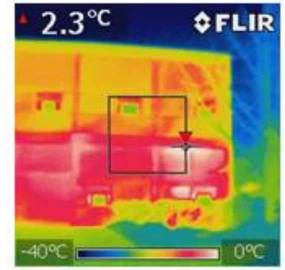
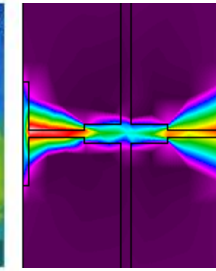
CAE 331/513
Building Science
Fall 2014



Week 9: October 21, 2014
HVAC systems (mechanical properties)

Built
Environment
Research
@ IIT

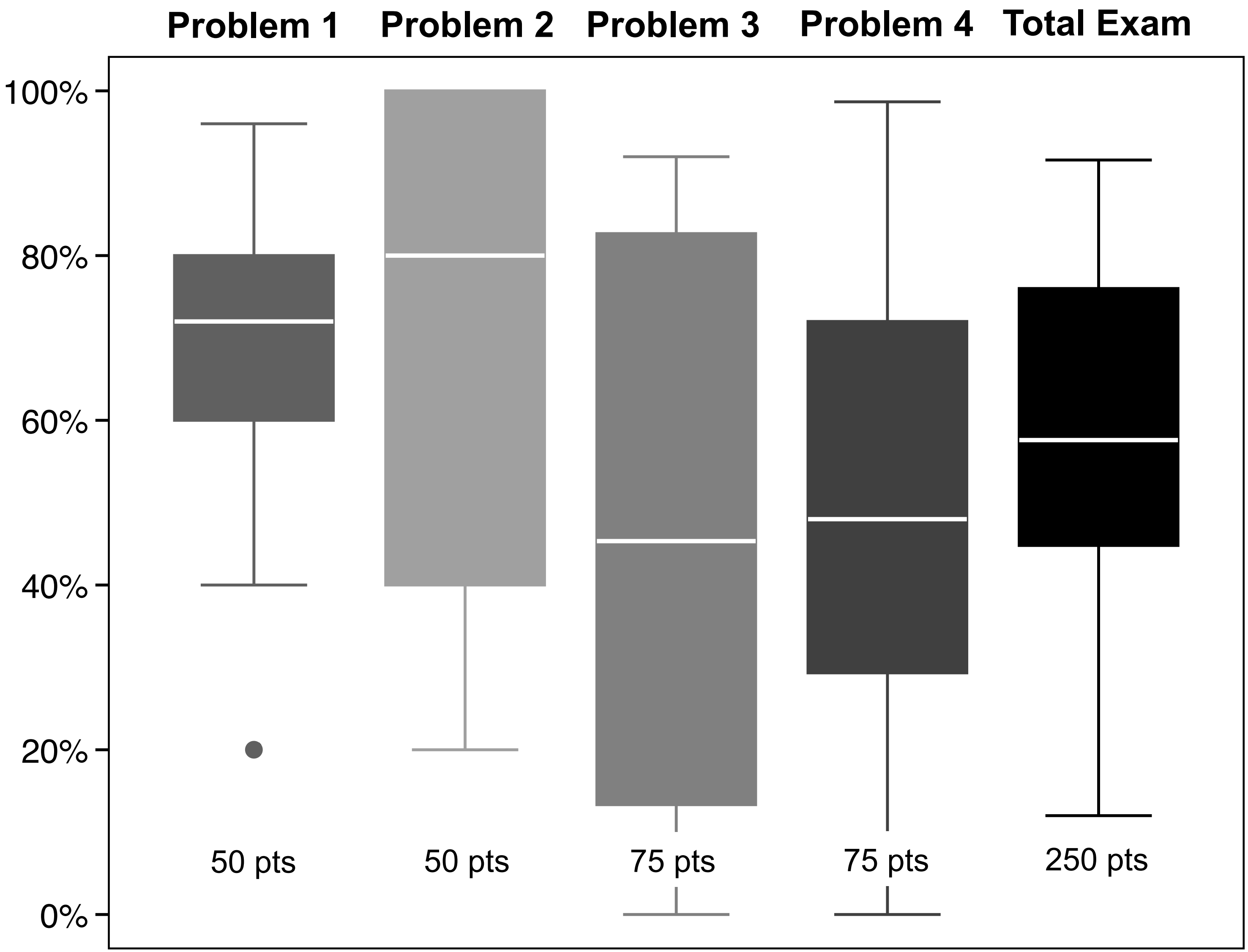
Advancing energy, environmental, and sustainability research within the built environment

www.built-envi.com

Twitter: @built_envi

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

Exam #1 (undergraduates)



N = 31
Max = 91.6%
Min = 12.0%
Median = 57.6%
Mean = 58%

(Uncorrected)
Grade distribution
A = 3
B = 2
C = 5
D = 4
F = 17

Exam #1 (graduate students)

- 8 graduate students took the exam
  - Open book but longer and more difficult
- Grade distribution:
  - A = 5
  - B = 1
  - C = 0
  - D = 1
  - F = 1

Last class period

- Guest lecture, Tommy Zakrzewski, Buro Happold and IIT
  - Building science applications in the real world

LOADS ANALYSIS AND
ENERGY ESTIMATING

BUROHAPPOLD
ENGINEERING

Last time we met for class (Oct 2)

- Finished psychrometric processes
  - Sensible and latent cooling
  - Heating and humidification
  - Evaporative cooling
  - Adiabatic mixing
- Introduction to HVAC systems
  - Overview of typical residential and commercial heating, ventilating, and air-conditioning systems and components
  - Central and distributed

Today's objectives

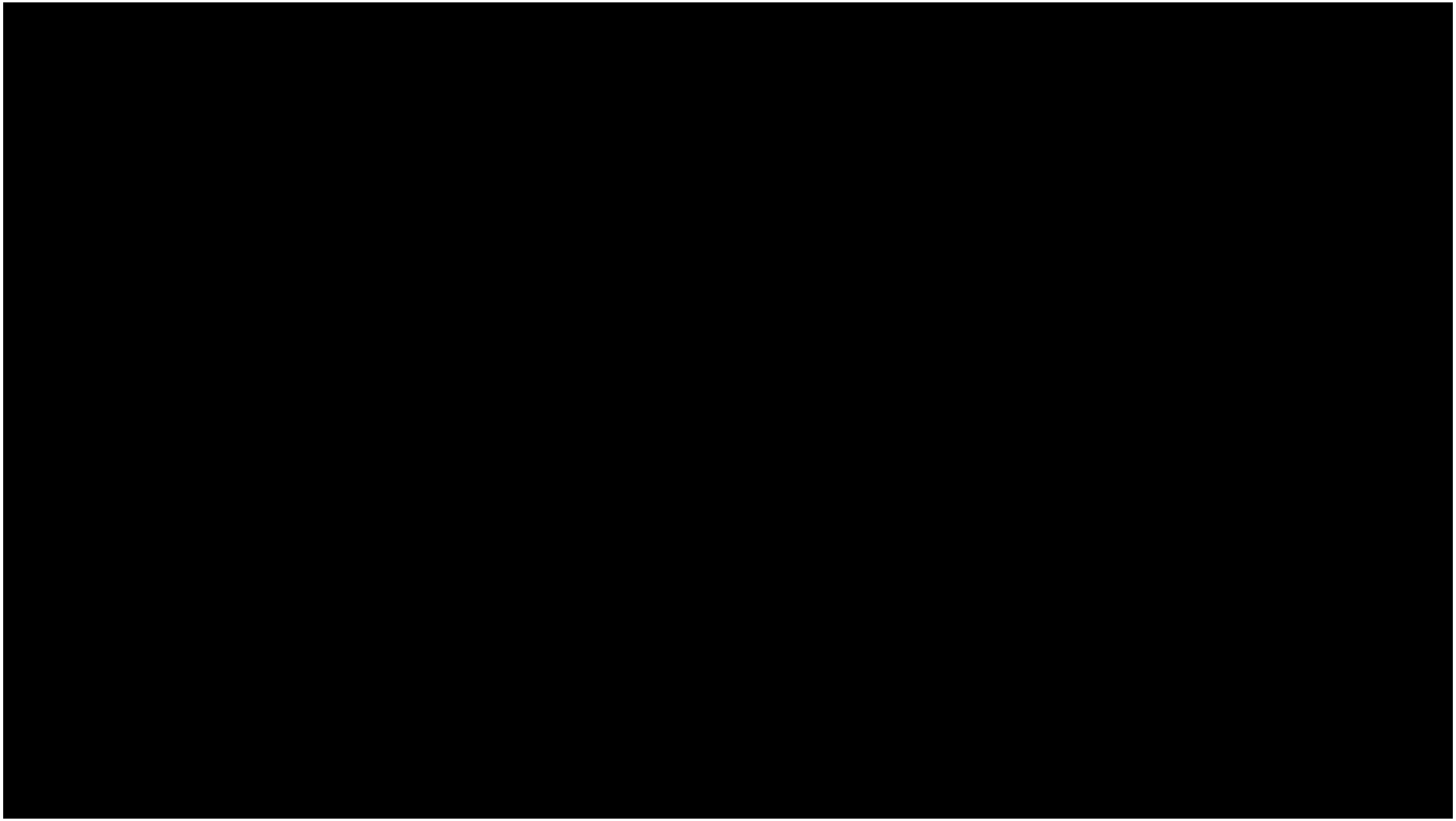
- Introduce HVAC systems and their mechanical properties
  - *How do they work?*

- This will lead into the rest of our course topics:
  - Ventilation and indoor air quality
  - Heating loads
  - Cooling loads
  - Energy estimation
  - Energy efficiency

HVAC SYSTEMS

How do they actually work?

How does a residential furnace work?

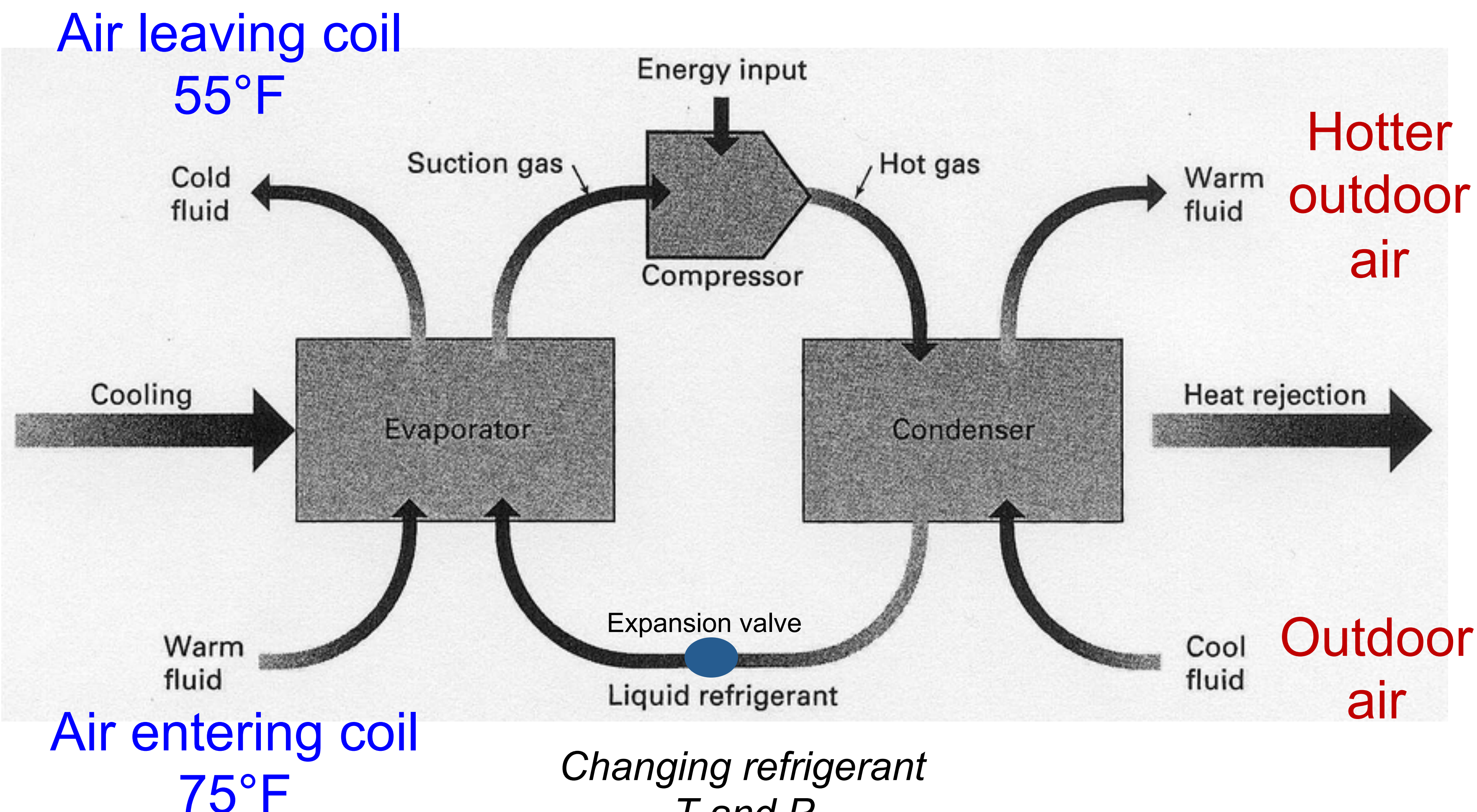


https://www.youtube.com/watch?v=VbSO23tnpuE

How does a residential furnace work?

https://www.youtube.com/watch?v=_IFUlA1PZ8U

Vapor compression cycle: AC units



Changing refrigerant
T and P

Refrigerant characteristics

- What makes a good refrigerant?
  - High heat of vaporization
  - Low boiling point
  - Non-corrosive
  - Safe, non-toxic
  - Non-flammable
  - Minimal or no environmental impact (e.g., ozone depletion)
- In the past, we have used ammonia, sulfur dioxide, methyl chloride
  - All 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

Thermodynamics for HVAC vapor compression

Enthalpy, h [J/kg, Btu/lb]

- Temperature change, ΔT

  $\Delta h = C_p \Delta T$ – only for the same phase (e.g. air or water)

What if we have change of the phase?

- Evaporation or condensation

- Specific Entropy, s [J/kgK, Btu/lb°F]

  $\Delta h = T \Delta s$ for evaporation or condensation

Vapor compression cycle: AC units

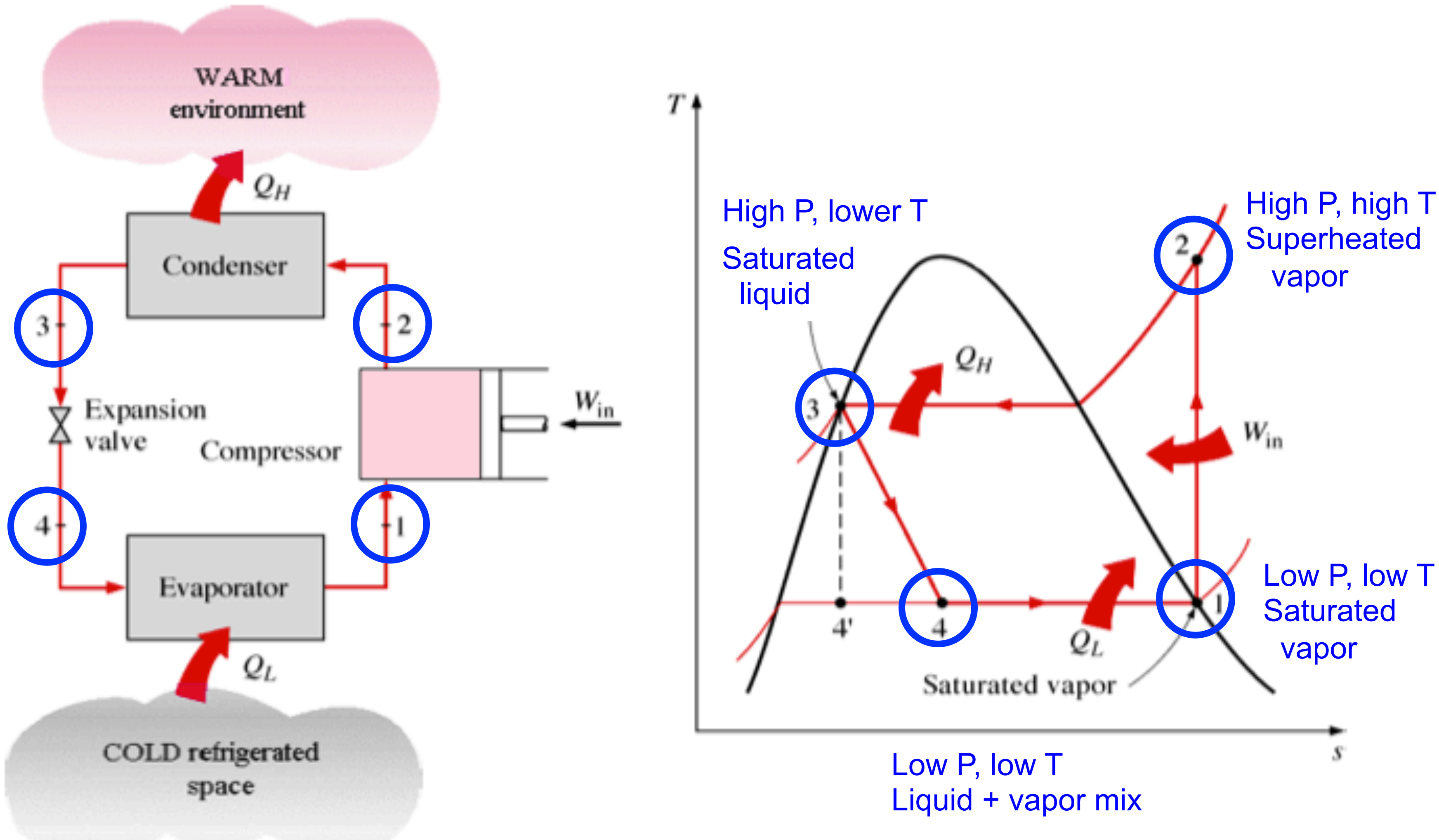


Figure 4-1: Ideal vapor compression cycle (Çengel and Turner 2001, 377)

Question: What is the COP?

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

$$COP = \frac{\text{Provided cooling energy} \quad [\text{W}]}{\text{Used electric energy [W]}} = \eta$$

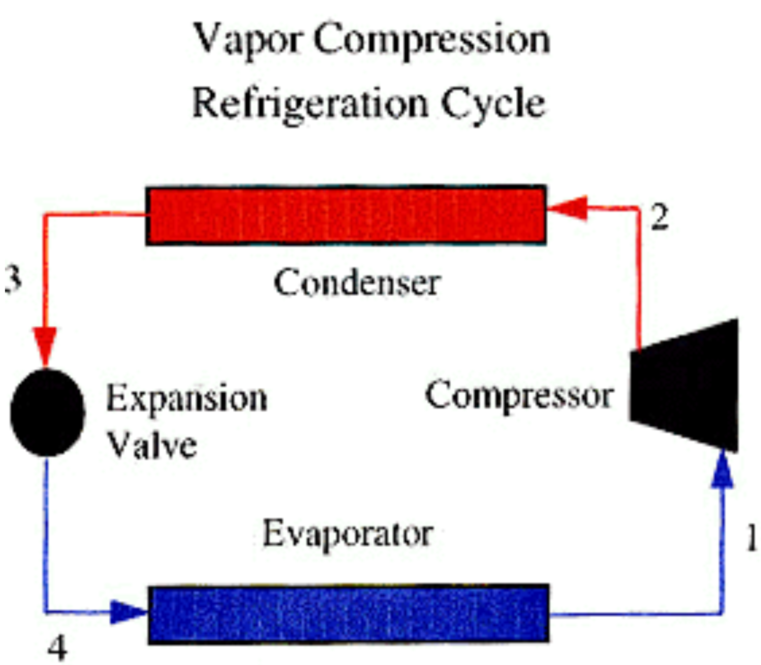
Equivalent to the efficiency of an air-conditioning unit

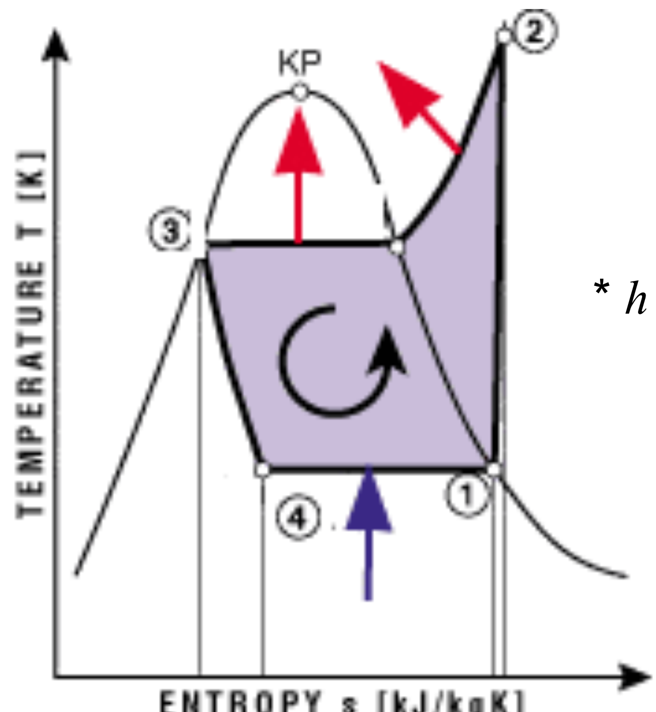
What is the efficiency of a typical residential AC unit?

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

For an ideal refrigeration cycle:

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





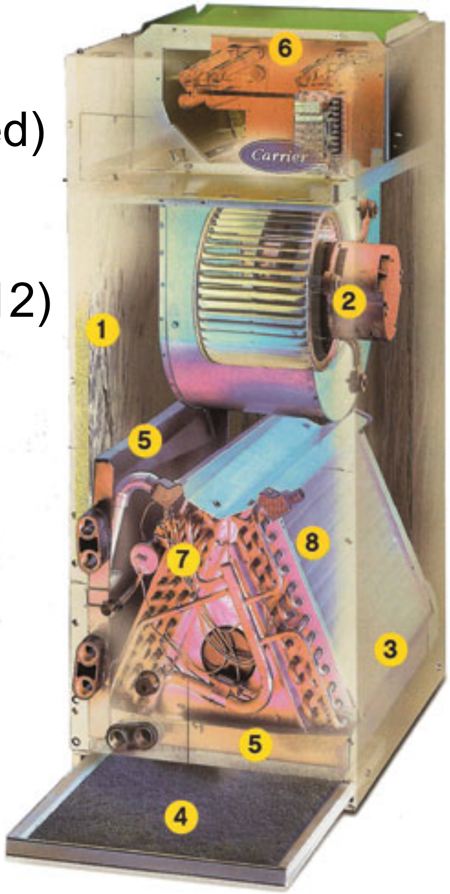
* $h = Ts$

Typical residential AC unit by the numbers

- Capacity = 3 tons
  - 36 kBTU/hr
  - 10.5 kW

- Power draw while operating:
  - 3500 W = 3.5 kW

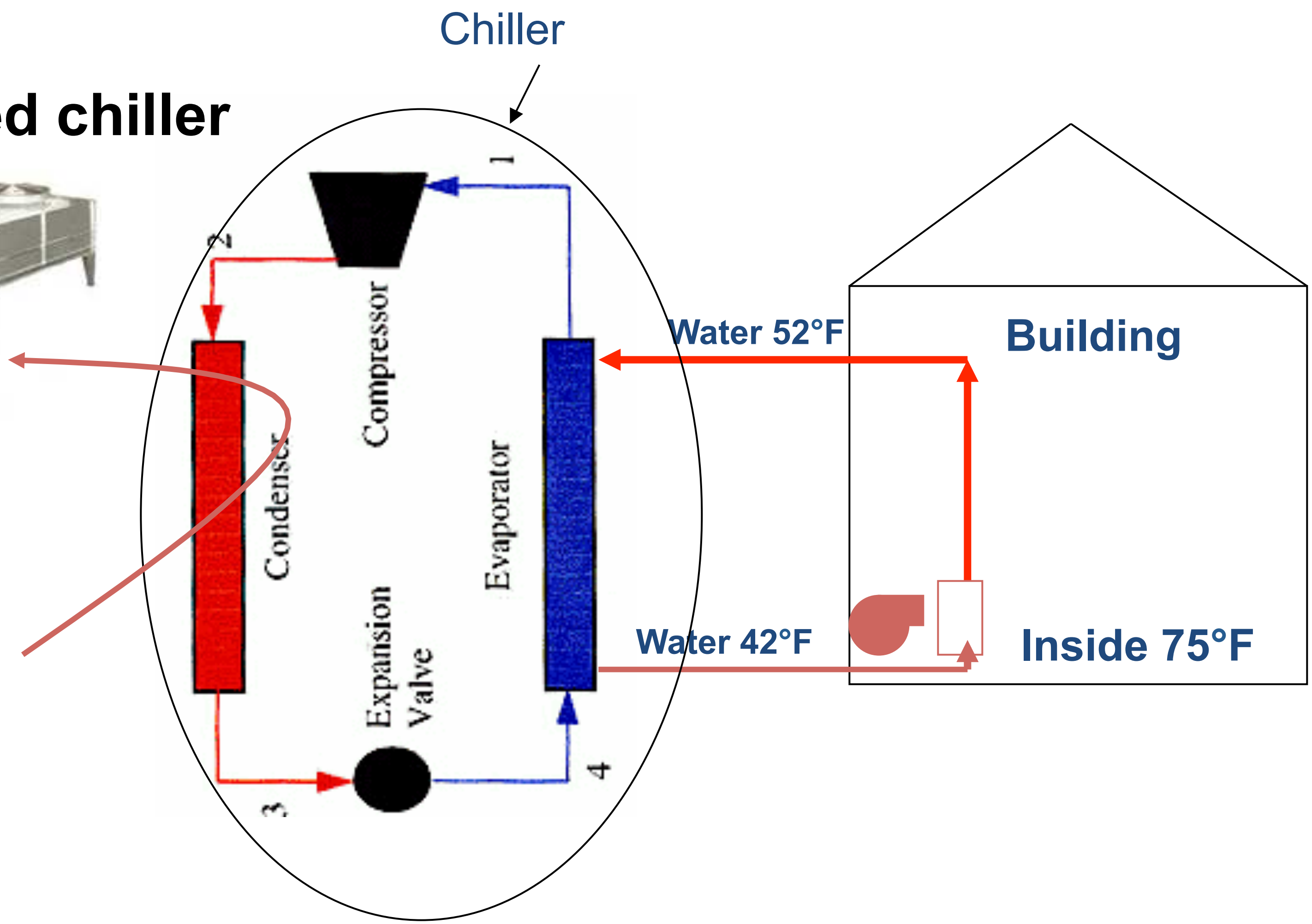
$\Delta T = 12 - 24\ °C$
$\Delta T = -12\ K$
$\dot{V} = 400$ CFM/ton (typical rated)
$\dot{V} = 1200$ CFM
$\dot{V} = 0.566\ m^3/s$
$Q_{sens} = (1.15)(1.006)(0.566)(12)$
$Q_{sens} = 7.9$ kW
SHR = 0.75 (typical)
$Q_{total} = 7.9/0.75 = 10.5$ kW
COP = 10.5/3.5 = 3.0



Chillers (commercial systems)

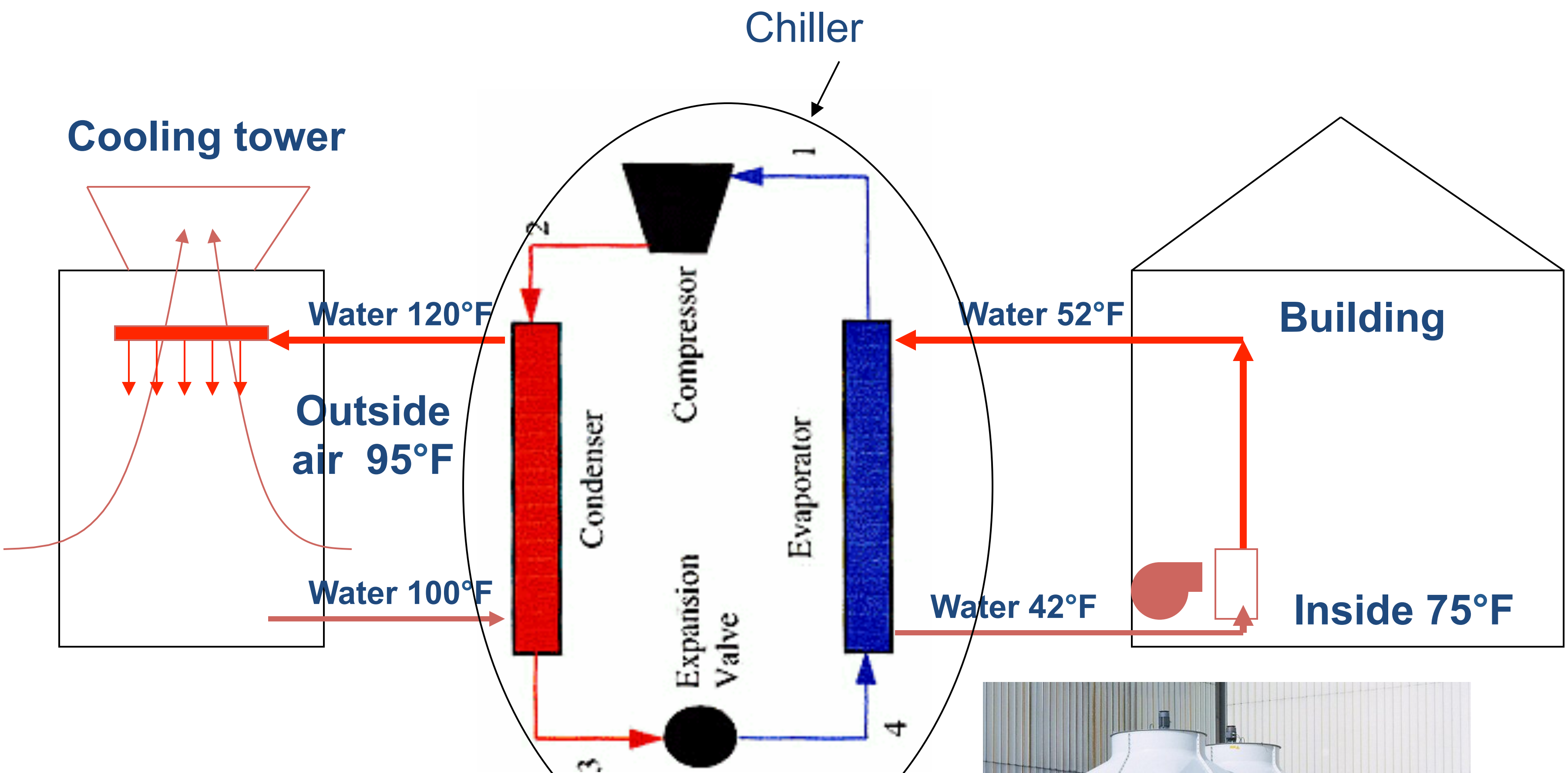
- Chillers use vapor compression or absorption systems to produce chilled water for cooling spaces

Air-cooled chiller

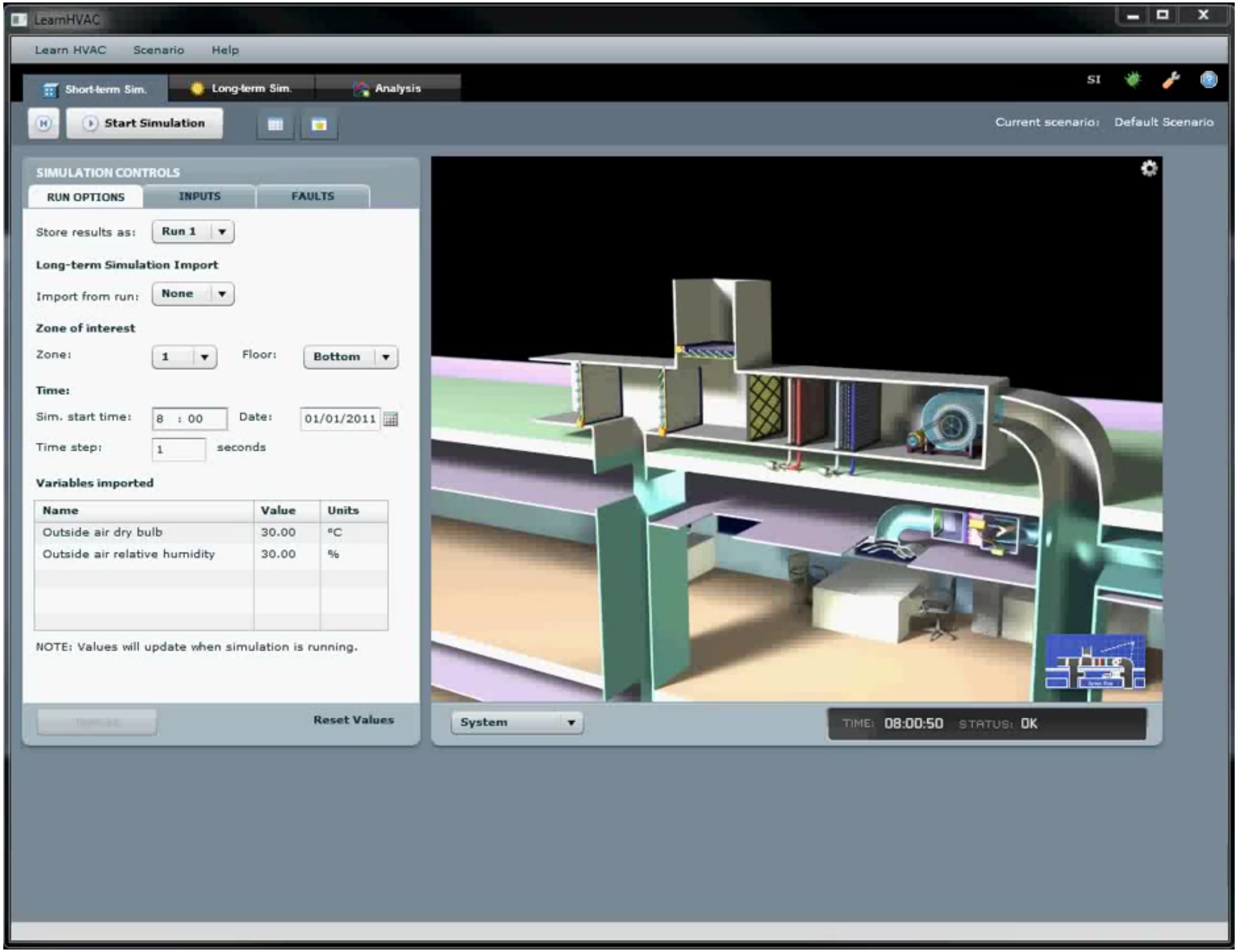


Outside air 95°F

Water cooled chiller



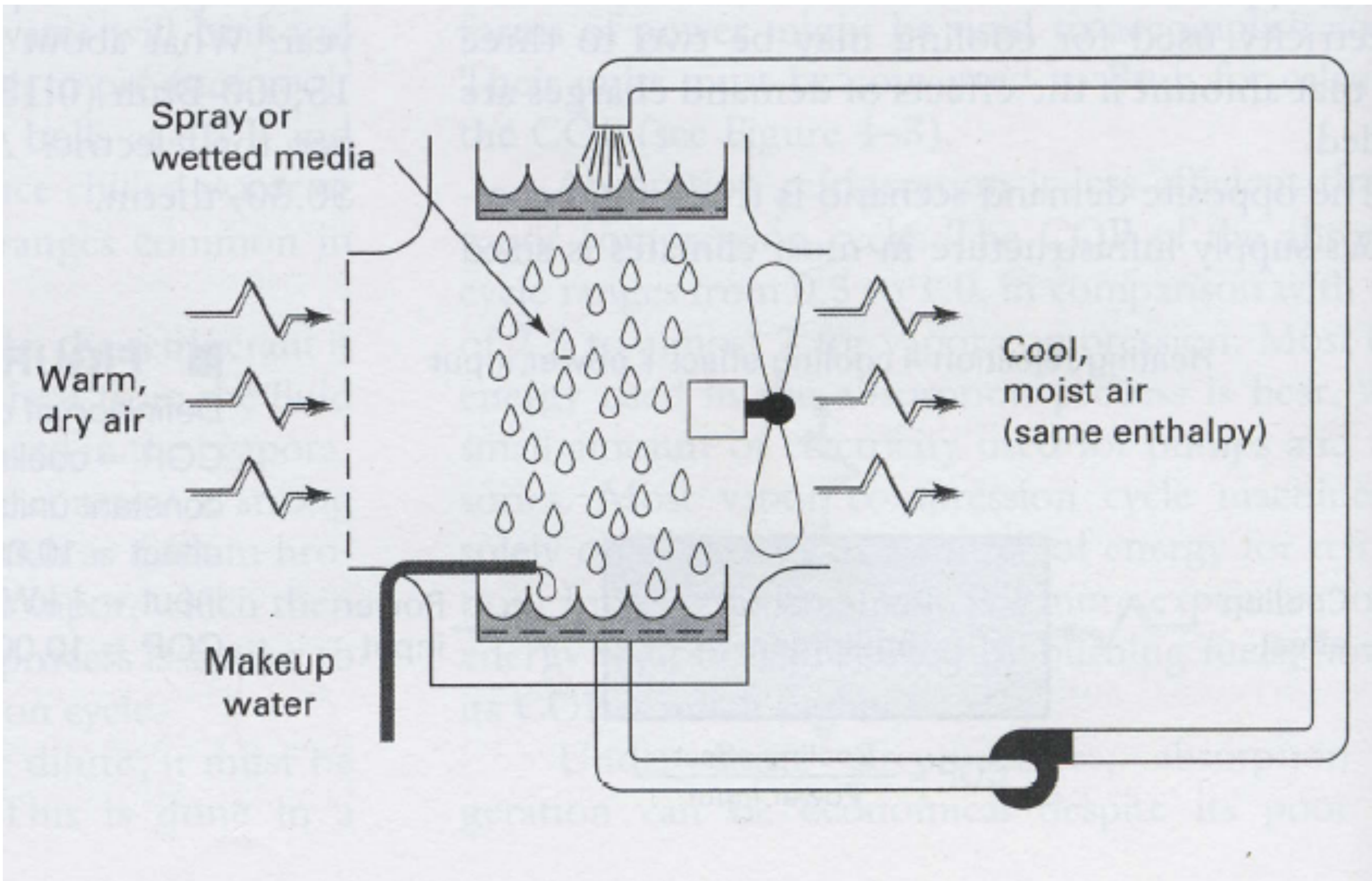
“Learn HVAC” for commercial systems



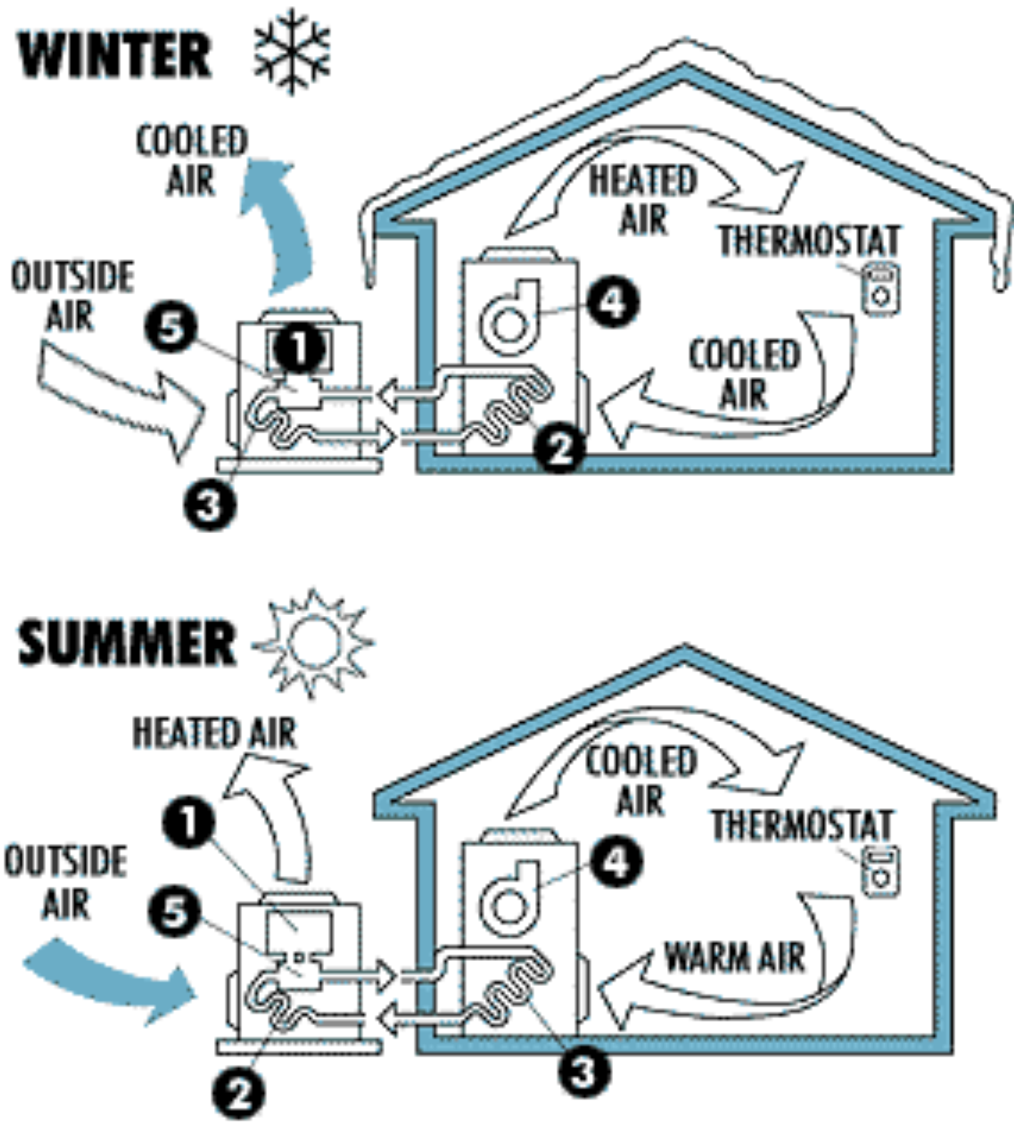
https://www.youtube.com/watch?v=fjZidB4N5Vc http://www.learnhvac.org

Evaporative cooling

- Wet media/water spray – direct
  - Raise absolute humidity, lowers temperature of conditioned air



Heat pumps (AC unit run in reverse)



1) Compressor

2) Condenser

3) Evaporator

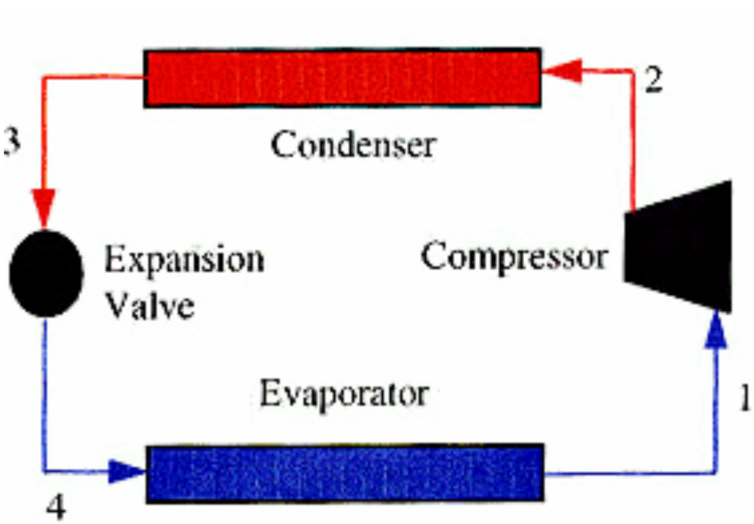
4) Air handler

5) Reversing valve and expansion valve

Heat pumps

Cooling

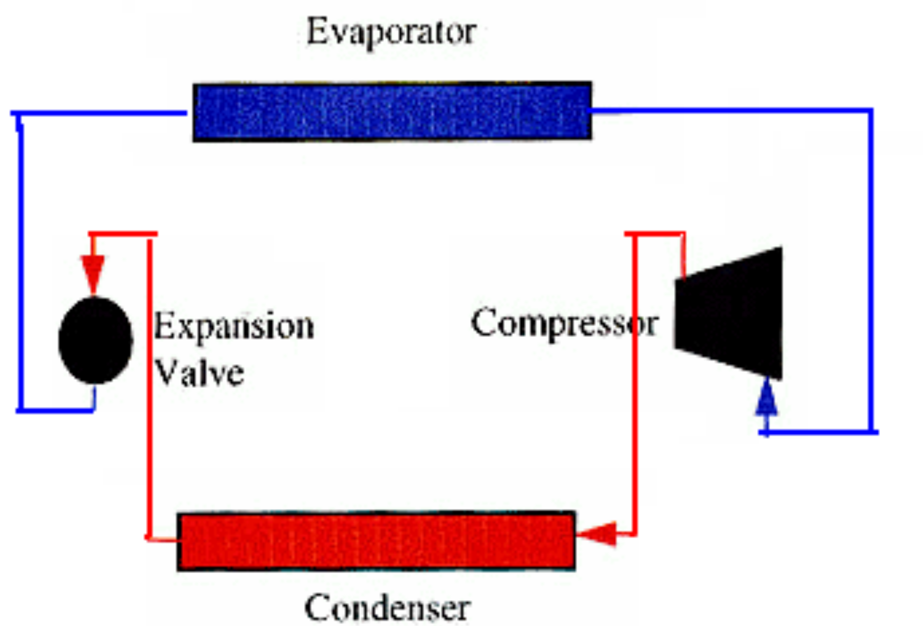
Outside 95°F



Inside 75°F

Heating

Outside 55°F



Inside 75°F

Air-conditioner run in reverse

What do we need to know about cooling systems?

Equipment selection example

Need 1.2 tons
of water cooling
1 ton = 12000 Btu/hr
1.2 tons = 14,400 Btu/hr

Capacity is 1.35 ton
only for:

115 F air condenser temp
50 F of 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.

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

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

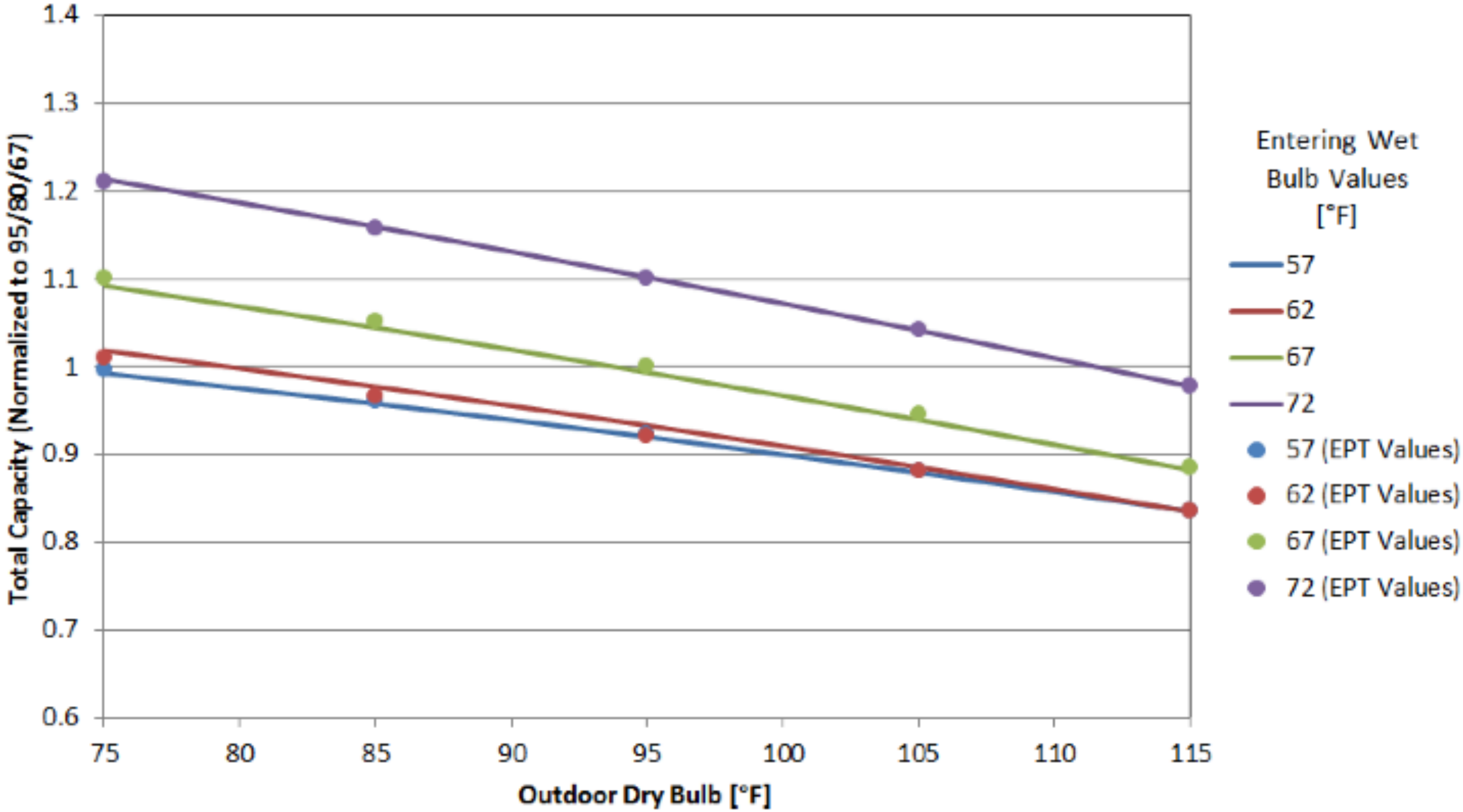
Evaporator Air		Condenser Air °F (°C)								
		75 (23.9)			95 (35)			105 (40.6)		
cfm	EWB °F (°C)	Capacity kBtu/h Total[1]	Capacity kBtu/h Sens[1,2]	Total Sys kW[3]	Capacity kBtu/h Total[1]	Capacity kBtu/h Sens[2]	Total Sys kW[3]	Capacity kBtu/h Total[1]	Capacity kBtu/h Sens[2]	Total Sys kW[3]
875	72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

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 weird mixed units: $(\mathrm{Btu/hr})/\mathrm{W}$
  - Example from previous page:

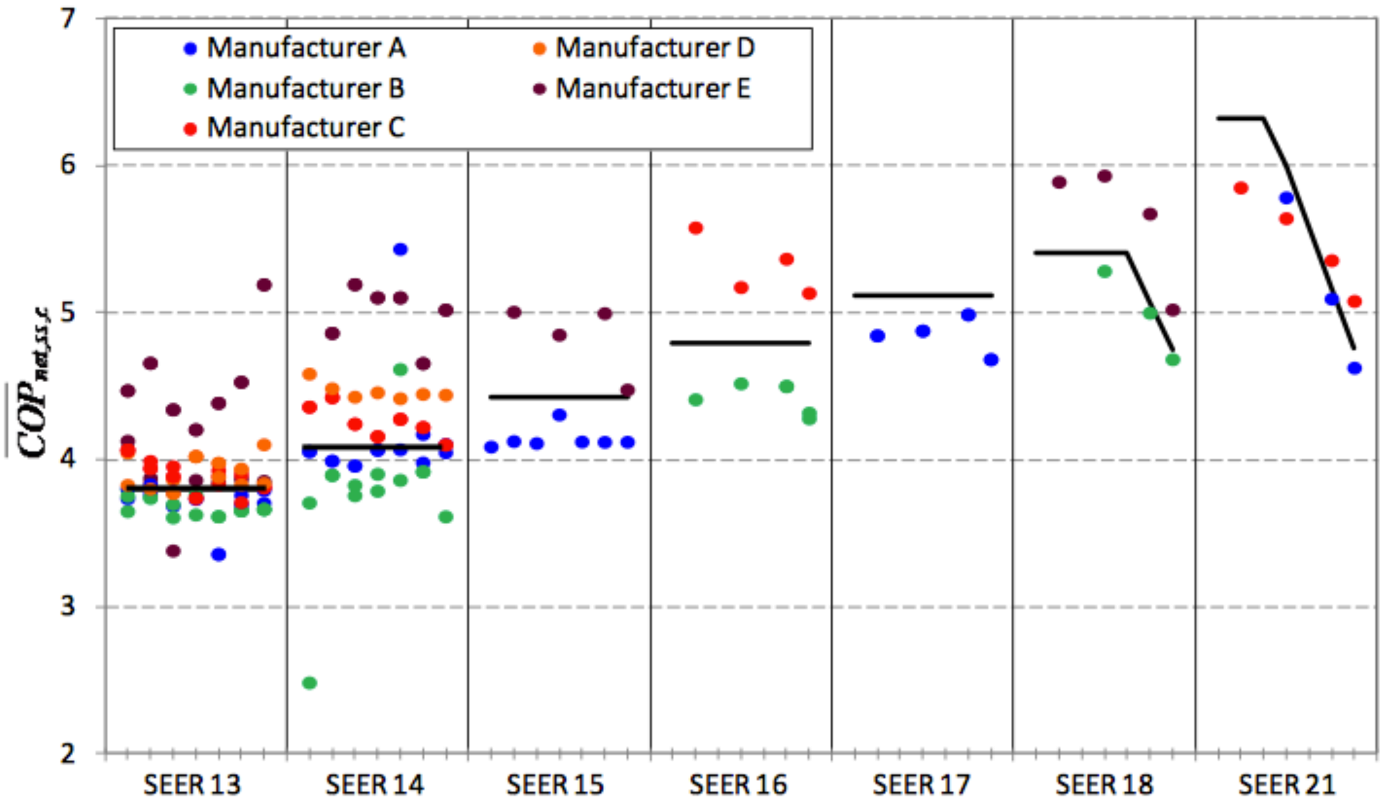
$$COP = \frac{8.5\ [\mathrm{kW}]}{2.48\ [\mathrm{kW}]} = 3.43 \qquad EER = \frac{29.0\ [\mathrm{kBtu/hr}]}{2.48\ [\mathrm{kW}]} = 11.7$$

$$EER = COP \times 3.41$$

- SEER = seasonal energy efficiency ratio, units: $[\mathrm{Btu/Wh}]$
  - 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 EER to estimate energy consumption

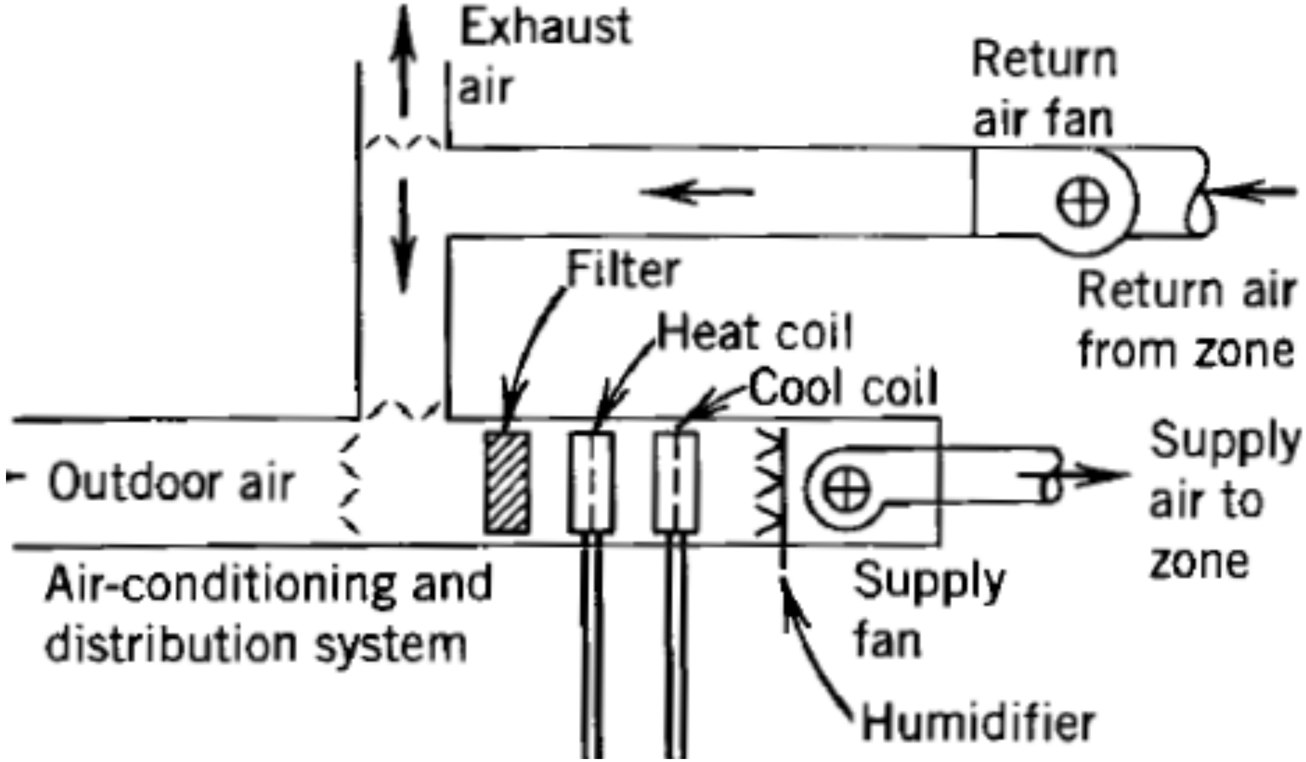
- If you know the load and you know the EER, you can estimate the instantaneous electric power draw required to meet the load:

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

- Multiply by the number of hours and sum over period of time and get energy consumption:

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

- Can break into bins if COP/EER changes with varying conditions



FLUID FLOWS AND FAN/PUMP POWER

For distribution systems

Fluid flows in buildings

- We use liquids and gases to deliver heating or cooling energy in building mechanical systems
  - Water, refrigerants, and air
- We often need to understand fluid motion, pressure loses, and pressure rises by pumps and fans in order to size systems
- We can use the Bernoulli equation to describe fluid flows in HVAC systems

$$\mathrm{p}_1 + \frac{1}{2}\rho_1 v_1^2 + \rho_1 g h_1 = \mathrm{p}_2 + \frac{1}{2}\rho_2 v_2^2 + \rho_2 g h_2 + K\frac{v^2}{2}$$

Static pressure | Velocity pressure | Pressure head | Friction

If friction and head are negligible: $\dot{V} = C_d A_o \sqrt{2\,\Delta p/\rho}$

Pressure losses

- We often need to find the pressure drop in pipes and ducts
  - Most flows in HVAC systems are turbulent

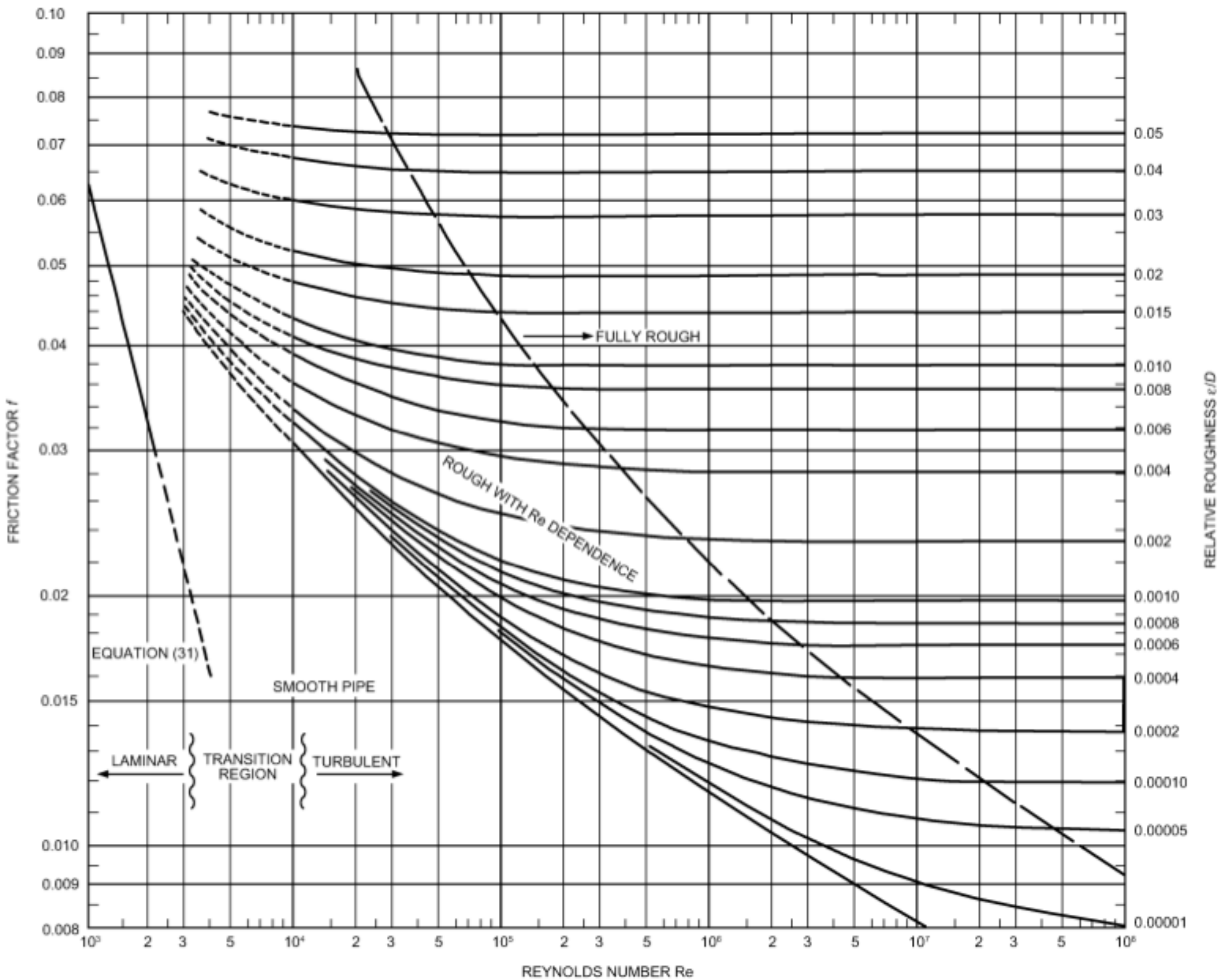
$$\Delta p_{friction} = f\left(\frac{L}{D_h}\right)\left(\frac{1}{2}\rho v^2\right)$$

$$D_h = \frac{4A}{P} = \text{hydraulic diameter}$$

$$K = f\left(\frac{L}{D_h}\right)$$ In a straight pipe

$$K = f\left(\frac{L}{D_h} + \sum_{fittings} K_f\right)$$ In a straight pipe with fittings

Friction factor



Reynolds number

- Reynolds number relates inertial forces to viscous forces:

$$\mathrm{Re} = \frac{VL}{\nu}$$

L = D_h in a pipe or duct

- Kinematic viscosity

$$\nu = \frac{\mu}{\rho} = 1.5\times10^{-5}\ \frac{\mathrm{m}^2}{\mathrm{s}}\ \text{(for air at T=25°C)}$$

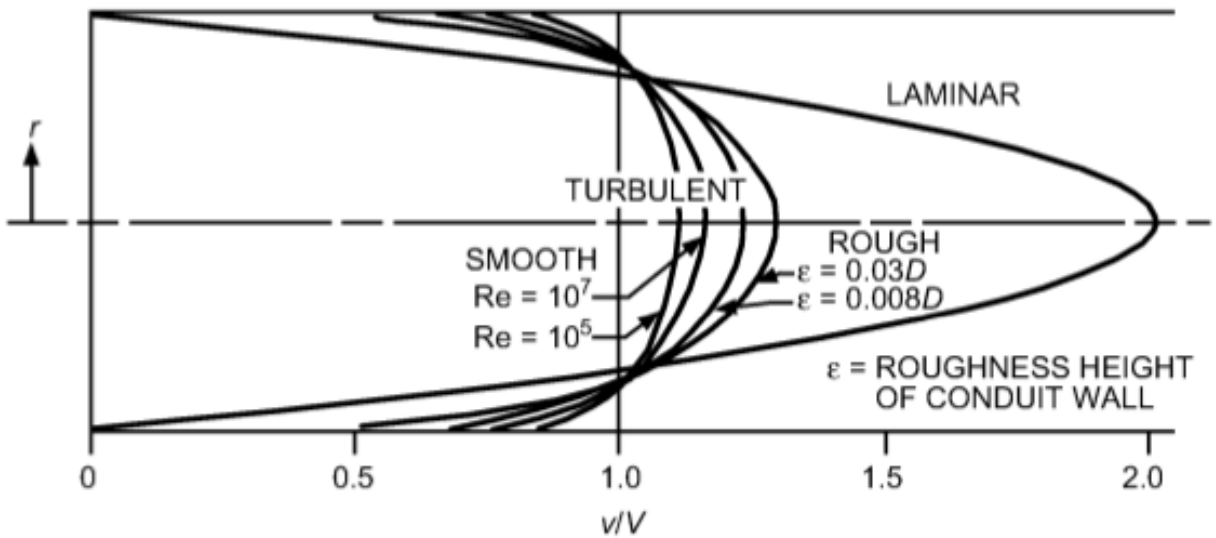
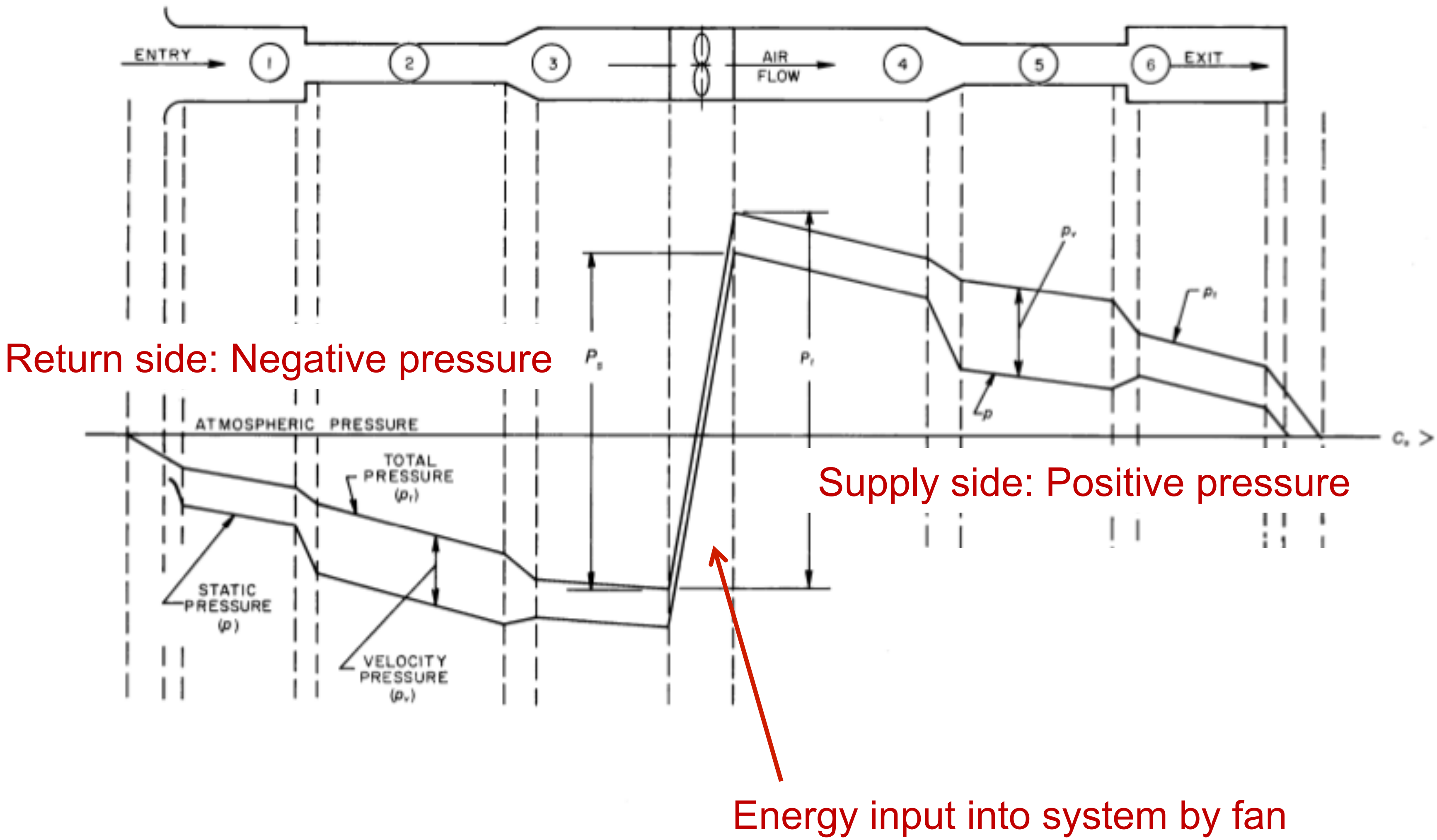
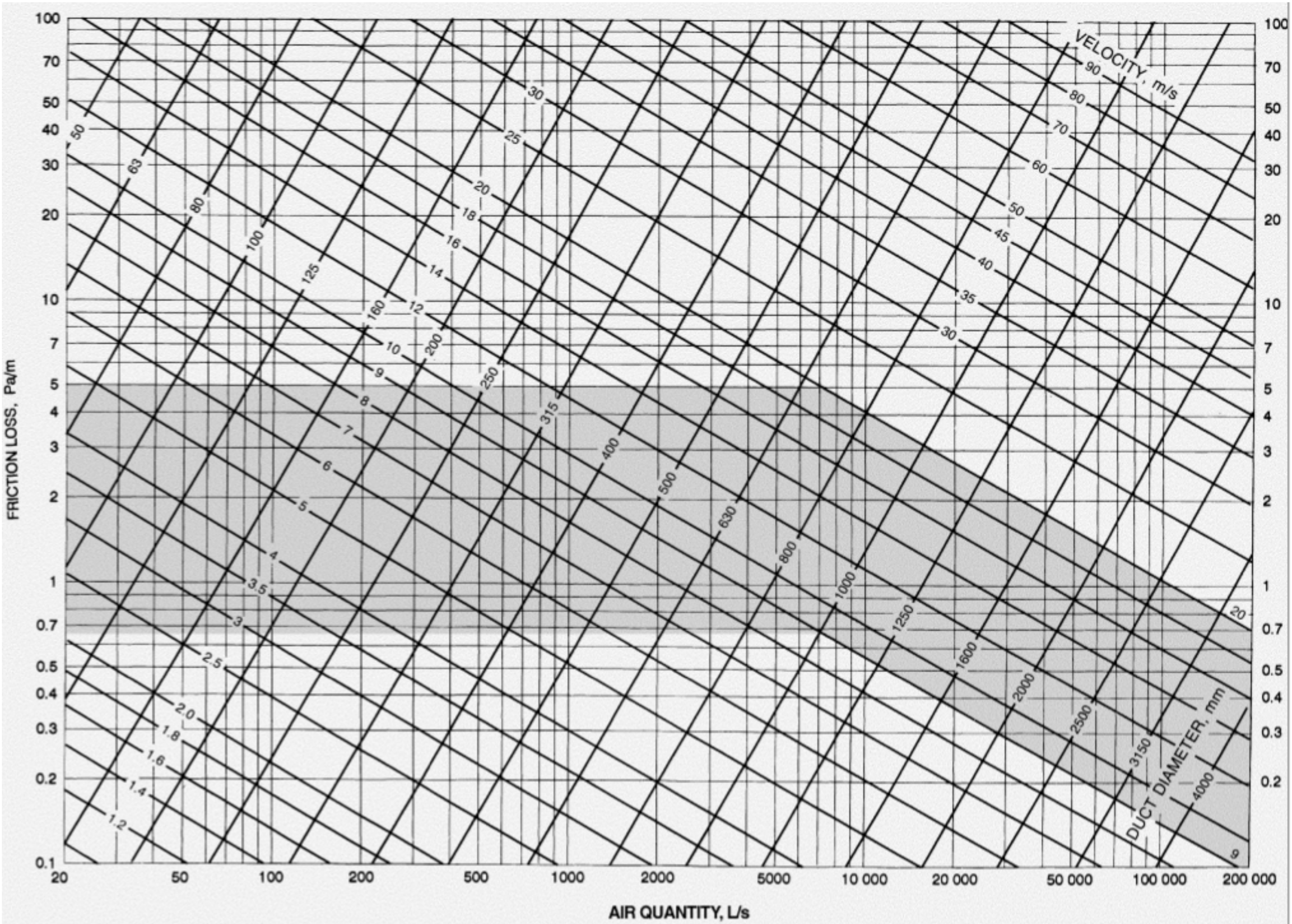


Fig. 4 Velocity Profiles of Flow in Pipes

Pressure losses and rises in HVAC systems

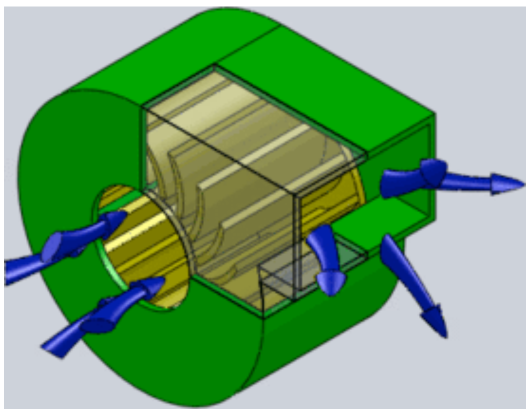


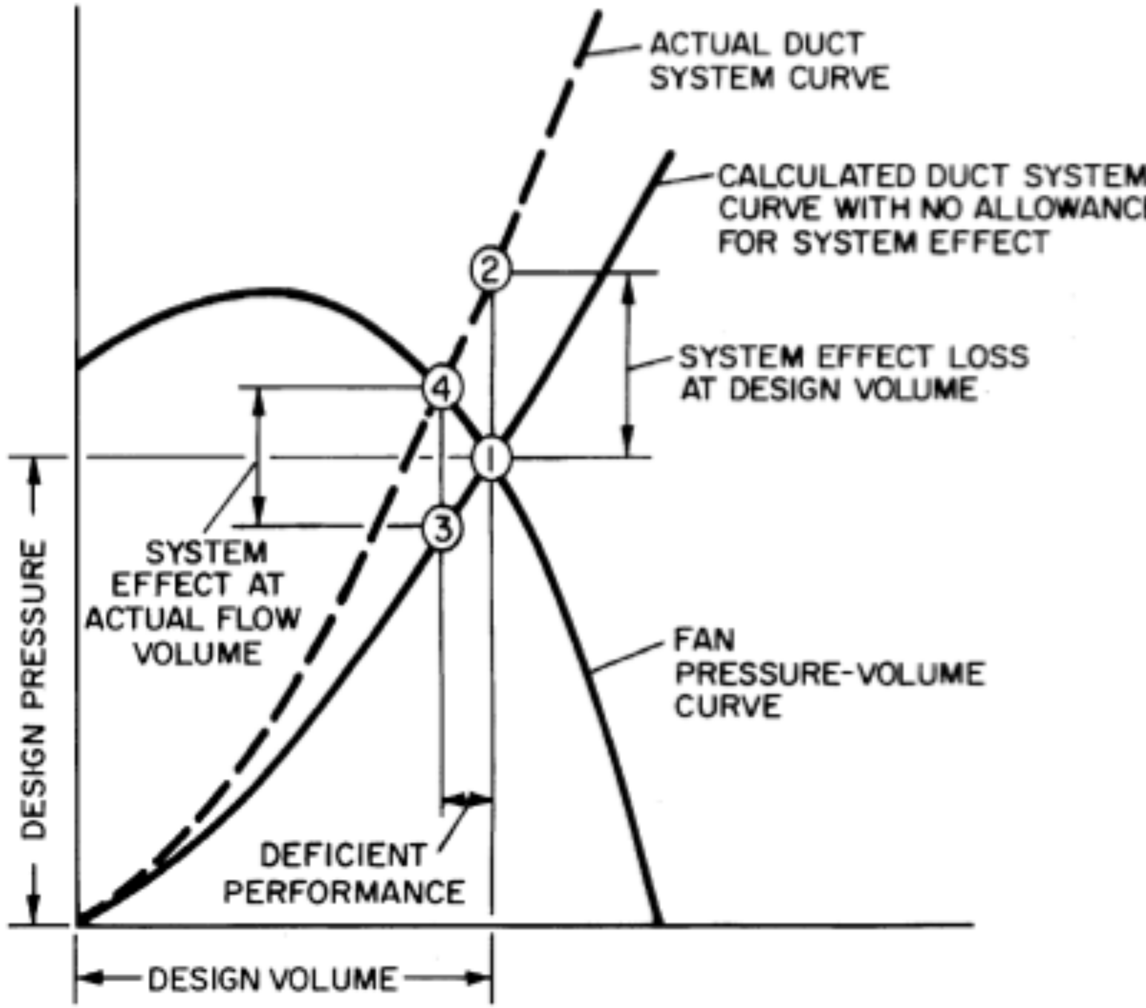
Duct friction charts



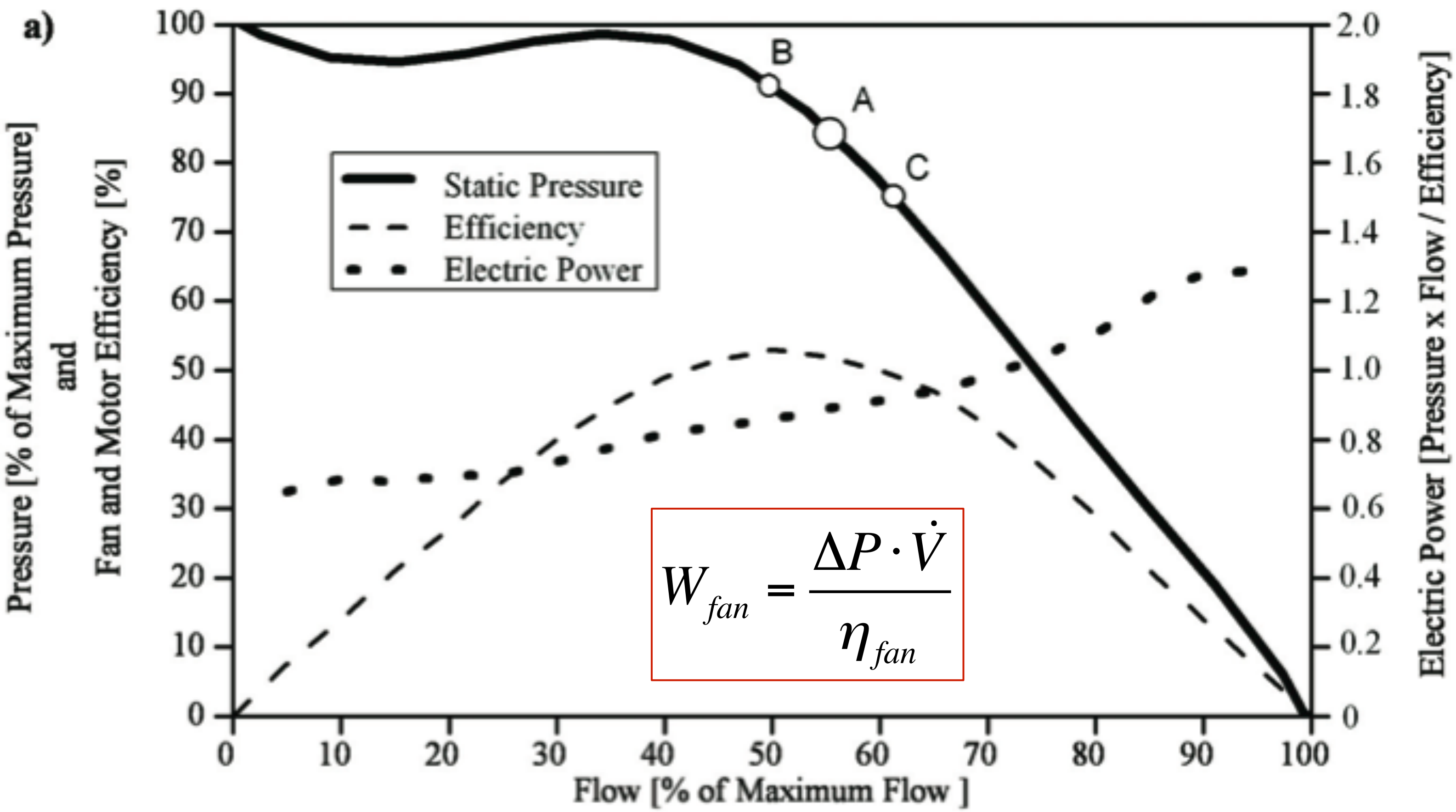
Fan and system pressures

- Fan curves
- System curves



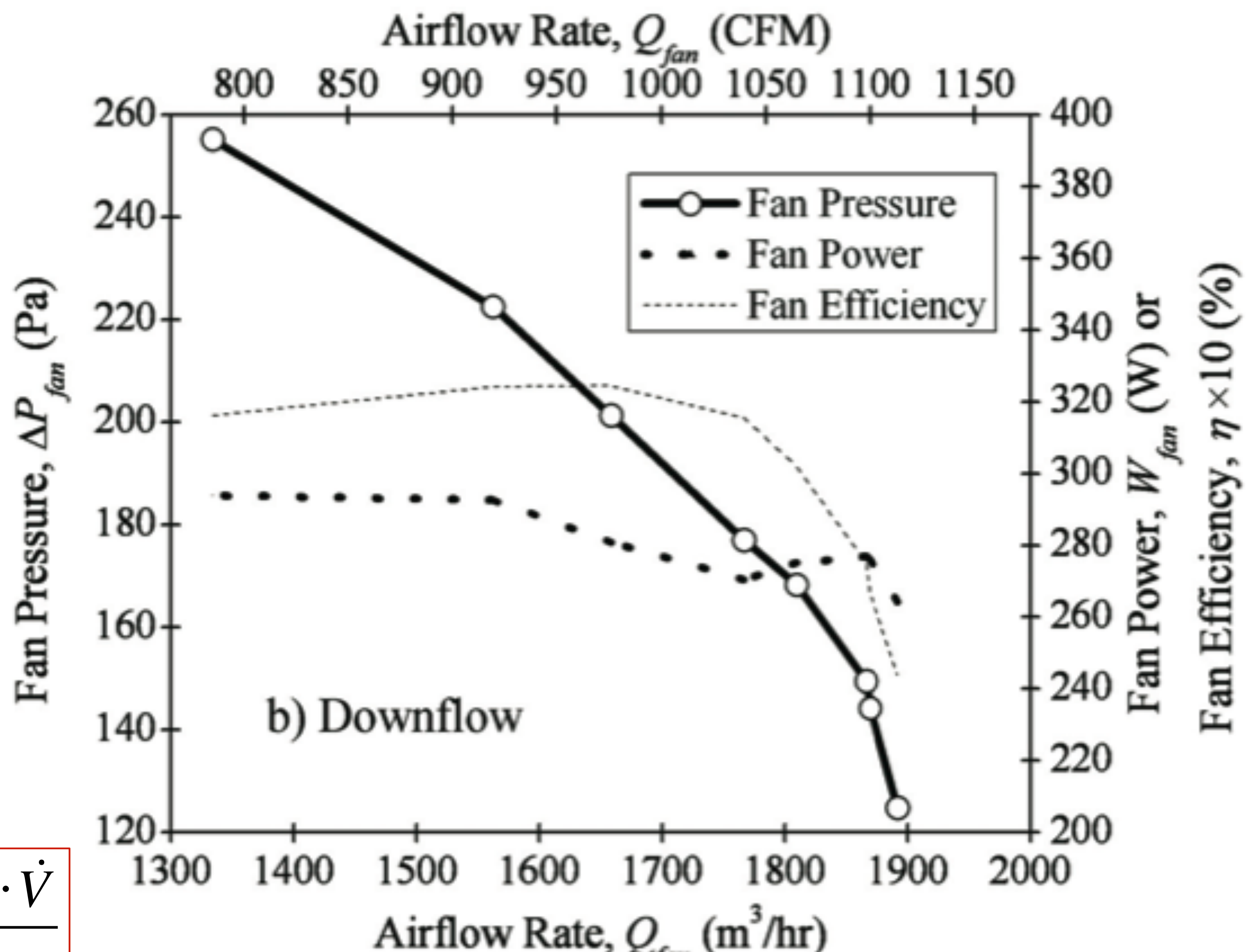


Fan and system curves: Ideal



$$W_{fan} = \frac{\Delta P \cdot \dot{V}}{\eta_{fan}}$$

Fan and system curves: Real



$$W_{fan} = \frac{\Delta P \cdot \dot{V}}{\eta_{fan}}$$