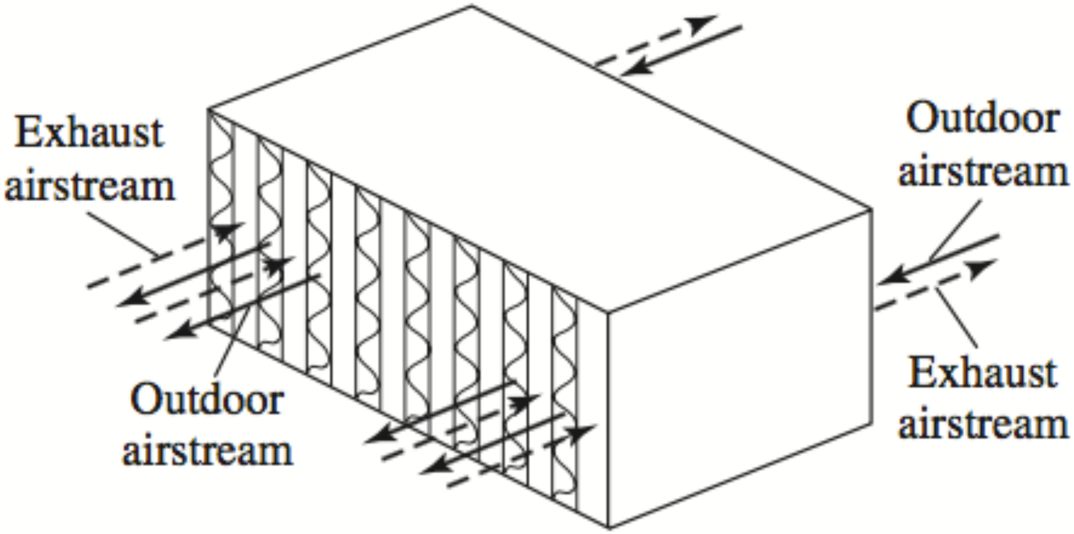
by: Michael Ermann and Clark Coots

https://www.youtube.com/watch?v=j1nYipLAv0U

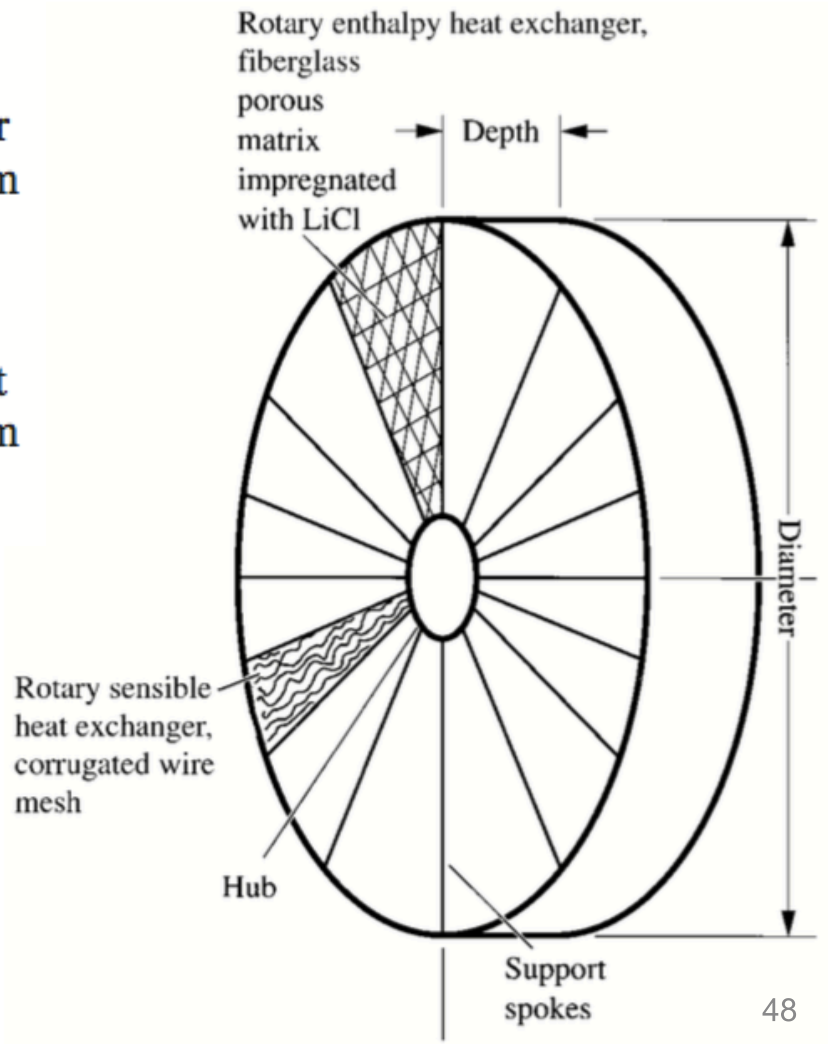
HEAT/ENERGY RECOVERY SYSTEMS

Heat/energy recovery systems

Air to air heat recovery



Rotary/enthalpy wheel



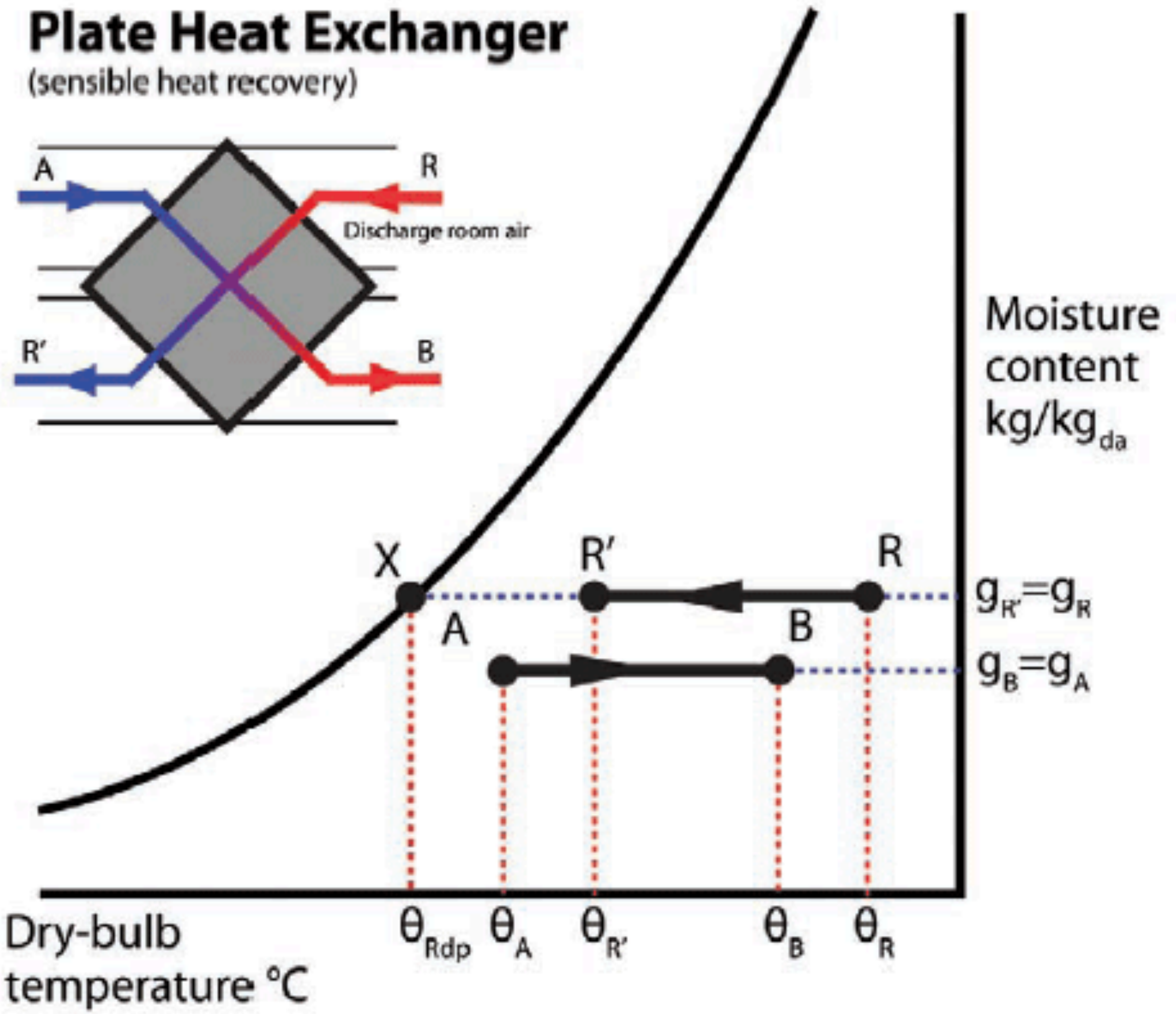
Heat/energy recovery systems

https://www.youtube.com/watch?v=QOSelUK6dpQ

Heat/energy recovery systems

Plate heat exchanger or thermal wheel

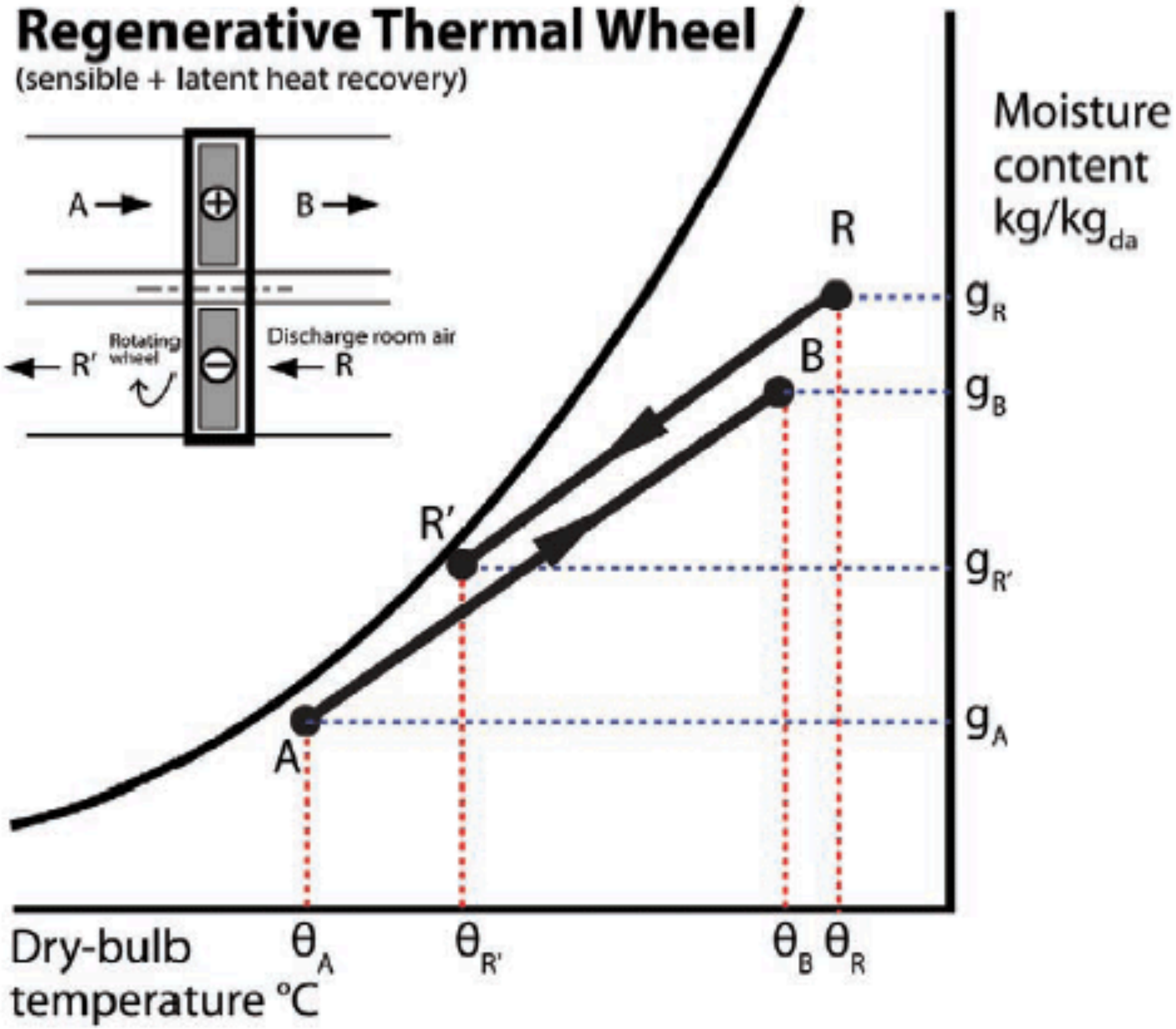
Figure 1 – Psychrometry of Plate Heat Exchanger



https://www.cibsejournal.com/cpd/modules/2009-12/

Energy recovery systems

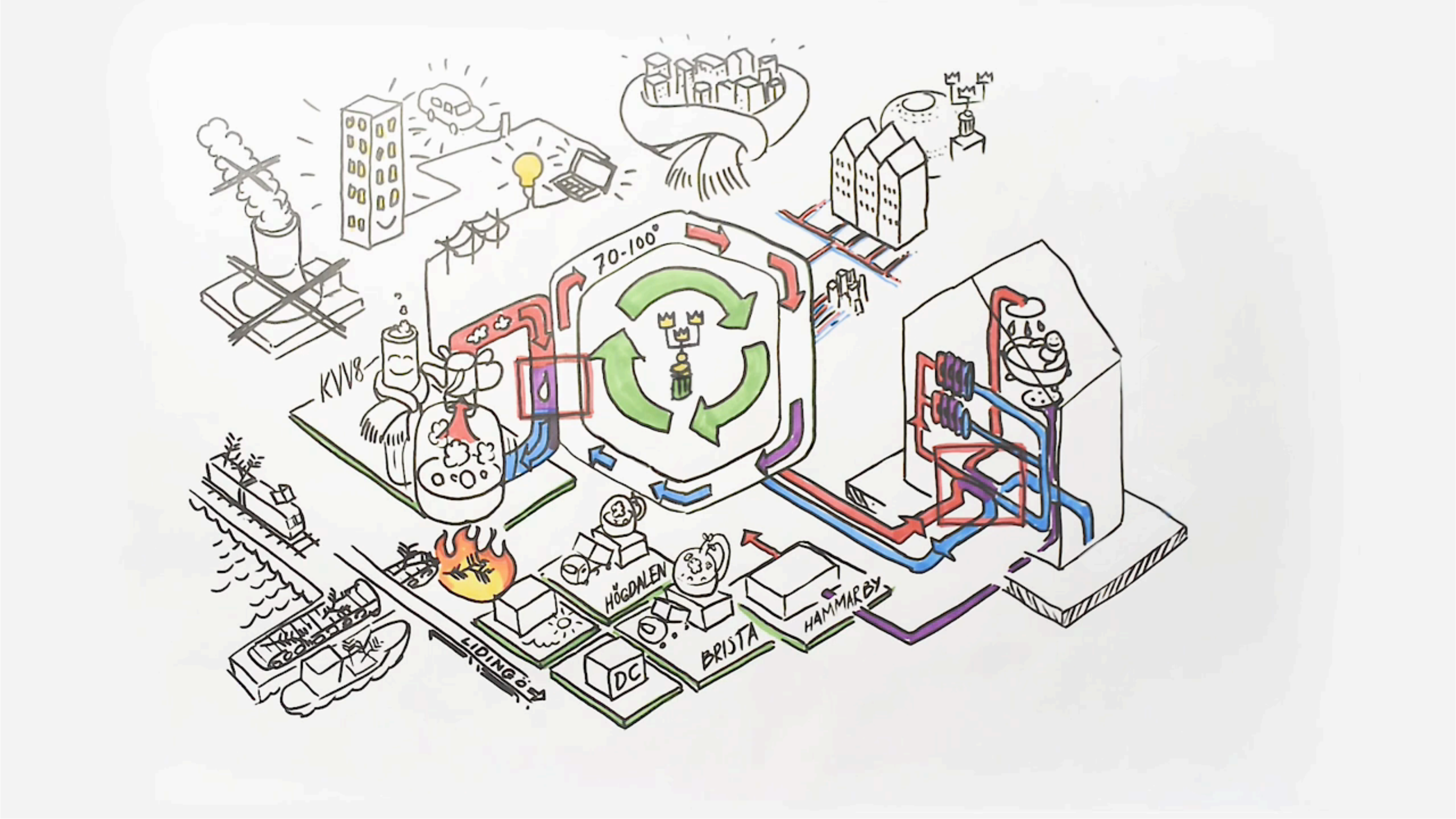
Enthalpy wheel (sensible + latent)



https://www.cibsejournal.com/cpd/modules/2009-12/

DISTRICT ENERGY SYSTEMS

District heating and combined heat and power

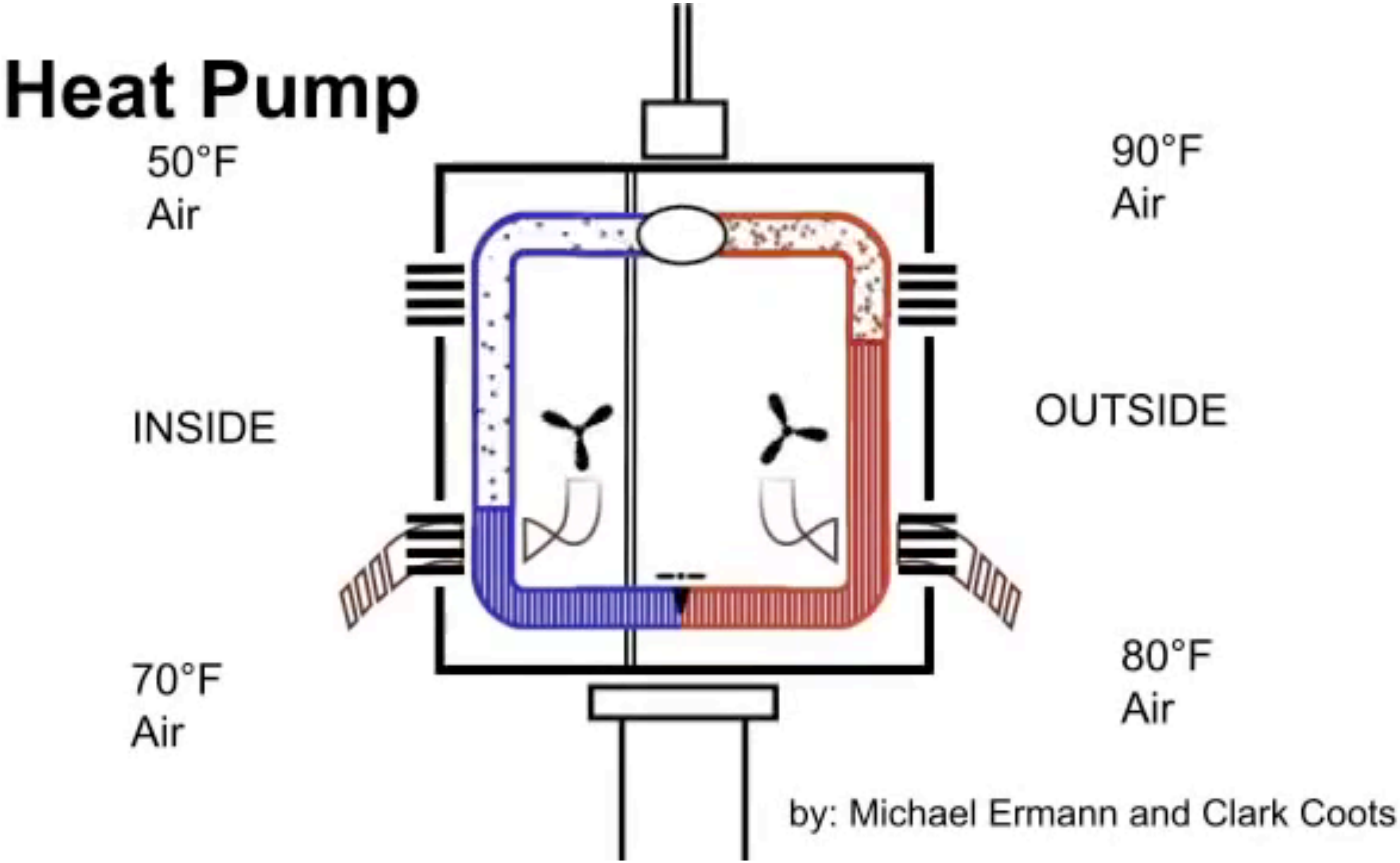


https://www.youtube.com/watch?v=MhJVsSkxg7s

District cooling

https://www.youtube.com/watch?v=7IZ3PBr7dO4

Heat pumps



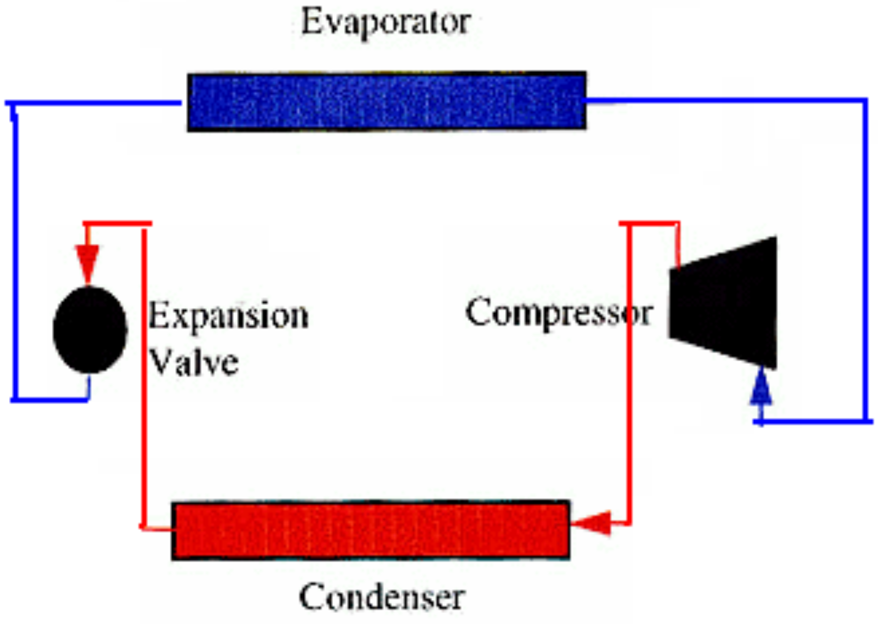
https://www.youtube.com/watch?v=NyNeh7wPQQk

Heat pumps

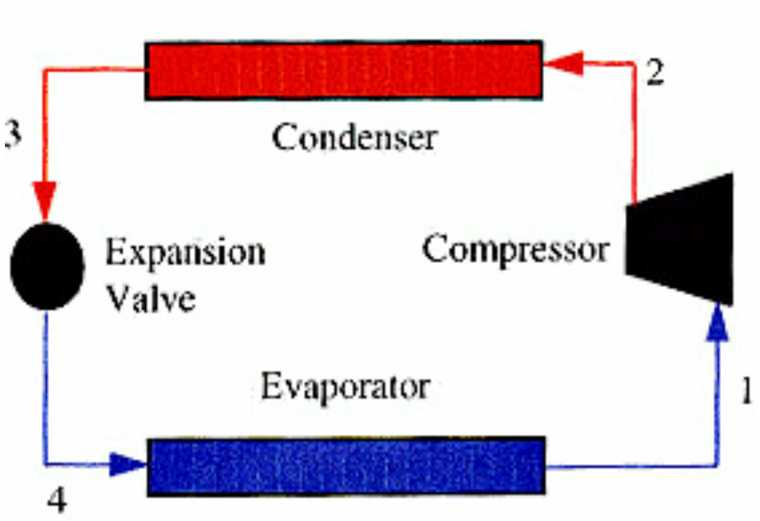
Cooling

Heating

Outside 45°F



Outside 95°F

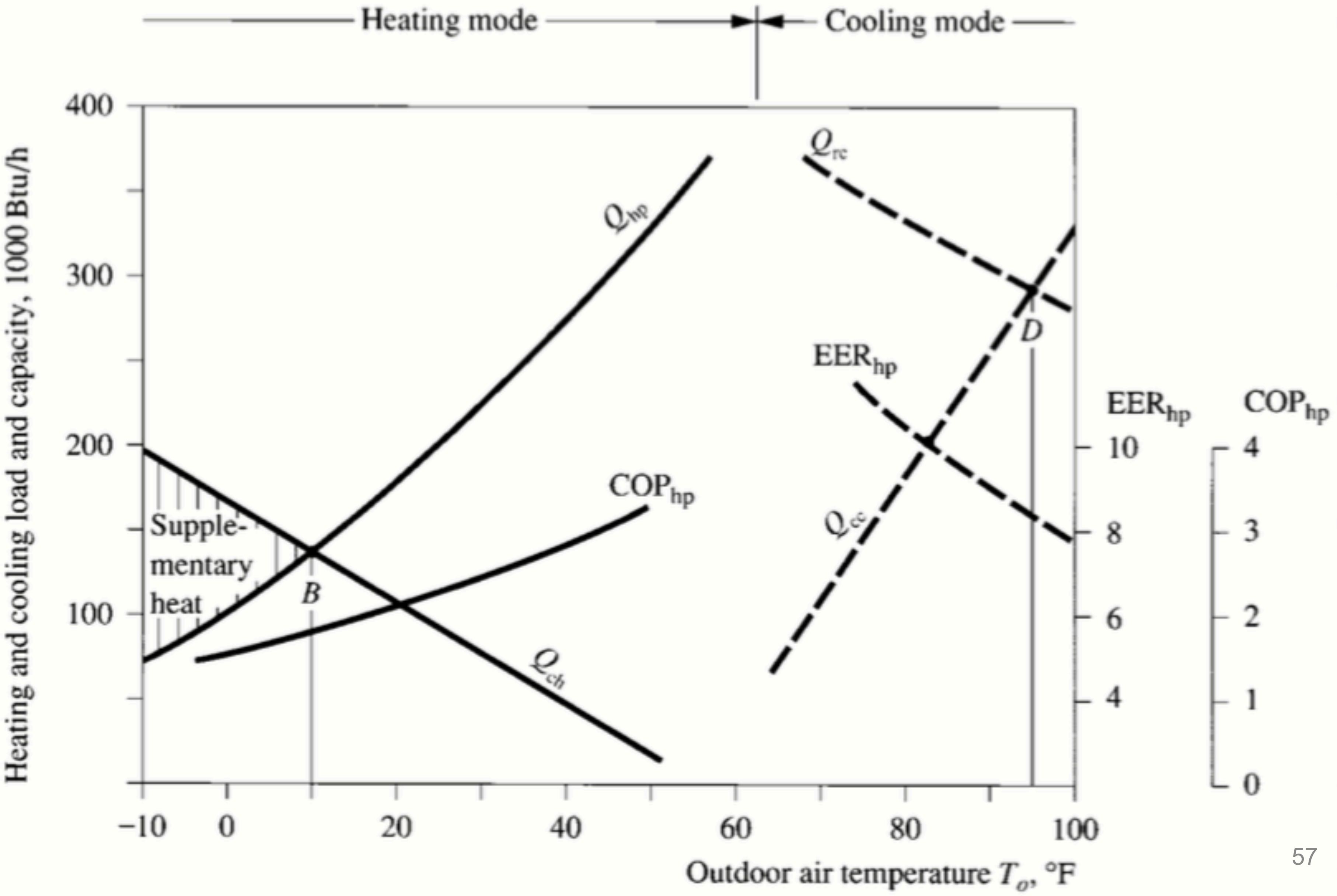


Inside 75°F

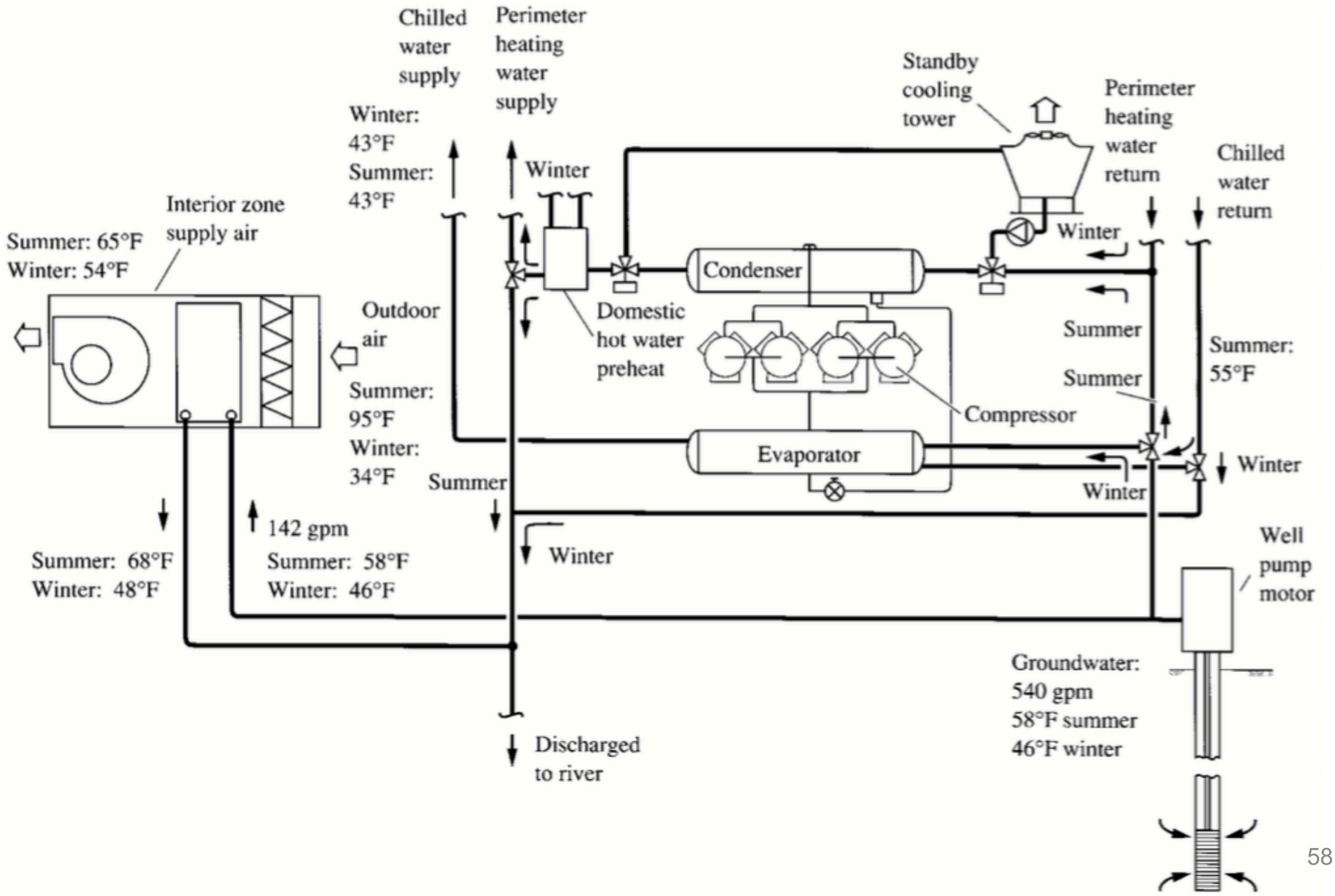
Inside 75°F

Air-conditioner run in reverse

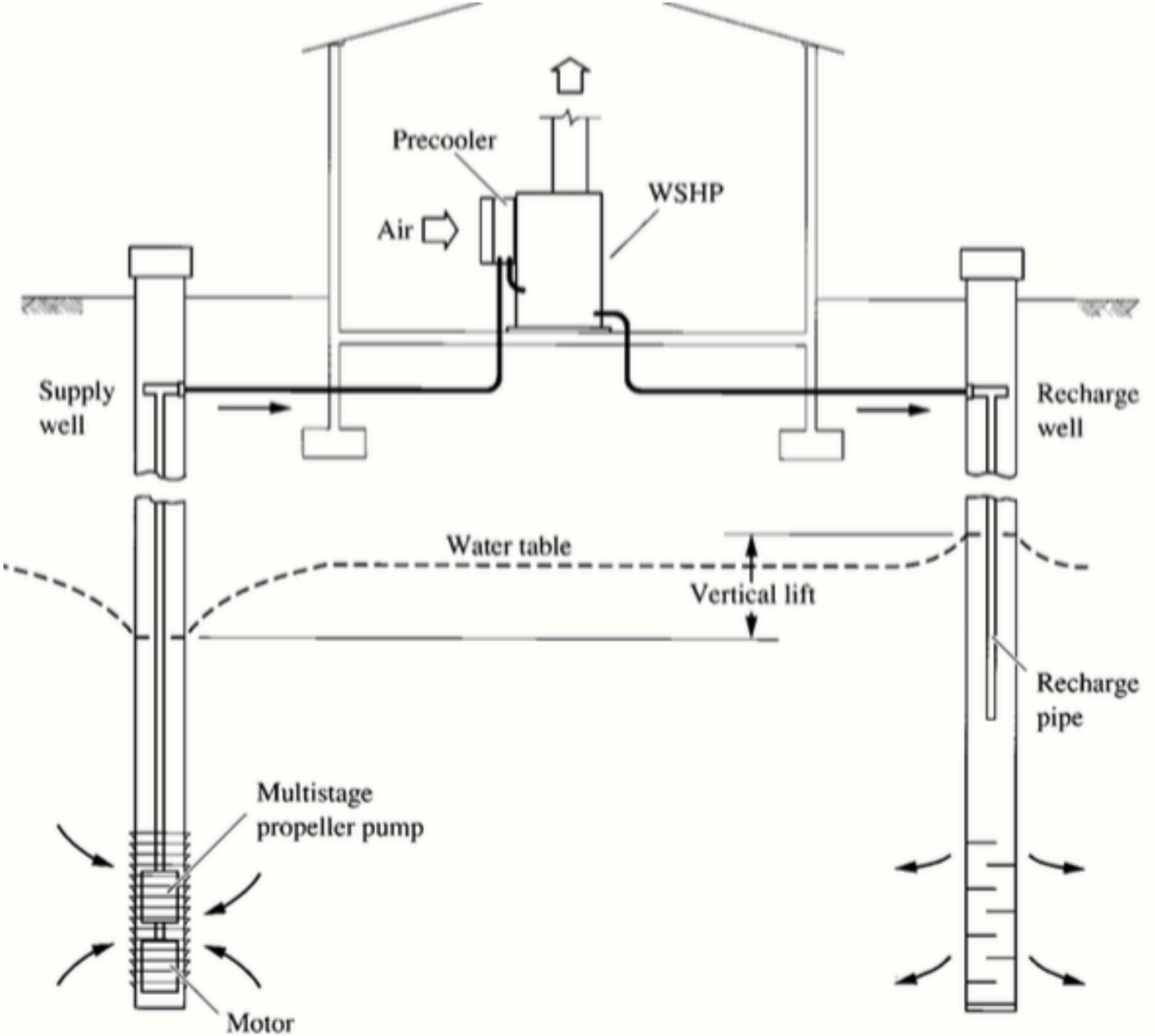
Air-source heat pumps



Ground-source heat pumps



Ground-source heat pumps



Ground-source heat pumps