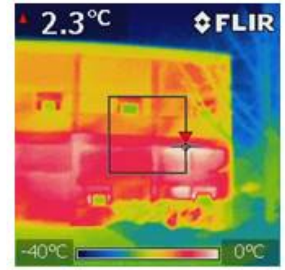
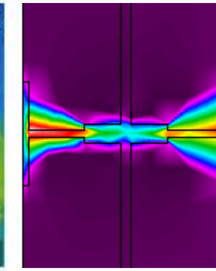
CAE 331/513
Building Science
Fall 2014



Week 9: October 23, 2014
Finish HVAC systems
Ventilation and indoor air quality

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Today's objectives

- Finish HVAC systems
- Introduce ventilation and indoor air quality (IAQ)

Vapor compression cycle: AC units

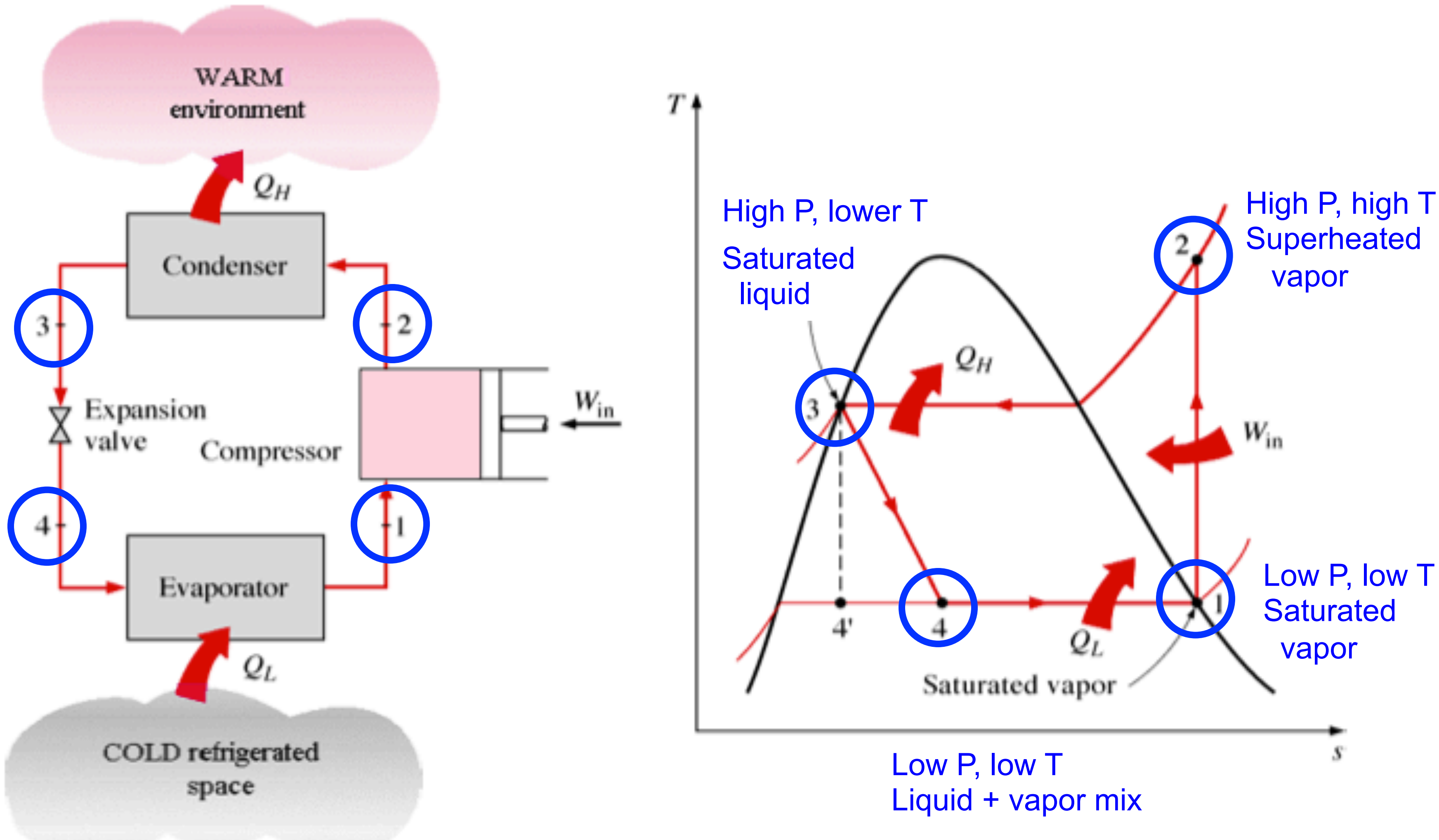


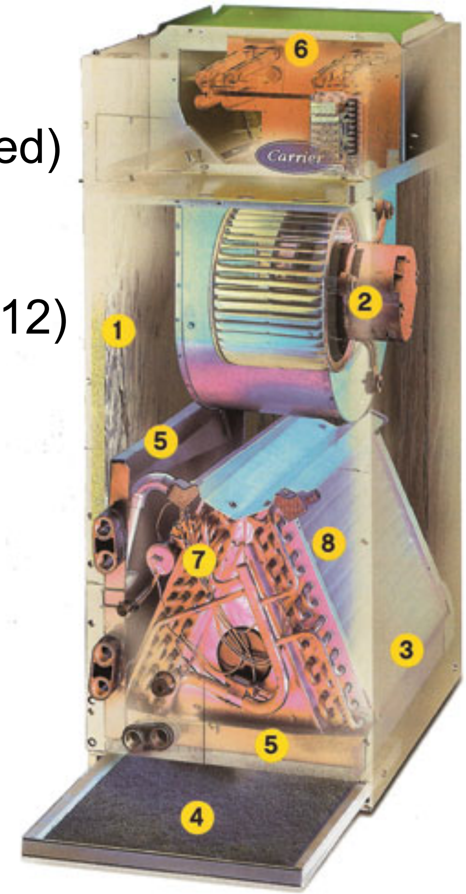
Figure 4-1: Ideal vapor compression cycle (Çengel and Turner 2001, 377)

Typical residential AC unit by the numbers

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

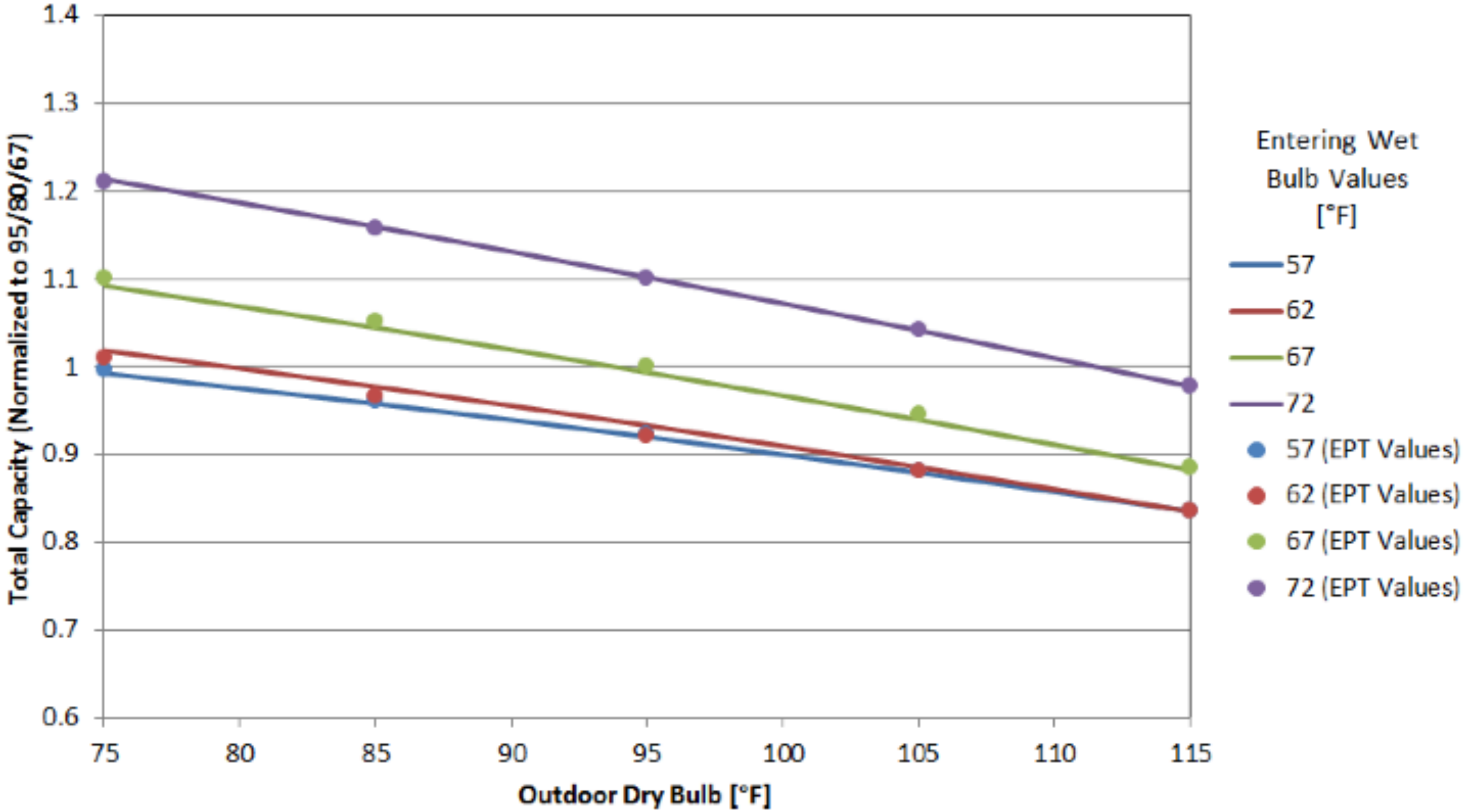
- Power draw while operating:
  - 3500 W = 3.5 kW

ΔT = 12 - 24 °C
ΔT = -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



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

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: (Btu/hr)/W
  - Example from previous page:

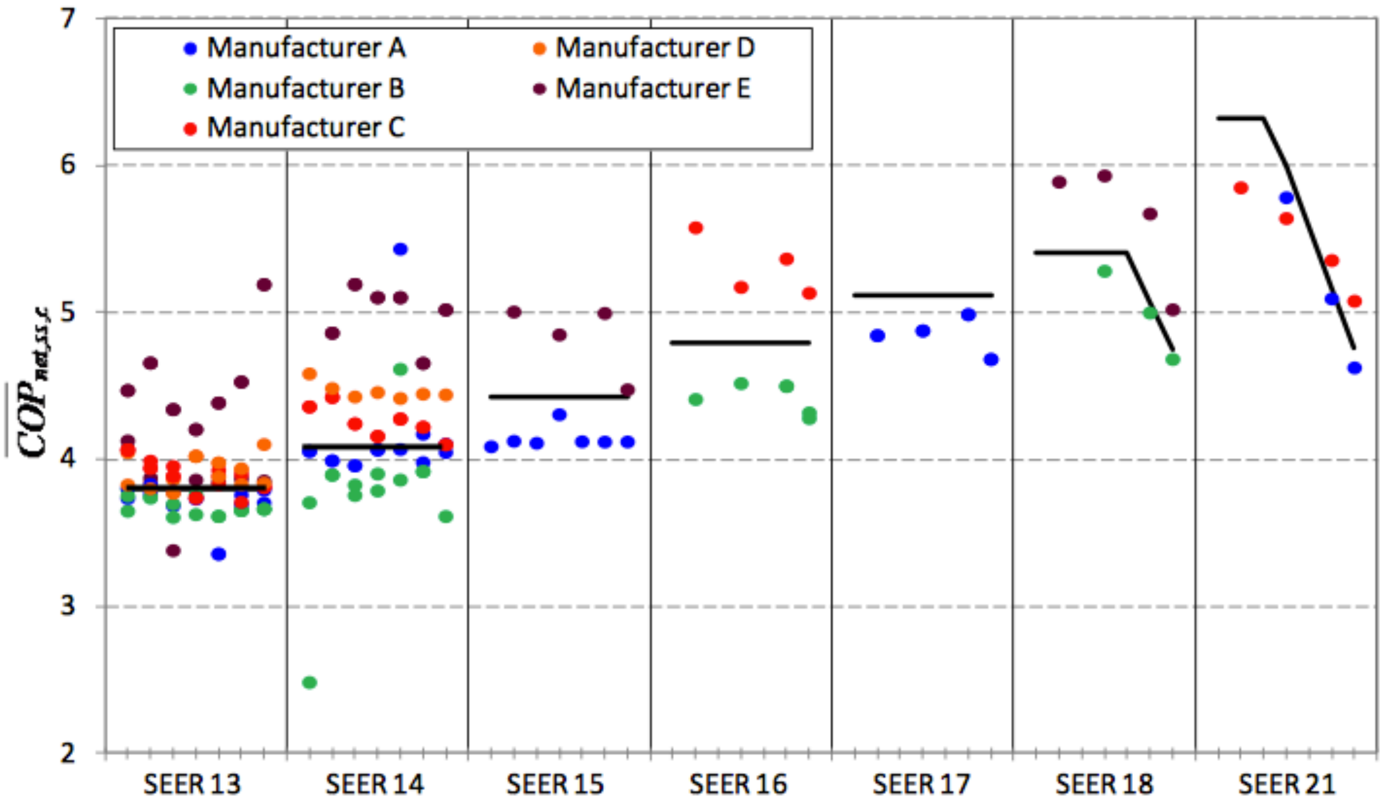
$$COP = \frac{8.5\ [\mathrm{kW}]}{2.48\ [\mathrm{kW}]} = 3.43 \qquad EER = \frac{29.0\ [\mathrm{kBtu/hr}]}{2.48\ [\mathrm{kW}]} = 11.7$$

$$EER = COP \times 3.41$$

- 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 EER to estimate energy consumption

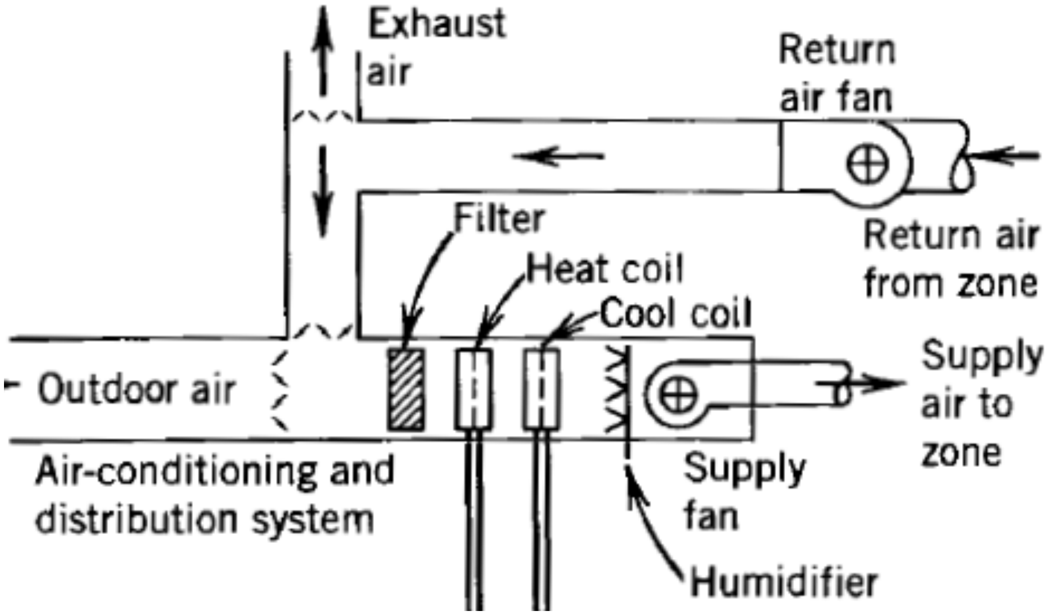
- If you know the load and you know the EER, you can estimate the instantaneous electric power draw required to meet the load:

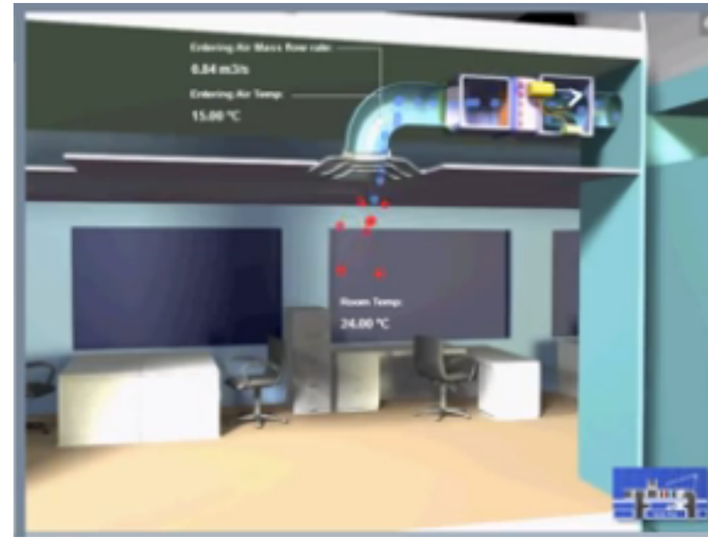
$$\mathrm{P}_{elec} = \frac{Q_{cooling,load}}{COP} \quad \text{[W or kW]}$$

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

$$E = \sum \mathrm{P}_{elec}\,\Delta t \quad \text{[Wh or kWh]}$$

- Can break into bins if COP/EER changes with varying conditions (which it typically does)





FLUID FLOWS AND FAN/PUMP POWER

For distribution systems

Fluid flows in buildings

- We use liquids and gases to deliver/extract 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

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

Static pressure | Velocity pressure | Pressure head | Friction losses

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

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

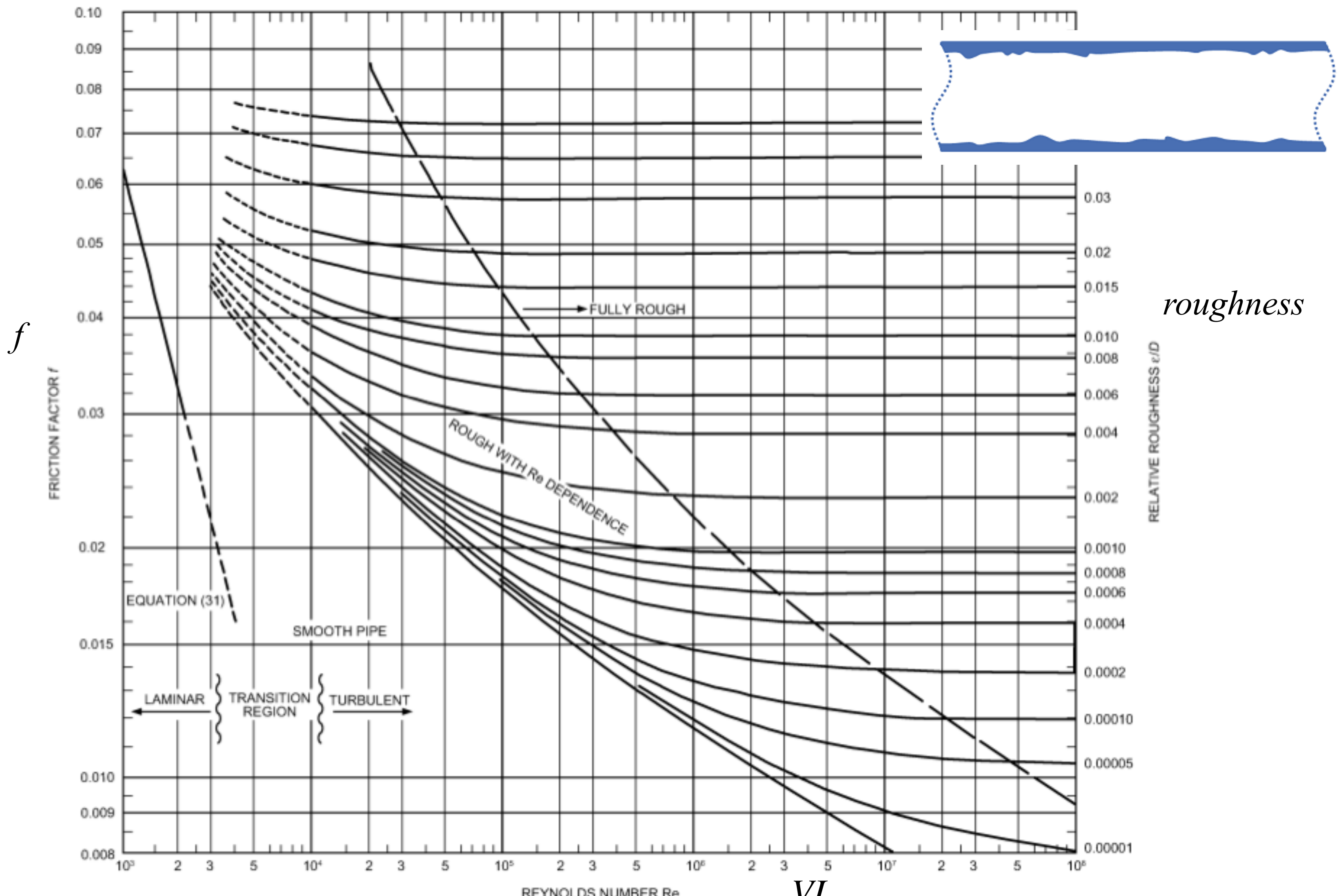
$$D_h = \frac{4A}{P} = \text{hydraulic diameter}$$

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

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

f = friction factor (-)
L = length (m)
D_h = hydraulic diameter (m)
ρ = fluid density (kg/m^3)
v = fluid velocity (m/s)

Friction factor



$$\mathrm{Re} = \frac{VL}{\nu} \qquad (L = D_h)$$

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

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

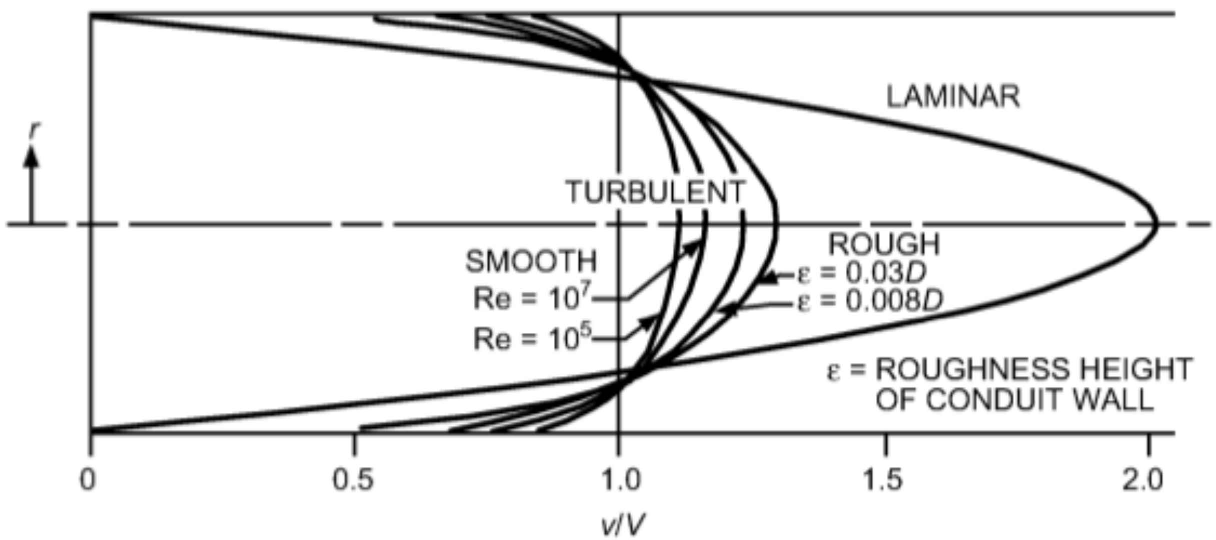
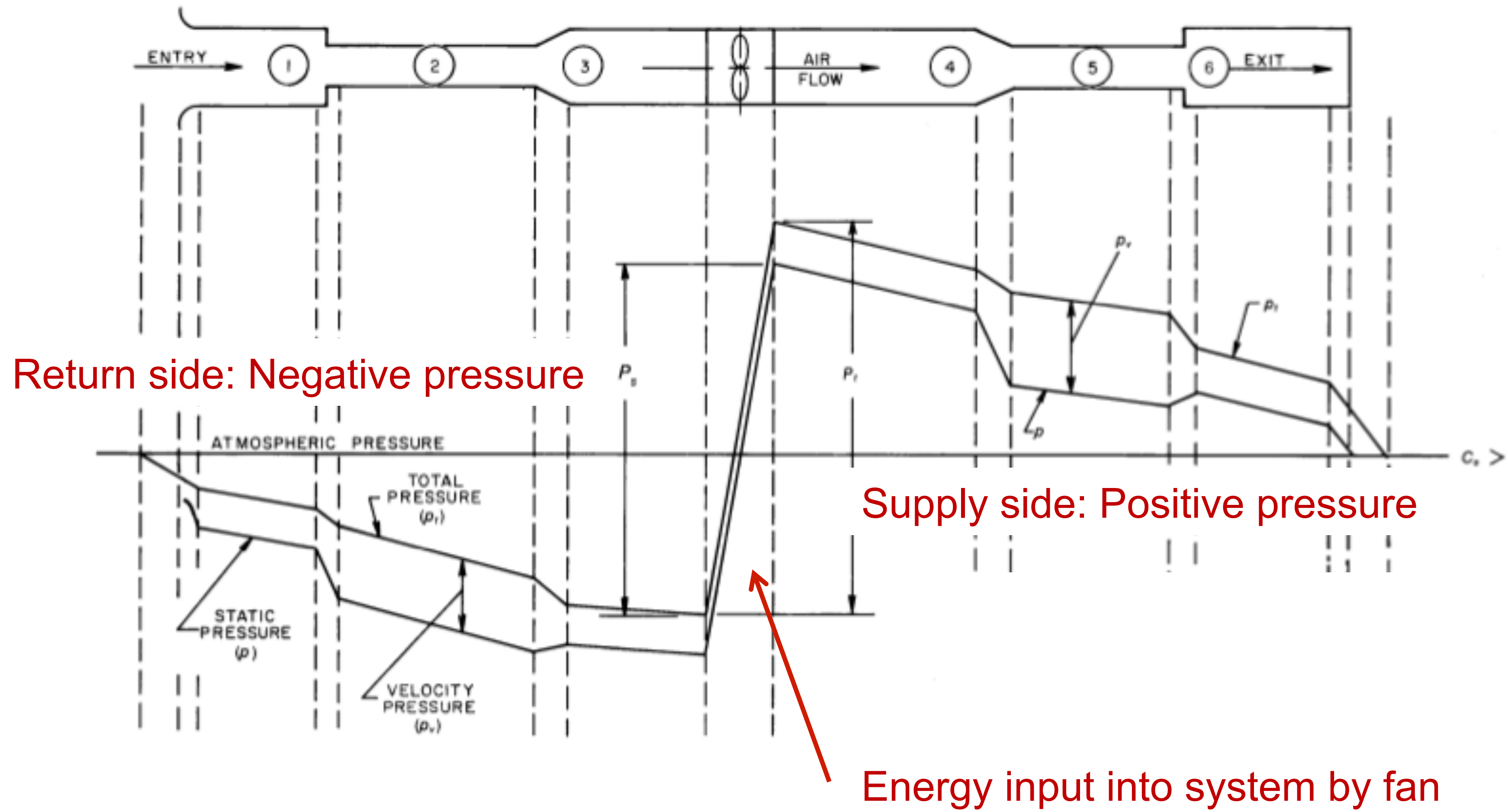
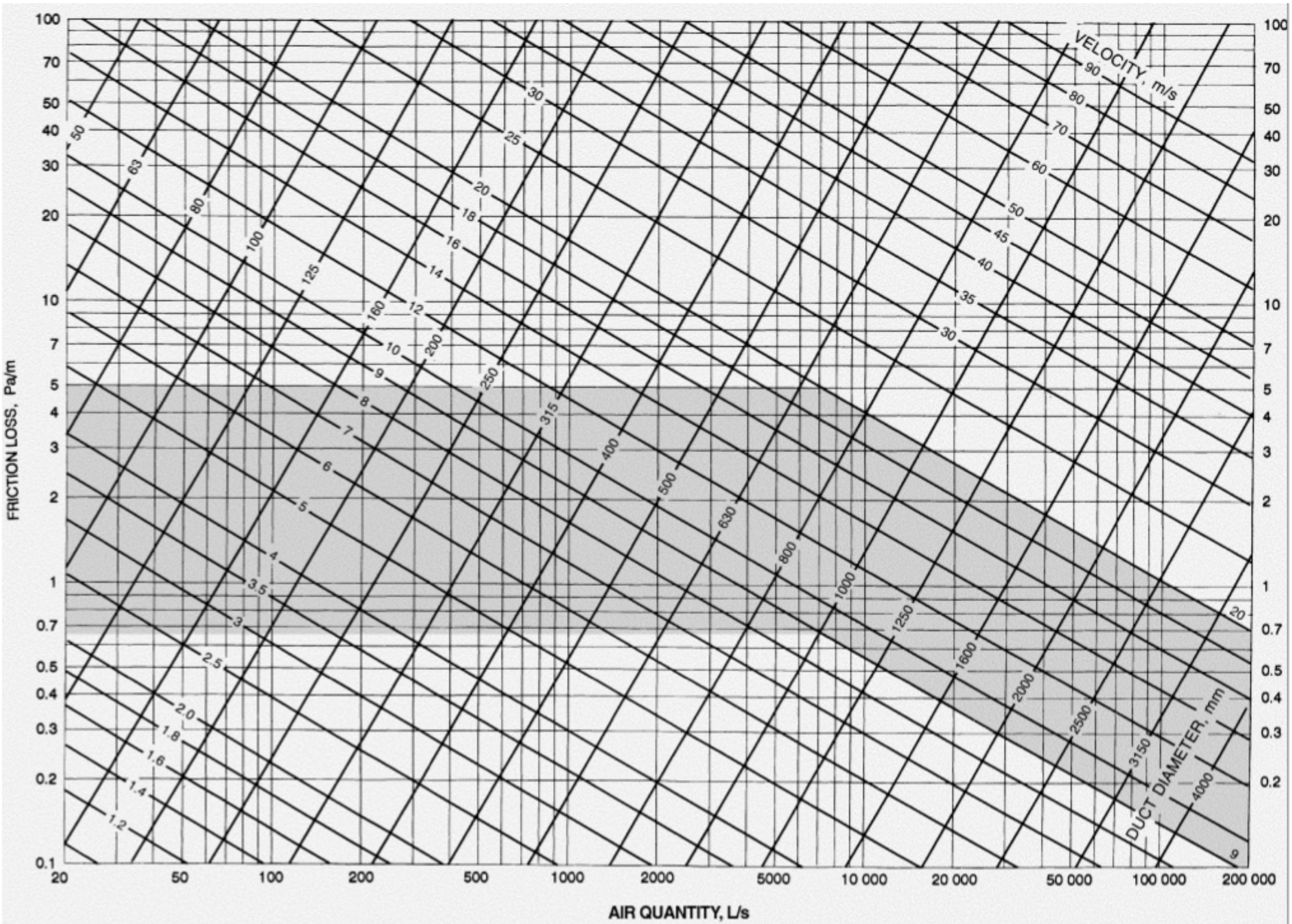


Fig. 4 Velocity Profiles of Flow in Pipes

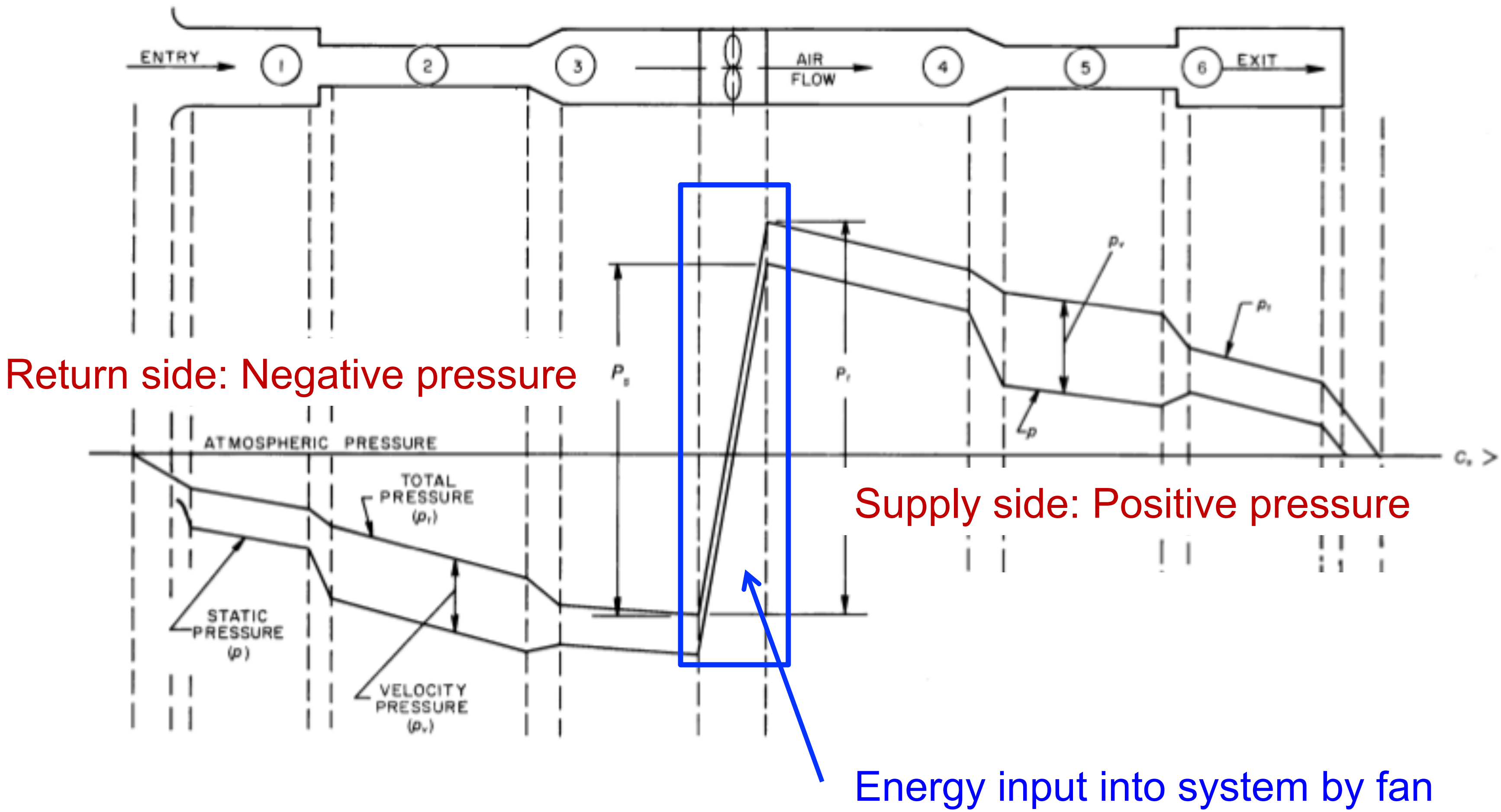
Pressure losses and rises in HVAC systems



Duct friction charts

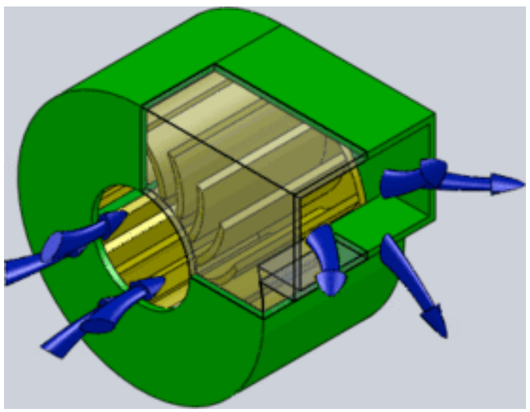


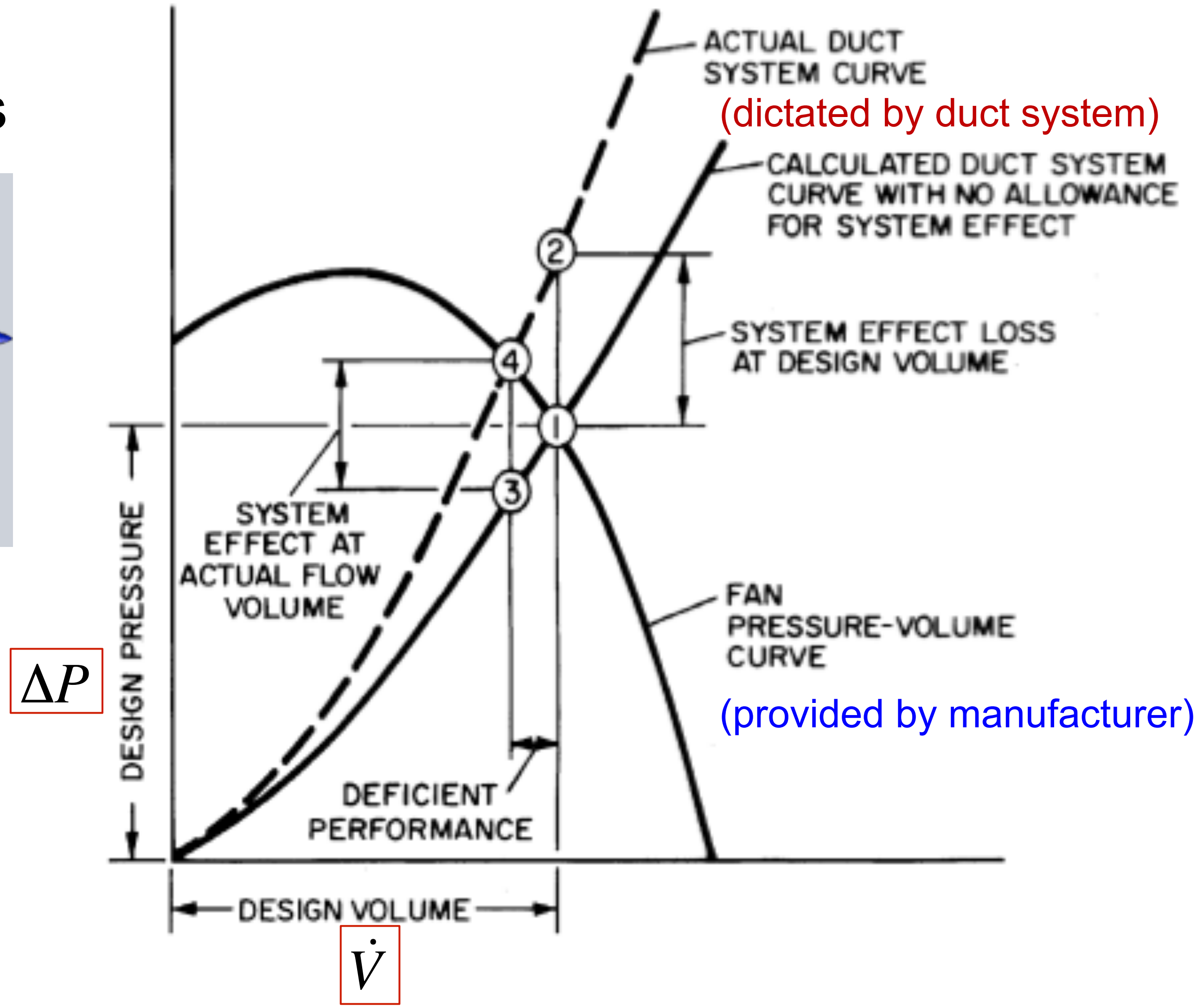
Pressure losses and rises in HVAC systems



Fan and system pressures

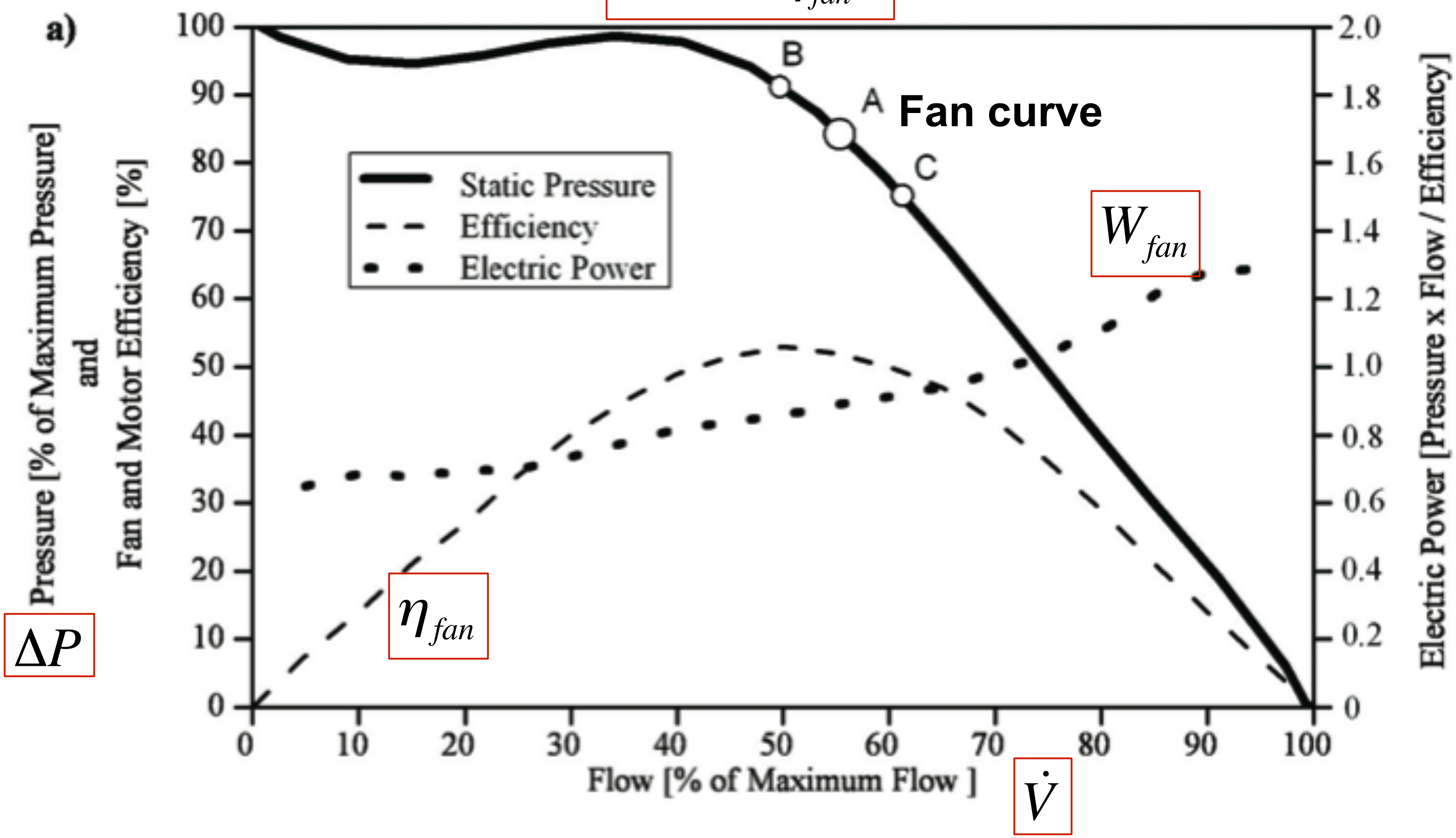
- Fan curves
- System curves



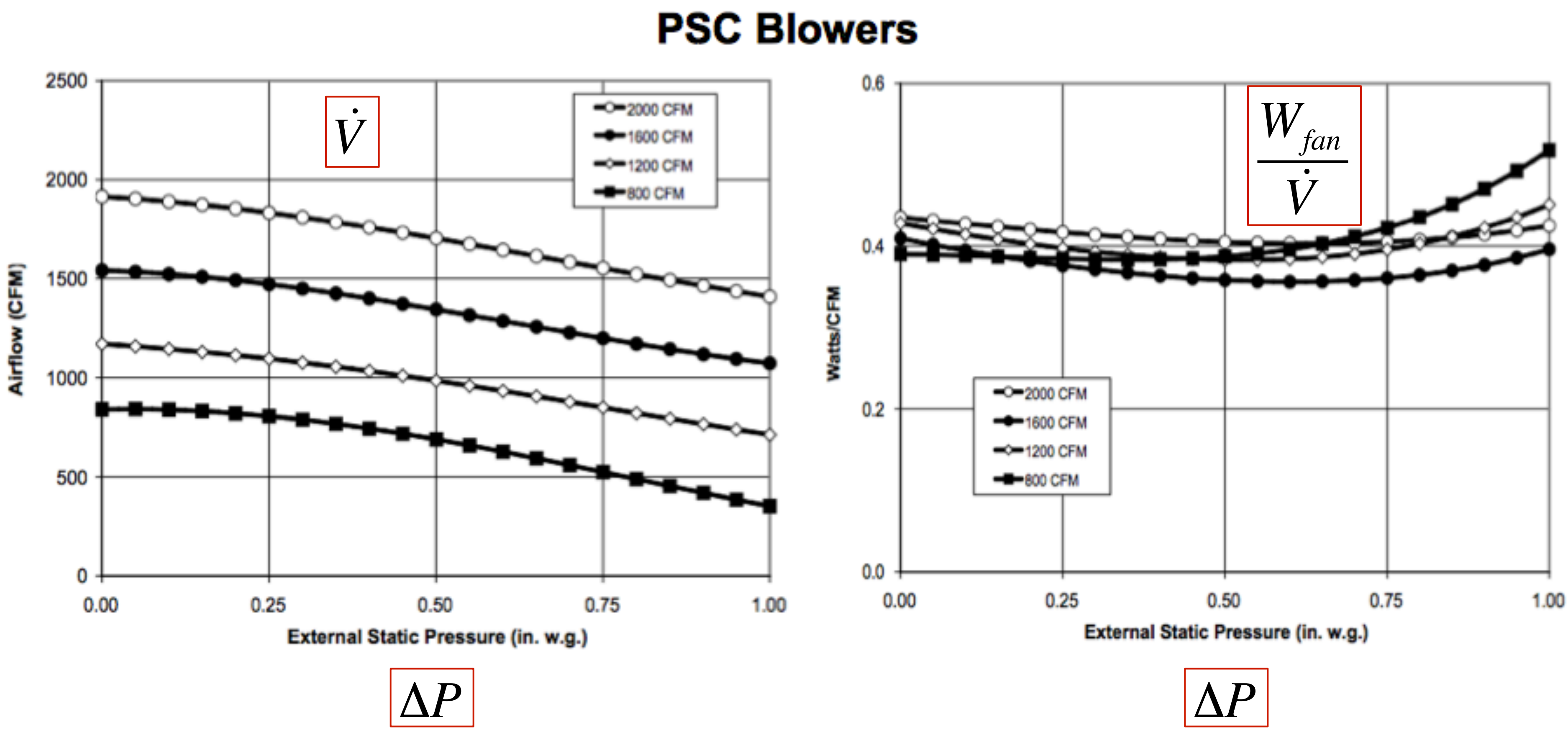


Fan and system curves: Ideal

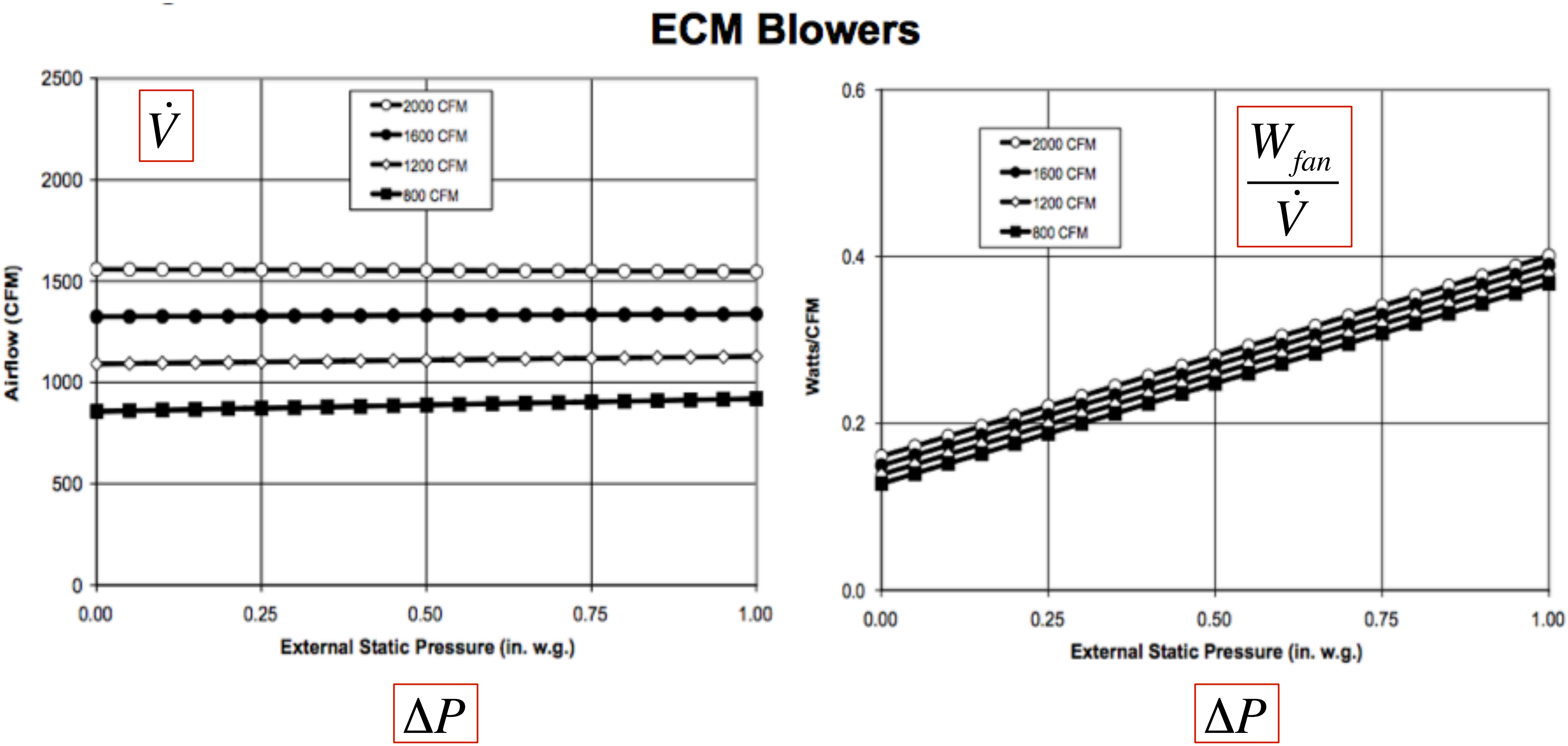
$$W_{fan} = \frac{\Delta P \cdot \dot{V}}{\eta_{fan}}$$



Real data: Residential furnace fan and efficiency curves



Real data: Residential furnace fan and efficiency curves

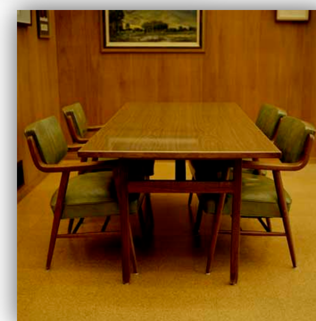


VENTILATION AND IAQ

Indoor air quality

- We spend most of our time indoors
  - Nearly 90% of the time, on average in the developed world
  - Approximately 18 hours indoors for every 1 hour outdoors
- We bring materials, furnishings, appliances, and activities into buildings, most of which emit/release a variety of substances
  - Some harmful, some not
- Buildings also exchange air without the outdoors
  - Outdoor air pollution can both dilute or become indoor air pollution
- Indoor air is a dominant environmental exposure
  - Most of the body's intake of air is done so inside buildings
  - 80-90% inhaled in buildings generally

Modern indoor environments



Types of indoor emission sources

- Building materials
  - Wood and composite wood
  - Gypsum wallboard
  - Concrete
  - Carpet
  - Vinyl flooring
- Furnishings
  - Bedding
  - Tables
  - Couches/chairs
  - Drapes
- Architectural coatings
  - Paints
  - Stains
  - Varnishes
- Consumer products
  - Cleaners
  - Fragrances
  - Personal care products
- Combustion
  - Cigarettes, cigars, pipes
  - Gas stoves
  - Space heaters
  - Candles
  - Incense
- Electronic equipment
  - Laser printers
  - Computers
  - Photocopiers
- Volatilization from water
- Soil vapor intrusion
- People, pets, insects

Some important classes of indoor pollutants

- Inorganic gases
  - CO, NO_2, O_3, NH_3, H_2S, SO_2, CO_2
- Organic gases
  - Volatile organic compounds (VOCs, hundreds of these)
  - Semi-volatile organic compounds (SVOCs) (partition/bind to solids)
  - Carbonyls
  - Acids
  - Radicals
- Particulate matter
  - Size, shape, mass, constituents (e.g., chemical species, metals)
- Radioactive gases and particles
- Microbiological
  - Bacteria, viruses, molds, mildew, fungi, dander, allergens

Units of measurement for air pollutants

- **Number concentrations** (# per volume of air, #/m^3)
  - # of molecules per m^3 (highly reactive species, e.g., OH radical)
  - # of particles per m^3 (particulate matter)
  - # of cells or colony forming units per m^3 (biological)
- **Mass concentrations** (mass per volume of air)
  - ng/m^3 typical for metals and for SVOCs
  - µg/m^3 typical for indoor VOCs and particulate matter
  - mg/m^3 big sources, e.g., ETS, cooking, industrial hygiene
- **Molar concentrations** (variations on $y_i = \mathrm{mol}_i/\mathrm{mol}_{air}$)
  - Mole fraction (y_i) = mol/mol
  - % concentration = moles per 100 moles = 100*y_i
  - Parts per million by **volume** (ppm$_v$) (or just ppm in this course)

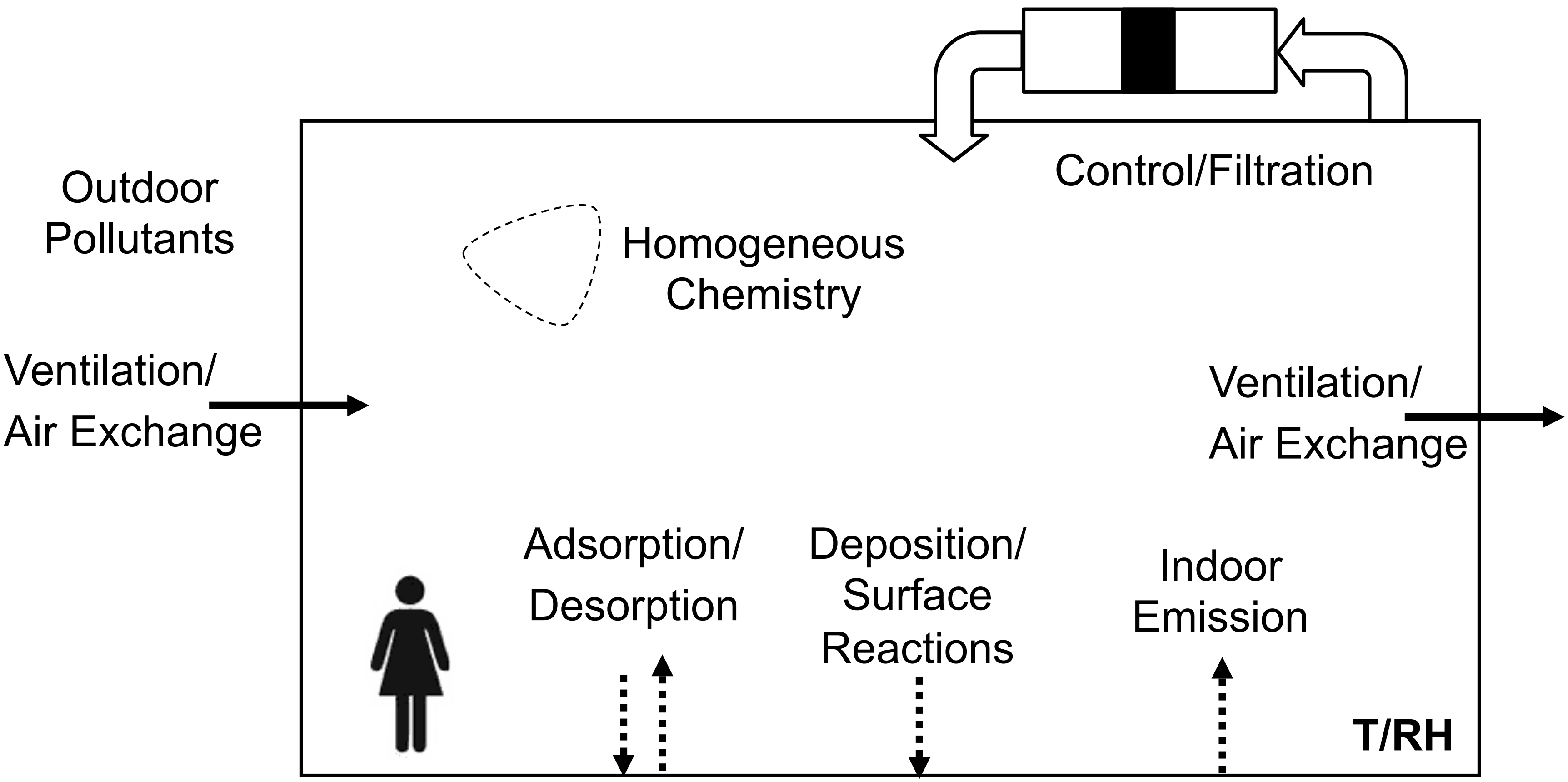
$$1\ \text{ppm} = \frac{1\ \text{mol of}\ i}{10^6\ \text{moles of air}} = 10^{-6}\ \frac{\text{moles of}\ i}{\text{moles of air}} = 10^{-6} * y_i$$

  - Parts per billion by **volume** (ppb$_v$) (or just ppb in this course)

$$1\ \text{ppb} = \frac{1\ \text{mol of}\ i}{10^9\ \text{moles of air}} = 10^{-9}\ \frac{\text{moles of}\ i}{\text{moles of air}} = 10^{-9} * y_i$$

Indoor environment: Mass balance

To understand the levels of airborne pollutants that we are exposed to, we need to understand the underlying physical, chemical, and biological mechanisms that drive pollutant emission, transport, and control



Indoor environment: Mass balance

- Simplest case (inert gas)
  - Neglecting indoor physics/chemistry
    - No deposition, no reaction

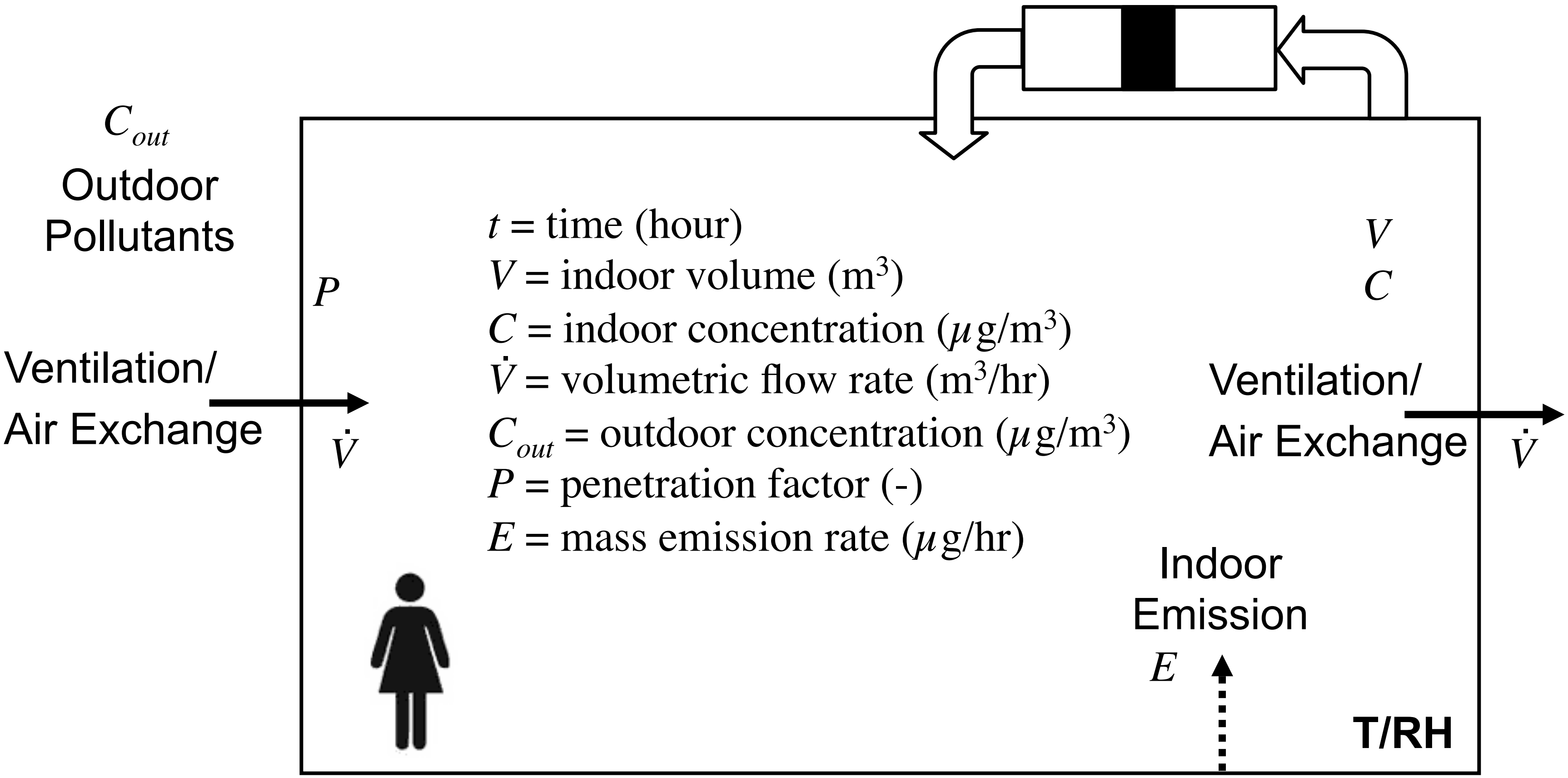
$$\begin{pmatrix}\text{Mass} \\ \text{accumulation} \\ \text{rate} \\ \text{[mass / time]}\end{pmatrix} = \begin{pmatrix}\text{Mass flow in} \\ \text{[mass / time]}\end{pmatrix} - \begin{pmatrix}\text{Mass flow out} \\ \text{[mass / time]}\end{pmatrix} + \begin{pmatrix}\text{Mass emitted} \\ \text{[mass / time]}\end{pmatrix}$$

$$\frac{dm}{dt} = \frac{dCV}{dt} = V\frac{dC}{dt} + C\cancelto{0}{\frac{dV}{dt}}$$

Assumptions:

- Building/room can be treated as well-mixed
- Ventilation/air exchange rate is constant
- Outdoor pollutant concentration is constant
- Indoor sources emit at a constant rate

Indoor environment: Mass balance



$$V\frac{dC}{dt} = P\dot{V}C_{out} - \dot{V}C + E$$

Indoor environment: Mass balance

$$V\frac{dC}{dt} = P\dot{V}C_{out} - \dot{V}C + E$$

- Divide by volume

$$\frac{dC}{dt} = P\frac{\dot{V}}{V}C_{out} - \frac{\dot{V}}{V}C + \frac{E}{V}$$

$$\boxed{\frac{dC}{dt} = P\lambda C_{out} - \lambda C + \frac{E}{V}}$$

$$\lambda = \frac{\dot{V}}{V} = \text{air exchange rate } (\frac{1}{\text{hr}})$$

Indoor environment: Mass balance

- Assume steady-state conditions:

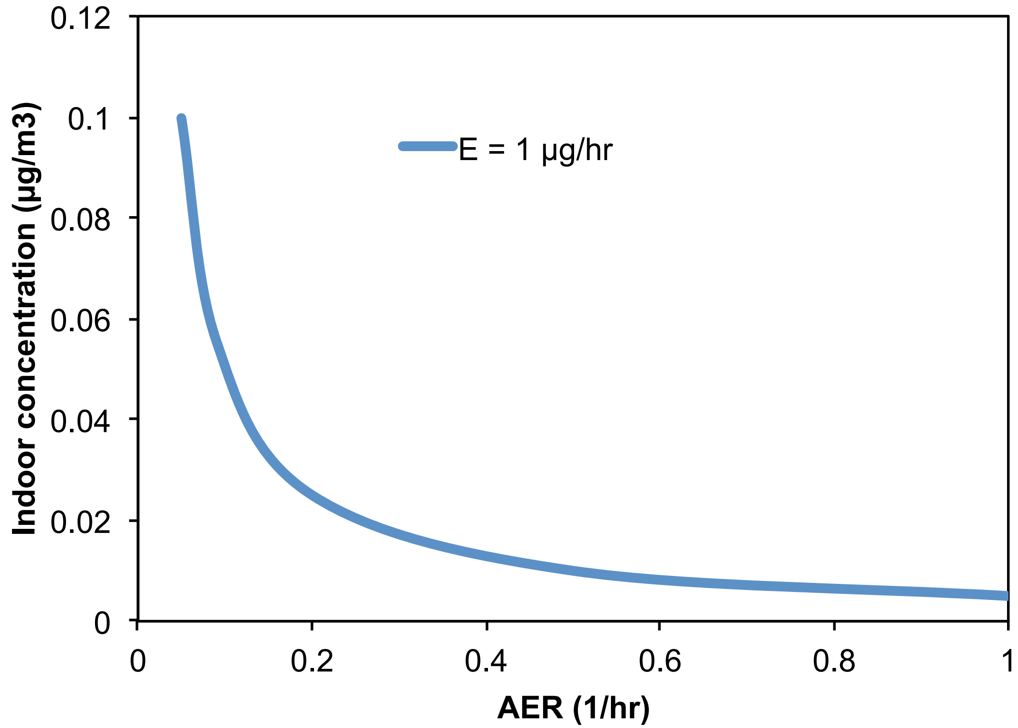
$$\underbrace{\cancel{\frac{dC}{dt}}}_{0} = P\lambda C_{out} - \lambda C + \frac{E}{V}$$

$$\boxed{C_{ss} = PC_{out} + \frac{E}{\lambda V}}$$

- If λ is large (and/or E is small): $PC_{out} >> E/\lambda V$
  - C approaches C_{out} (depending on P)
  - This means outdoor sources are relatively more important
- If λ is small (and/or E is large): $PC_{out} << E/\lambda V$
  - C approaches $E/\lambda V$
  - This means indoor sources are relatively more important

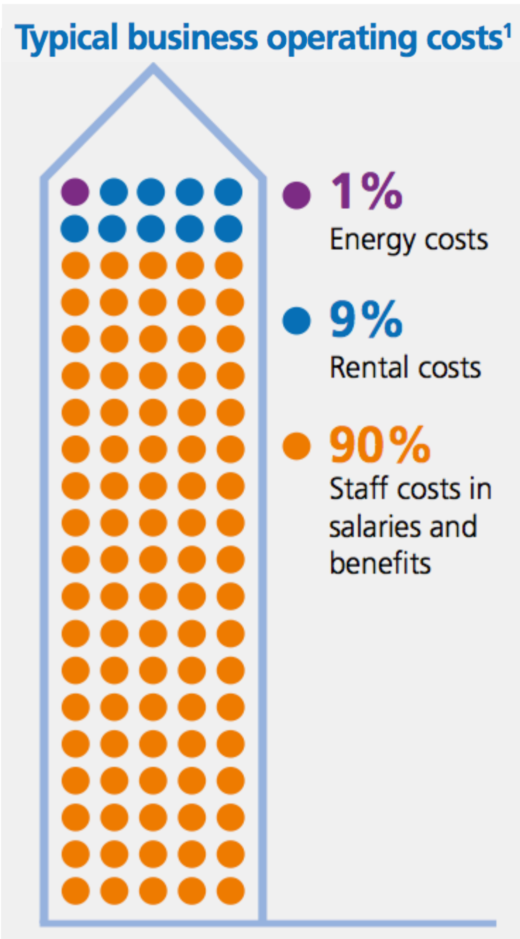
Steady state mass balance and air exchange

- Example steady state calculations: $$C_{ss} = PC_{out} + \frac{E}{\lambda V}$$
- Assume $C_{out} = 0$: $$C_{ss} = \frac{E}{\lambda V}$$
- Assume V = 200 m^3 and E = 1 μg/hr: how are C_{ss} and λ related?

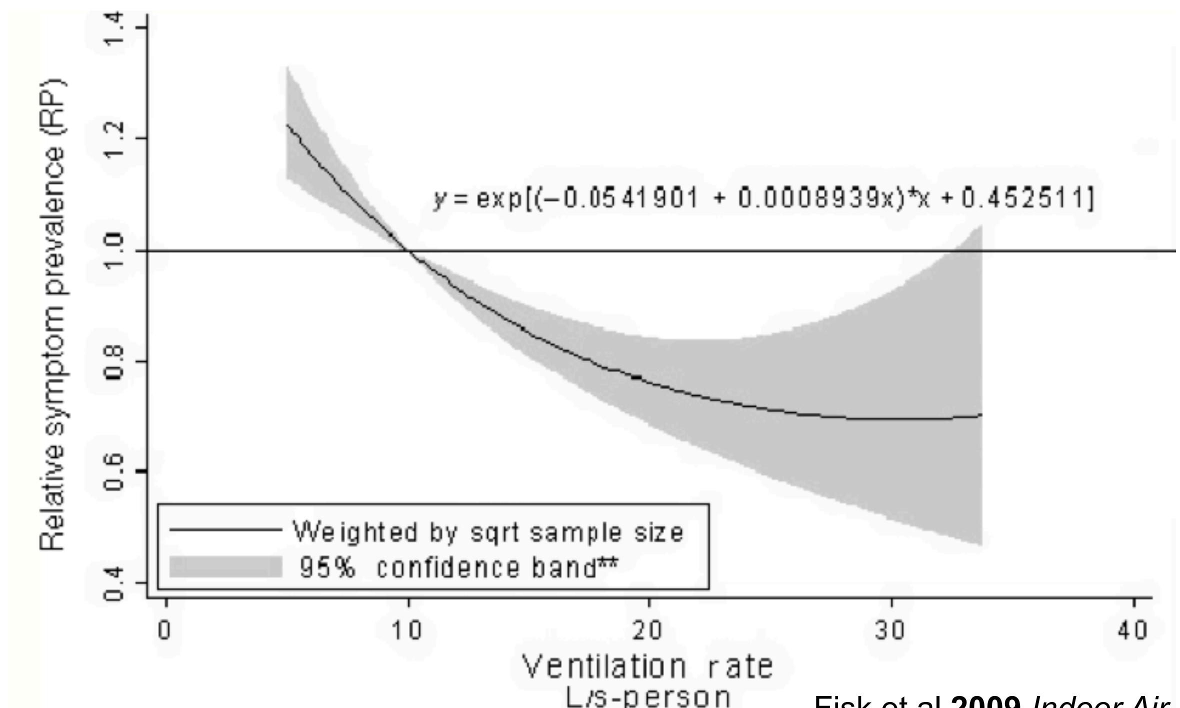


Importance of ventilation

- Outdoor air ventilation is used to dilute indoor-generated pollutants



Quantitative relationship of sick building syndrome symptoms with ventilation rates



Fisk et al **2009** *Indoor Air*

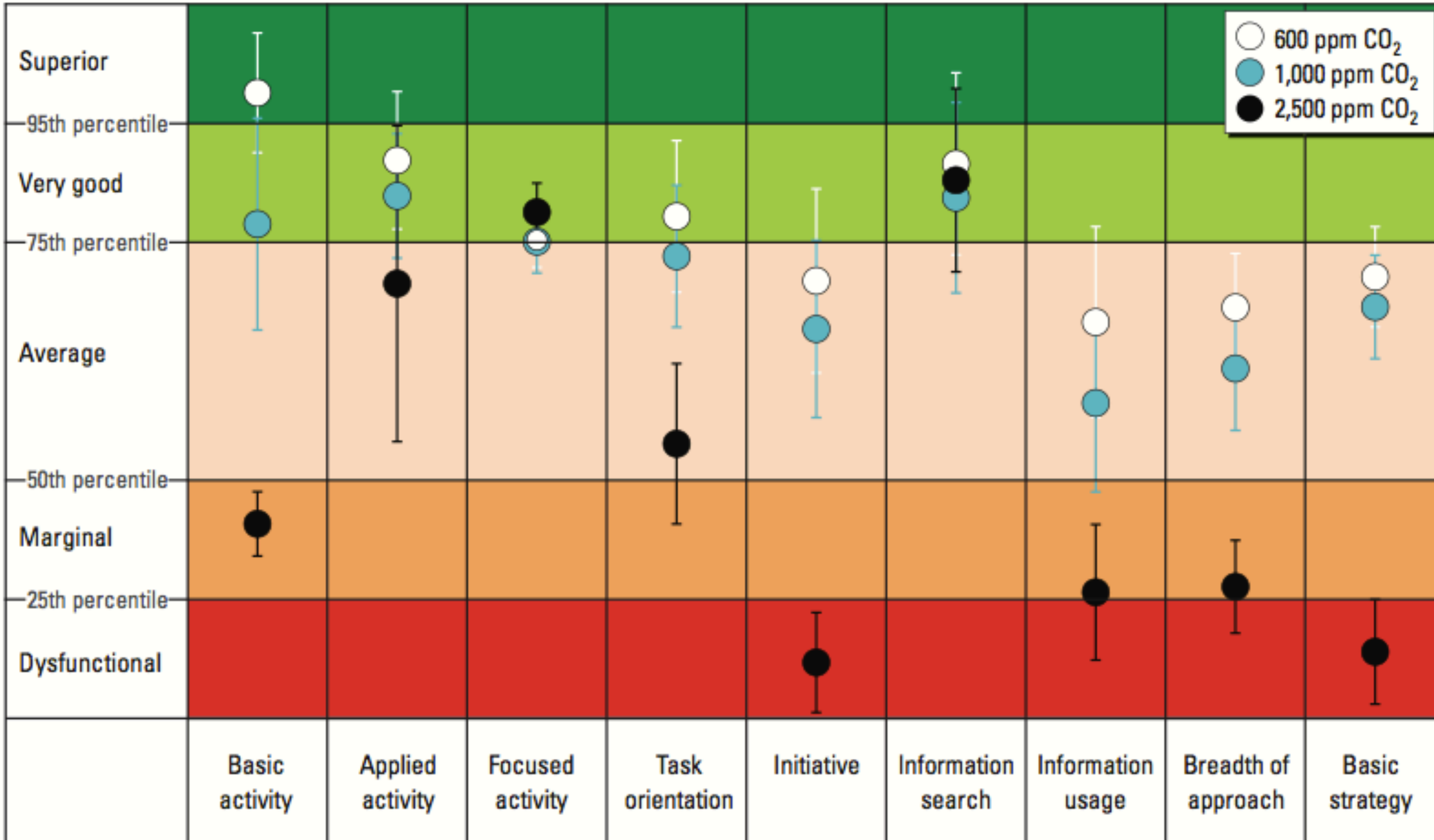
Ventilation and CO_2

- CO_2 is often used as a surrogate for IAQ
  - Imperfect, but instructive

- The average CO_2 production rate per person at an activity level of 1.2 met is 0.005 L/s
  - CO_2 concentrations will be elevated in poorly ventilated spaces

- Recent evidence also suggests that CO_2 might be a pollutant on its own
  - Affecting decision making

Ventilation and CO_2

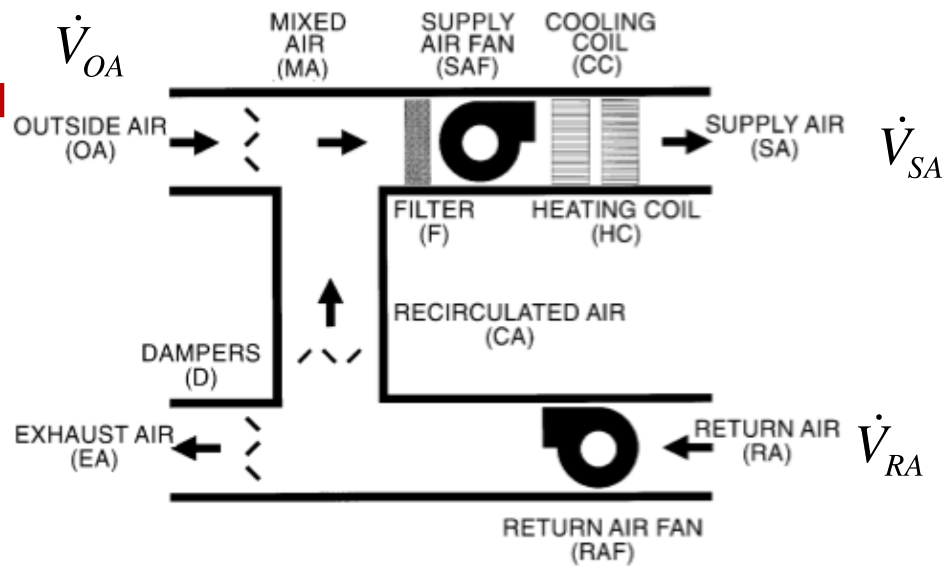


Satish et al **2012** *Environ Health Perspectives*

Mass balance example problem w/ CO_2

- What outdoor airflow rate is needed per occupant to keep the indoor CO_2 concentration below 1000 ppm?
  - Assume outdoors is 400 ppm
- In a 150 m^3 room with 30 people present, what would be the required air exchange rate?

532 CFM
required



$$F_{OA} = \frac{\dot{V}_{OA}}{\dot{V}_{SA}} = \frac{\dot{V}_{OA}}{\dot{V}_{OA} + \dot{V}_{CA}}$$

Ventilation and IAQ

- How do we determine the correct ventilation rate?

ASHRAE Standard 62.1-2010

ANSI/ASHRAE Standard 62.1-2010
(Supersedes ANSI/ASHRAE Standard 62.1-2007)
Includes ANSI/ASHRAE addenda listed in Appendix J

ASHRAE STANDARD

Ventilation for Acceptable Indoor Air Quality

1. PURPOSE

1.1 The purpose of this standard is to specify minimum ventilation rates and other measures intended to provide indoor air quality that is acceptable to human occupants and that minimizes adverse health effects.

1.2 This standard is intended for regulatory application to new buildings, additions to existing buildings, and those changes to existing buildings that are identified in the body of the standard.

1.3 This standard is intended to be used to guide the improvement of indoor air quality in existing buildings.

2. SCOPE

2.1 This standard applies to all spaces intended for human occupancy except those within single-family houses, multifamily structures of three stories or fewer above grade, vehicles, and aircraft.

2.2 This standard defines requirements for ventilation and air-cleaning system design, installation, commissioning, and operation and maintenance.

ASHRAE Standard 62.1-2010

Ventilation rate procedure

6.2.2.1 Breathing Zone Outdoor Airflow. The outdoor airflow required in the breathing zone of the occupiable space or spaces in a *ventilation zone*, i.e., the breathing zone outdoor airflow (V_{bz}), shall be no less than the value determined in accordance with Equation 6-1.

$$V_{bz} = R_p \cdot P_z + R_a \cdot A_z \tag{6-1}$$

where

A_z = zone floor area: the net occupiable floor area of the *ventilation zone* ft^2 (m^2)

P_z = zone population: the number of people in the *ventilation zone* during typical usage.

R_p = outdoor airflow rate required per person as determined from Table 6-1

Note: These values are based on adapted occupants.

R_a = outdoor airflow rate required per unit area as determined from Table 6-1

ASHRAE Standard 62.1-2010: VRP

TABLE 6-1 MINIMUM VENTILATION RATES IN BREATHING ZONE
(This table is not valid in isolation; it must be used in conjunction with the accompanying notes.)

Occupancy Category	People Outdoor Air Rate R_p		Area Outdoor Air Rate R_a		Notes	Default Values: Occupant Density (see Note 4)	Default Values: Combined Outdoor Air Rate (see Note 5)		Air Class
	cfm/person	L/s·person	cfm/ft²	L/s·m²		#/1000 ft² or #/100 m²	cfm/person	L/s·person	
Correctional Facilities									
Cell	5	2.5	0.12	0.6		25	10	4.9	2
Dayroom	5	2.5	0.06	0.3		30	7	3.5	1
Guard stations	5	2.5	0.06	0.3		15	9	4.5	1
Booking/waiting	7.5	3.8	0.06	0.3		50	9	4.4	2
Educational Facilities									
Daycare (through age 4)	10	5	0.18	0.9		25	17	8.6	2
Daycare sickroom	10	5	0.18	0.9		25	17	8.6	3
Classrooms (ages 5–8)	10	5	0.12	0.6		25	15	7.4	1
Classrooms (age 9 plus)	10	5	0.12	0.6		35	13	6.7	1
Lecture classroom	7.5	3.8	0.06	0.3		65	8	4.3	1
Lecture hall (fixed seats)	7.5	3.8	0.06	0.3		150	8	4.0	1
Art classroom	10	5	0.18	0.9		20	19	9.5	2
Science laboratories	10	5	0.18	0.9		25	17	8.6	2
University/college laboratories	10	5	0.18	0.9		25	17	8.6	2
Wood/metal shop	10	5	0.18	0.9		20	19	9.5	2
Computer lab	10	5	0.12	0.6		25	15	7.4	1

ASHRAE Standard 62.1-2010: VRP

TABLE 6-1 MINIMUM VENTILATION RATES IN BREATHING ZONE *(Continued)*
(This table is not valid in isolation; it must be used in conjunction with the accompanying notes.)

Occupancy Category	People Outdoor Air Rate R_p		Area Outdoor Air Rate R_a		Notes	Default Values: Occupant Density (see Note 4)	Default Values: Combined Outdoor Air Rate (see Note 5)		Air Class
	cfm/person	L/s·person	cfm/ft^2	L/s·m^2		#/1000 ft^2 or #/100 m^2	cfm/person	L/s·person	
Office Buildings									
Breakrooms	5	2.5	0.12	0.6		50	7	3.5	1
Main entry lobbies	5	2.5	0.06	0.3		10	11	5.5	1
Occupiable storage rooms for dry materials	5	2.5	0.06	0.3		2	35	17.5	1
Office space	5	2.5	0.06	0.3		5	17	8.5	1
Reception areas	5	2.5	0.06	0.3		30	7	3.5	1
Telephone/data entry	5	2.5	0.06	0.3		60	6	3.0	1
Miscellaneous Spaces									
Bank vaults/safe deposit	5	2.5	0.06	0.3		5	17	8.5	2
Banks or bank lobbies	7.5	3.8	0.06	0.3		15	12	6.0	1
Computer (not printing)	5	2.5	0.06	0.3		4	20	10.0	1
General manufacturing (excludes heavy industrial and processes using chemicals)	10	5.0	0.18	0.9		7	36	18	3

ASHRAE Standard 62.1-2010

TABLE 6-4 Minimum Exhaust Rates

Occupancy Category	Exhaust Rate, cfm/unit	Exhaust Rate, cfm/ft^2	Notes	Exhaust Rate, L/s·unit	Exhaust Rate, $L/s \cdot m^2$	Air Class
Arenas	–	0.50	B	–	–	1
Art classrooms	–	0.70		–	3.5	2
Auto repair rooms	–	1.50	A	–	7.5	2
Barber shops	–	0.50		–	2.5	2
Beauty and nail salons	–	0.60		–	3.0	2
Cells with toilet	–	1.00		–	5.0	2
Copy, printing rooms	–	0.50		–	2.5	2
Darkrooms	–	1.00		–	5.0	2
Educational science laboratories	–	1.00		–	5.0	2
Janitor closets, trash rooms, recycling	–	1.00		–	5.0	3
Kitchenettes	–	0.30		–	1.5	2
Kitchens—commercial	–	0.70		–	3.5	2
Locker/dressing rooms	–	0.25		–	1.25	2
Locker rooms	–	0.50		–	2.5	2
Paint spray booths	–	–	F	–	–	4
Parking garages	–	0.75	C	–	3.7	2
Pet shops (animal areas)	–	0.90		–	4.5	2
Refrigerating machinery rooms	–	–	F	–	–	3
Residential kitchens	50/100	–	G	25/50	–	2
Soiled laundry storage rooms	–	1.00	F	–	5.0	3
Storage rooms, chemical	–	1.50	F	–	7.5	4

ASHRAE Standard 62.2-2010 (actually showing 2007)

ANSI/ASHRAE Standard 62.2-2007
(Supersedes ANSI/ASHRAE Standard 62.2-2004)
Includes ANSI/ASHRAE addenda listed in Appendix C

ASHRAE STANDARD

Ventilation and Acceptable Indoor Air Quality in Low-Rise Residential Buildings

1. PURPOSE

This standard defines the roles of and minimum requirements for mechanical and natural ventilation systems and the building envelope intended to provide acceptable indoor air quality (IAQ) in low-rise residential buildings.

2. SCOPE

This standard applies to spaces intended for human occupancy within single-family houses and multifamily structures of three stories or fewer above grade, including manufactured and modular houses. This standard does not apply to transient housing such as hotels, motels, nursing homes, dormitories, or jails.

2.1 This standard considers chemical, physical, and biological contaminants that can affect air quality. Thermal comfort requirements are not included in this standard (see *ANSI/ASHRAE Standard 55-2004*, *Thermal Environmental Conditions for Human Occupancy*).

2.2 While acceptable indoor air quality is the goal of this standard, it will not necessarily be achieved even if all requirements are met

ASHRAE Standard 62.2-2010

4. WHOLE-BUILDING VENTILATION

4.1 Ventilation Rate. A mechanical exhaust system, supply system, or combination thereof shall be installed for each dwelling unit to provide whole-building ventilation with outdoor air each hour at no less than the rate specified in Tables 4.1a and 4.1b or, equivalently, Equations 4.1a and 4.1b, based on the floor area of the conditioned space and number of bedrooms.

$$Q_{fan} = 0.01A_{floor} + 7.5(N_{br} + 1) \quad (4.1a)$$

where

Q_{fan} = fan flow rate, cfm
A_{floor} = floor area, ft^2
N_{br} = number of bedrooms; not to be less than one

$$Q_{fan} = 0.05A_{floor} + 3.5(N_{br} + 1) \quad (4.1b)$$

where

Q_{fan} = fan flow rate, L/s
A_{floor} = floor area, m^2
N_{br} = number of bedrooms; not to be less than one

TABLE 4.1a (I-P)
Ventilation Air Requirements, cfm

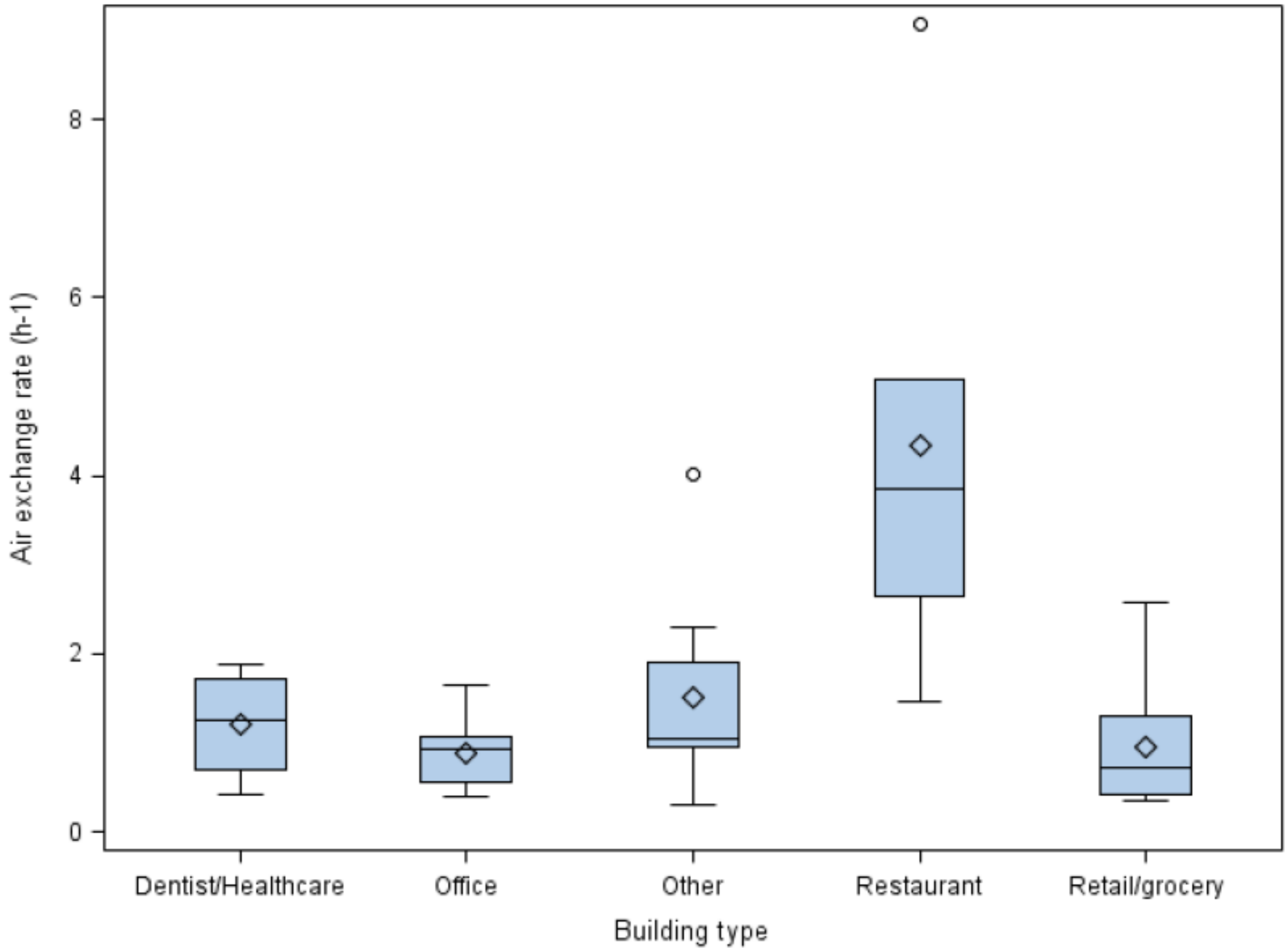
Floor Area (ft^2)	Bedrooms 0–1	2–3	4–5	6–7	>7
<1500	30	45	60	75	90
1501–3000	45	60	75	90	105
3001–4500	60	75	90	105	120
4501–6000	75	90	105	120	135
6001–7500	90	105	120	135	150
>7500	105	120	135	150	165

TABLE 4.1b (SI)
Ventilation Air Requirements, L/s

Floor Area (m^2)	Bedrooms 0–1	2–3	4–5	6–7	>7
<139	14	21	28	35	42
139.1–279	21	28	35	42	50
279.1–418	28	35	42	50	57
418.1–557	35	42	50	57	64
557.1–697	42	50	57	64	71
>697	50	57	64	71	78

Measured air exchange rates: Commercial buildings

- Recent study of ~40 commercial buildings in CA



Bennett et al. **2011** CEC Report

VENTILATION AND INFILTRATION

Air exchange: Ventilation and infiltration

Air exchange of outdoor air with air already in a building can be divided into two broad classifications:

Ventilation

Intentional introduction of outdoor air into a building

Subdivided into:

- *Mechanical (forced) ventilation:* The intentional movement of air into and out of a building using fans, intake vents, and exhaust vents
- *Natural ventilation:* The flow of air through open windows, doors, grilles, and other planned envelope penetrations, driven largely by natural or artificially induced pressure differences

Infiltration

Flow of outdoor air into a building through cracks, leaks, and other unintentional openings in the envelope (includes normal use of exterior doors) … i.e., *leakage*

Dealing with ventilation vs. infiltration

- Mechanical ventilation is straightforward
  - Fans move air through known openings
  - Flow rates typically known or at least measurable
- Natural ventilation is conceptually straightforward but physically complex
  - Known openings but highly varying wind speeds and directions
- Infiltration is complex
  - Typically unknown openings and multiple driving forces
- Need to know airflows through each of these in order to quantify IAQ and energy impacts

General models for air flows through leaks

- Given an opening:

$$\dot{V} = AC\Delta P^{n}$$

A = area of opening, ft^2 (m^2)
ΔP = pressure difference between inside and outside, in WG (Pa)
C = flow coefficient, ft/(min inWG^n) [m/(s Pa^n)]
n = exponent, between 0.4 and 1.0 (usually 0.65 for buildings)

- For a combination of i openings:

$$\dot{V} = \sum_{i} A_i C_i \Delta P_i^{n_i}$$

Driving forces of ventilation and infiltration: Δ*P*

- Three primary mechanisms generate pressure differences (driving forces)
  - Stack effect (natural buoyancy)
    - Caused by the weight of a column of air located inside/outside a building
    - Depends on air density and height above a neutral reference level
      - Density is also a function of temperature
  - Wind
    - Caused by wind impinging on a building, creating a distribution of pressures on the exterior surface
    - Depends on wind direction, wind speed, air density, surface orientation, and surrounding conditions
  - Mechanical air handling equipment (fans)
    - Fans are used to supply, recirculate, exhaust, and otherwise balance pressures and flows in buildings

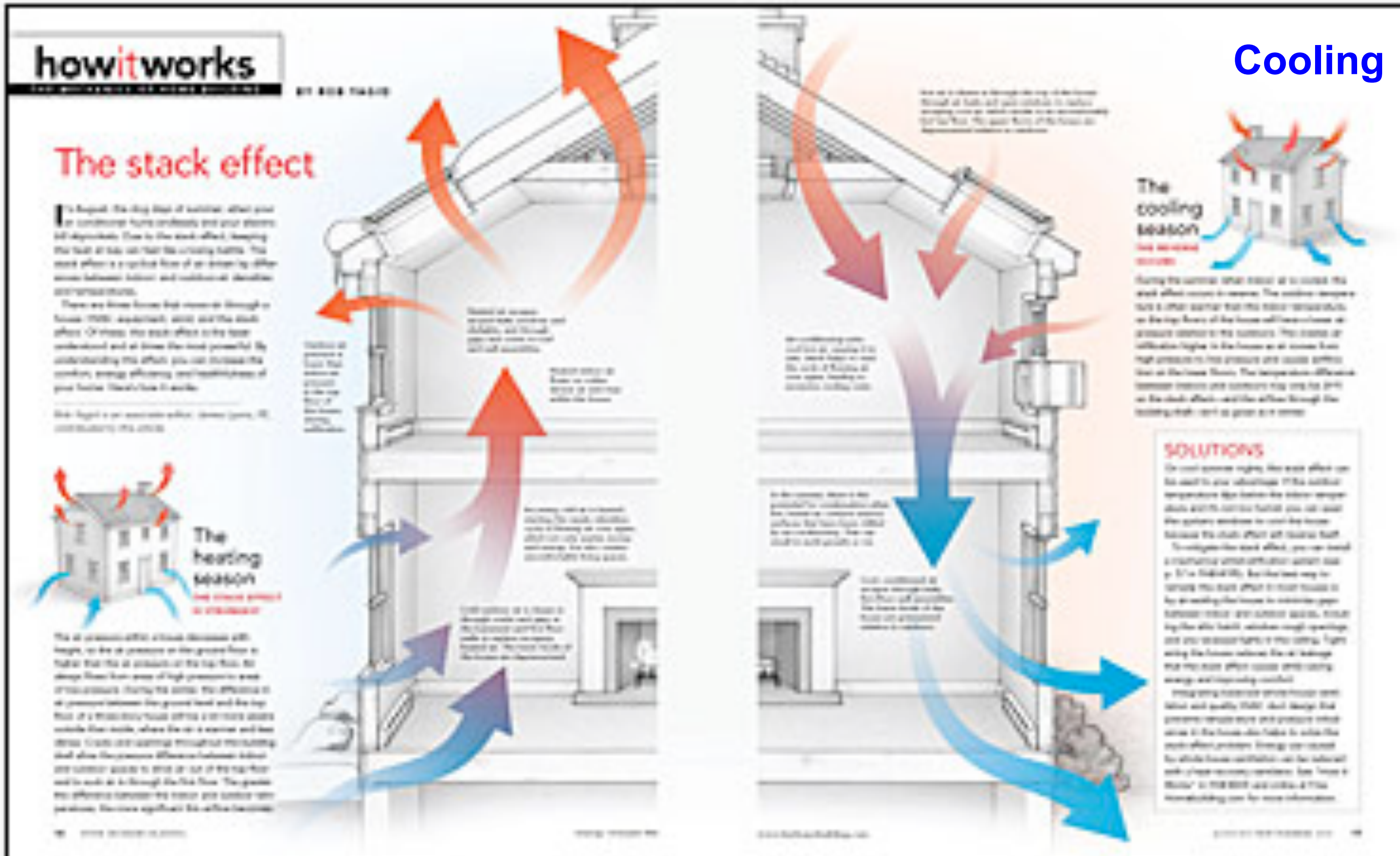
$$\Delta P = \Delta P_{wind} + \Delta P_{stack} + \Delta P_{vent}$$ (+ when causing flow to interior)

Stack effect

- **In wintertime**
  - Air within a building acts like a bubble of hot air in a sea of cold air
  - Rises to the top
  - Draws **outdoor air in from** cracks/gaps/openings in the **bottom**
  - Indoor air out through top
- **In summertime**
  - Air within a building acts like a bubble of cold air in a sea of hot air
  - Falls to the bottom
  - Drives **indoor air out through** cracks/gaps/openings in **bottom**
  - Outdoor air in through top
    - Temperature differences usually lower in the summer time so the amount of flow is smaller

$$\Delta P_{stack} = \rho_{in} C_d \left(\frac{T_{out} - T_{in}}{T_{in}} \right) g \left(H_{NPL} - H \right)$$

Stack effect: winter vs. summer



Cooling

Heating

Wind pressures

- From velocity component of Bernoulli Equation:

$$P_{velocity} = \frac{1}{2}\rho_{air}U_h^2$$

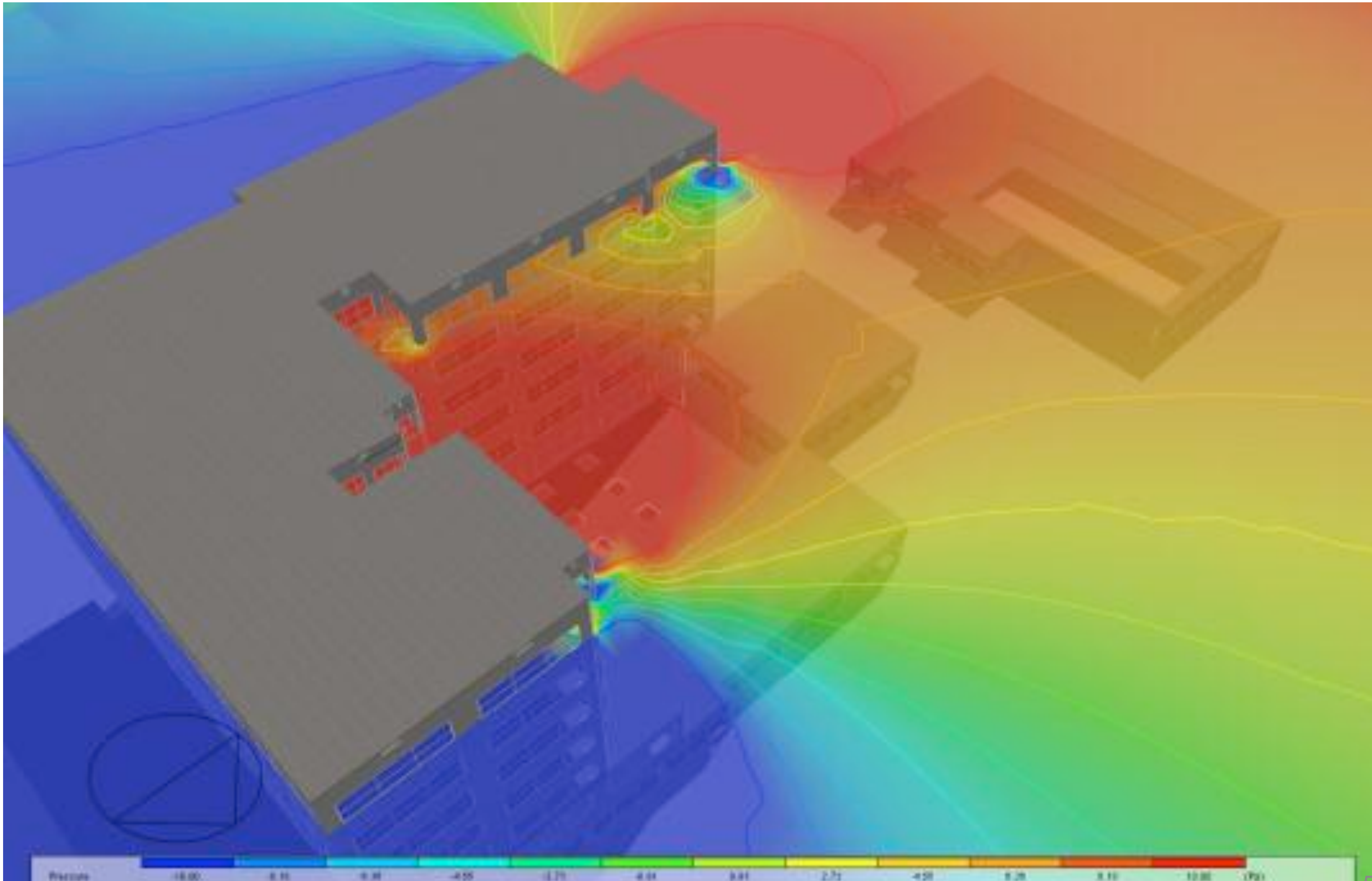
$P_{velocity}$ = wind velocity pressure; U_h = air velocity at building height, h; ρ_{air} = air density

- To convert velocity pressure to the difference between surface pressure and local atmospheric pressure:
  - Multiply by local wind pressure coefficient, C_p

$$P_{surface} = \Delta P = C_p P_{velocity} = \frac{1}{2} C_P \rho U_h^2$$

  - Get C_P (+ or -) from measurements or from *ASHRAE Handbook of Fundamentals 2013* Chapter 24 “Airflow around buildings”

Wind pressure coefficients (C_p) vary around buildings

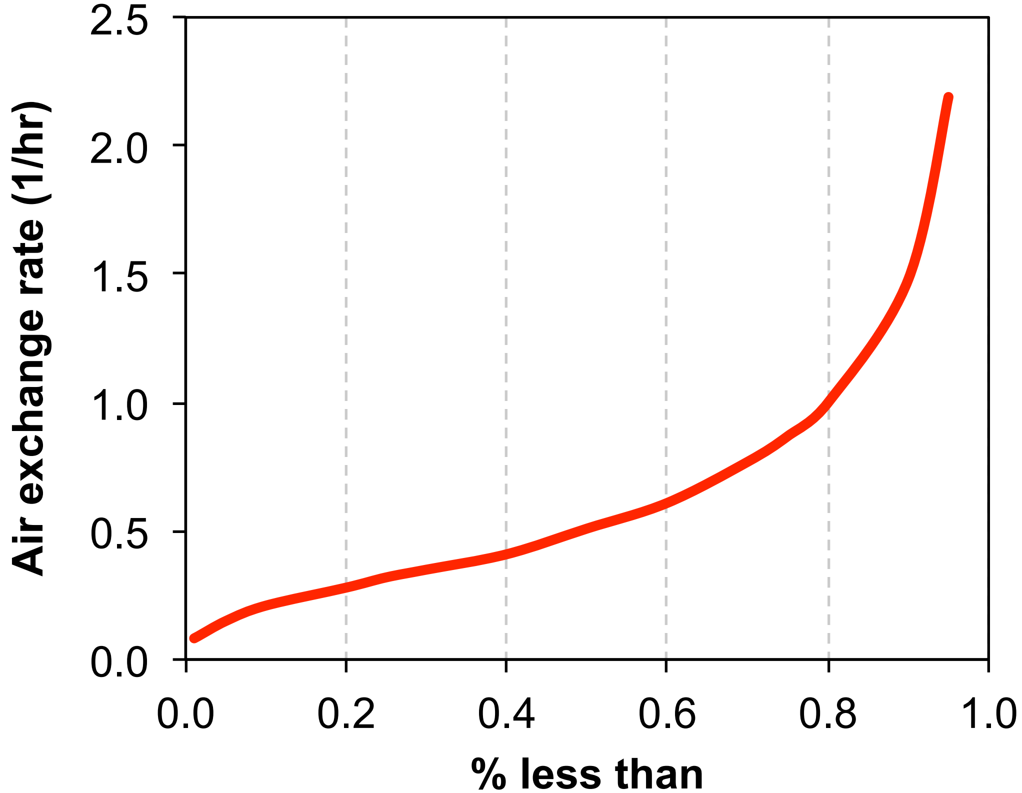


Typical air leakage sites in buildings

REAL DATA ON VENTILATION RATES IN BUILDINGS

What are typical values of λ (AER)?

- Distribution of AERs in ~2800 homes in the U.S.
  - Measured using PFT (perfluorocarbon tracer) in the early 1990s
  - Nearly all infiltration

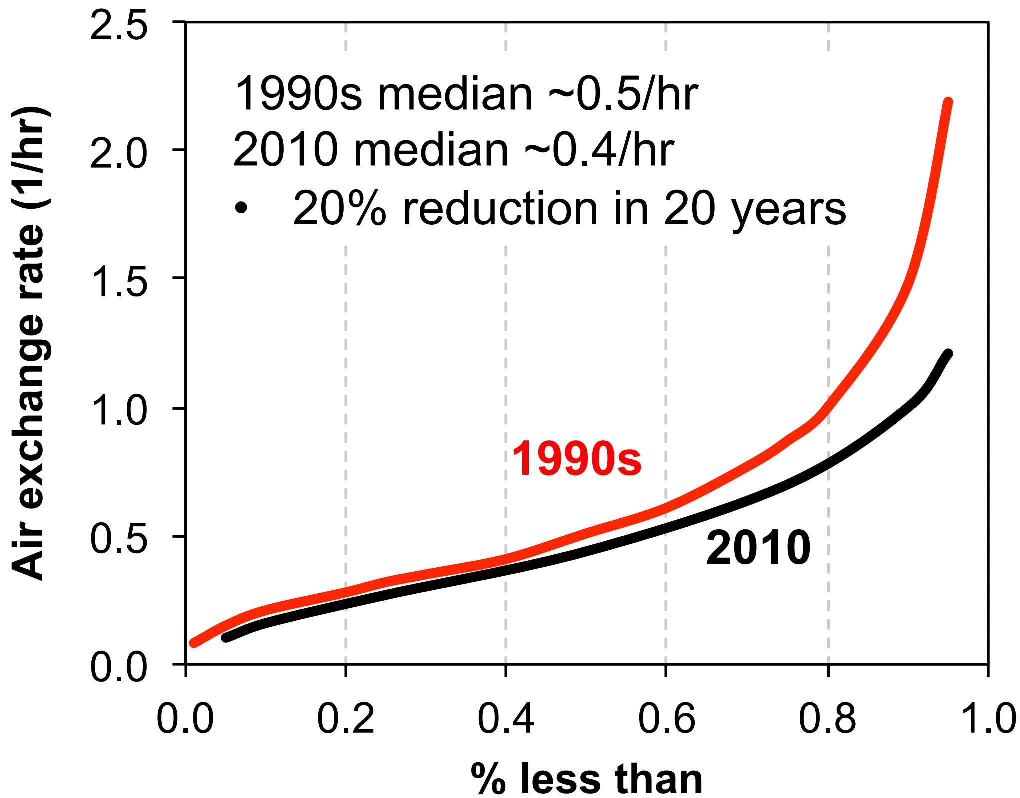


- What do you think this curve looks like now?

Murray and Burmaster, 1995 *Risk Analysis*

What are typical values of λ (AER)?

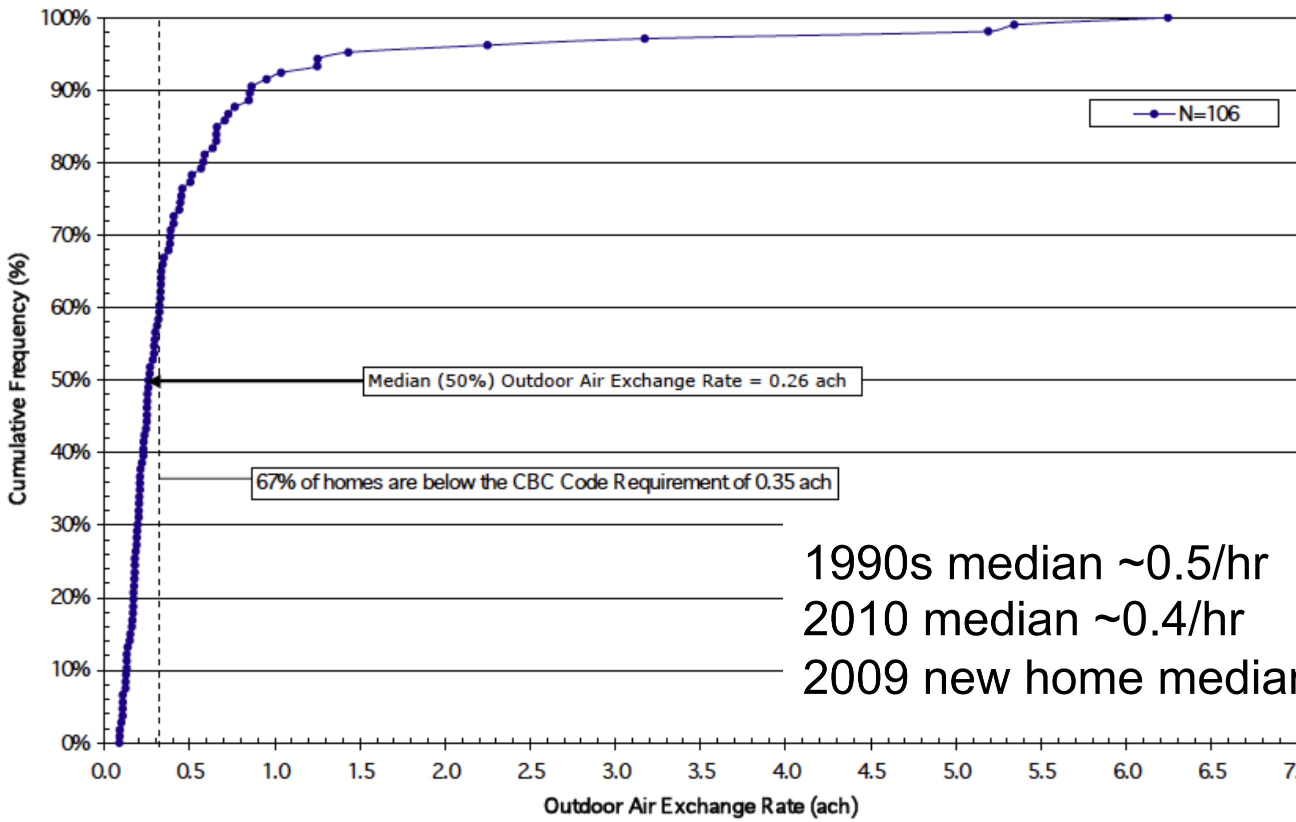
- Distribution of AERs U.S. homes: infiltration
  - Early 1990s and revisited in 2010 (Persily et al. 2010)



Murray and Burmaster, 1995 *Risk Analysis*; Persily et al. 2010 *Indoor Air*

What are typical values of λ (AER)?

- Distribution of AERs U.S. homes: infiltration
  - Addition of 106 new homes (Offermann et al., 2009)



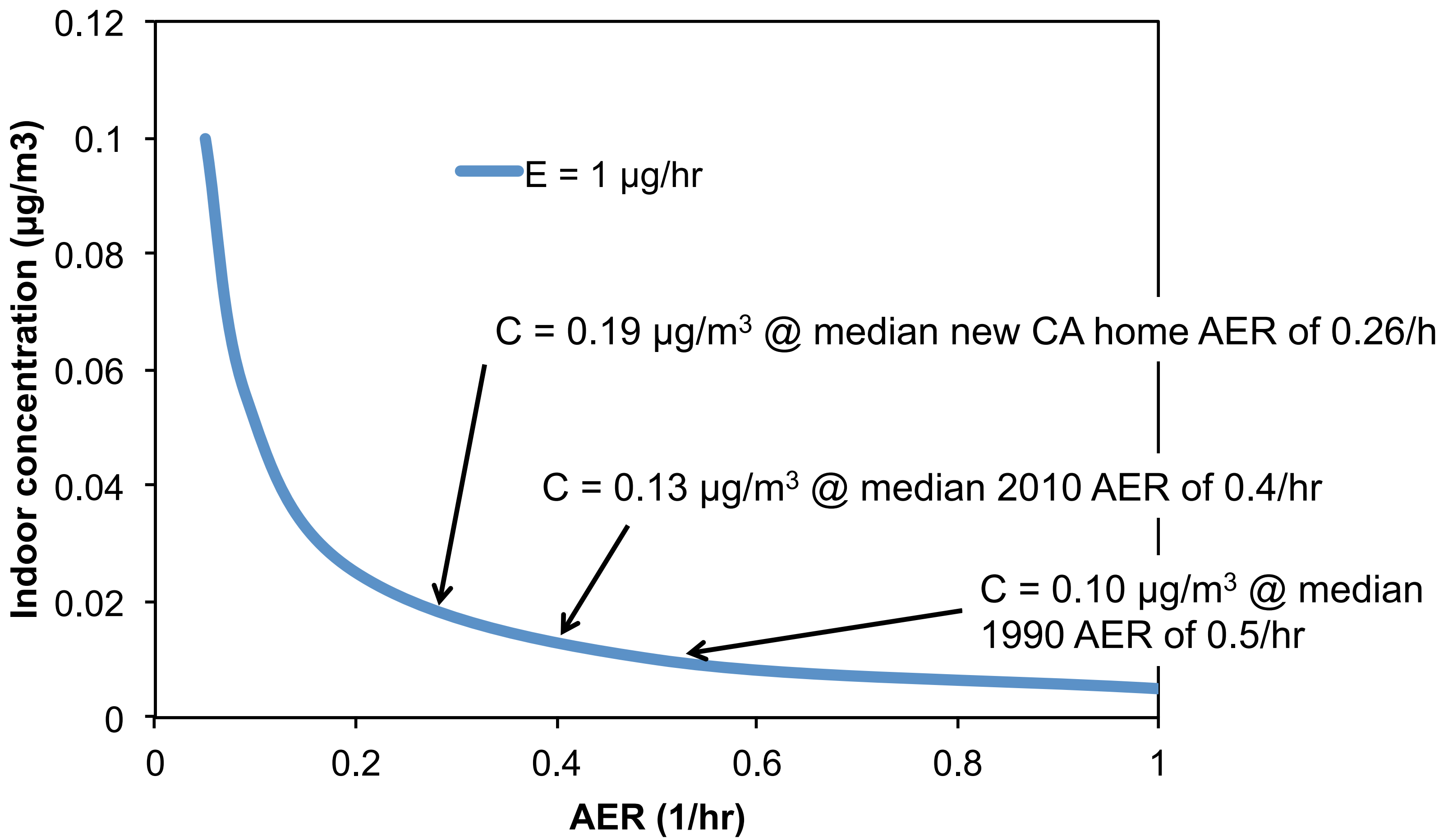
1990s median ~0.5/hr
2010 median ~0.4/hr
2009 new home median ~0.26/hr

- Not uncommon for new homes to have AER = 0.05-0.20 per hour

Offermann et al. 2009 CEC PIER Report

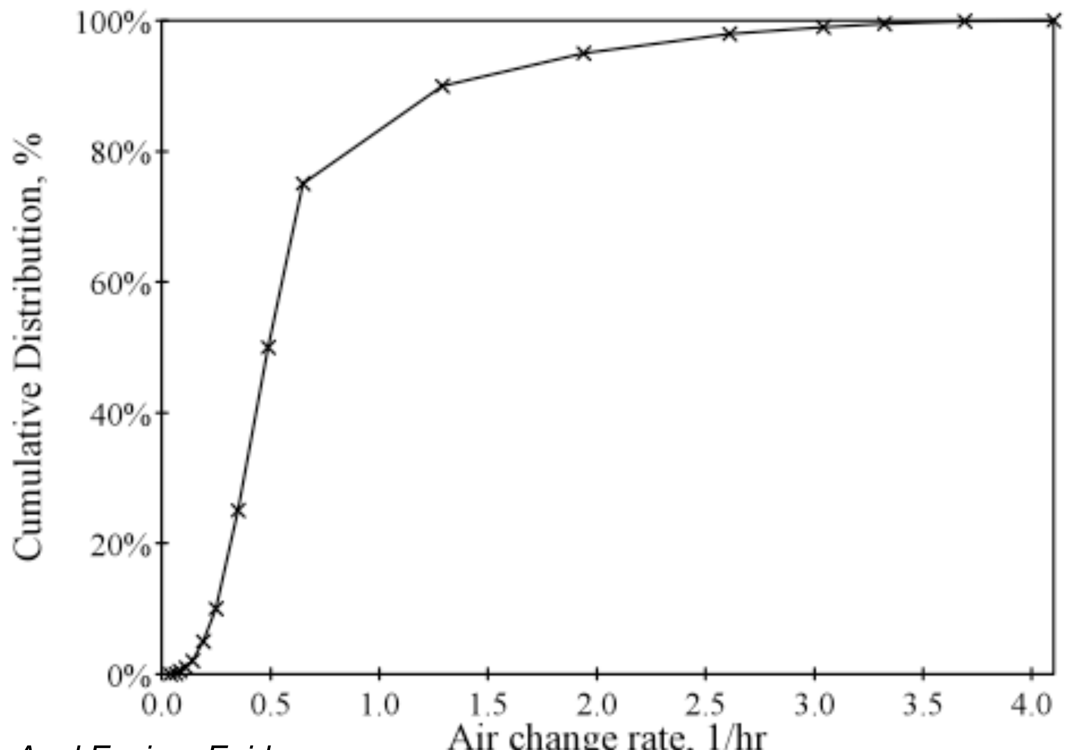
Steady state mass balance and real AERs

- Assume V = 200 m^3 and E = 1 µg/hr
- Lower AER → higher C_{ss}



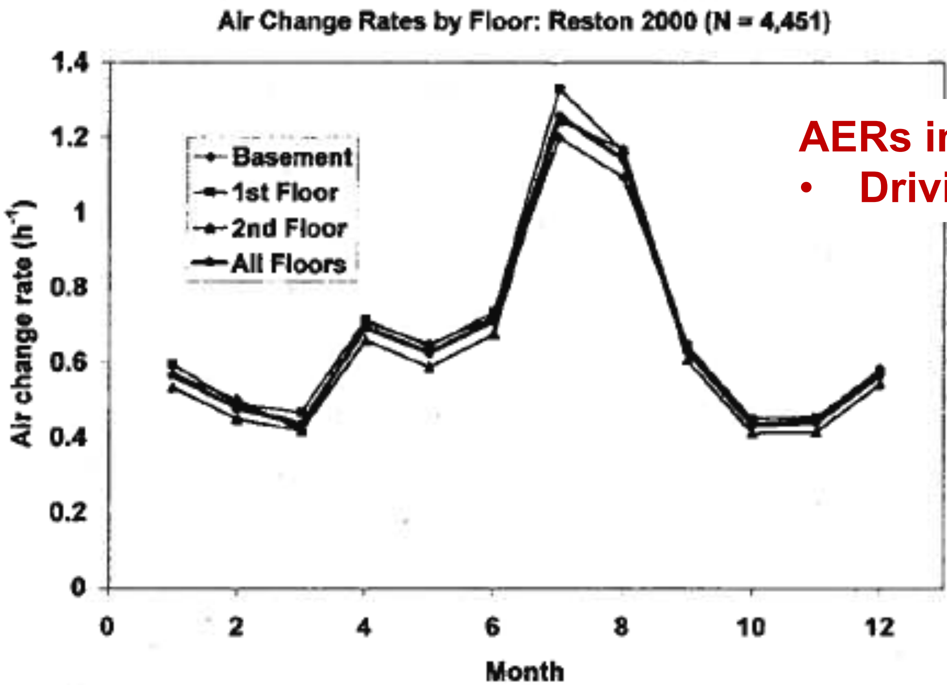
Variation in infiltration AER

- Air exchange rates differ both between buildings and within buildings
  - Differences vary by driving forces and building characteristics
- Example research: “Continuous measurements of air change rates in an occupied house for 1 year: the effect of temperature, wind, fans, and windows”
  - 4600 AERs measured by automated SF_6 system in one house for 2 years!



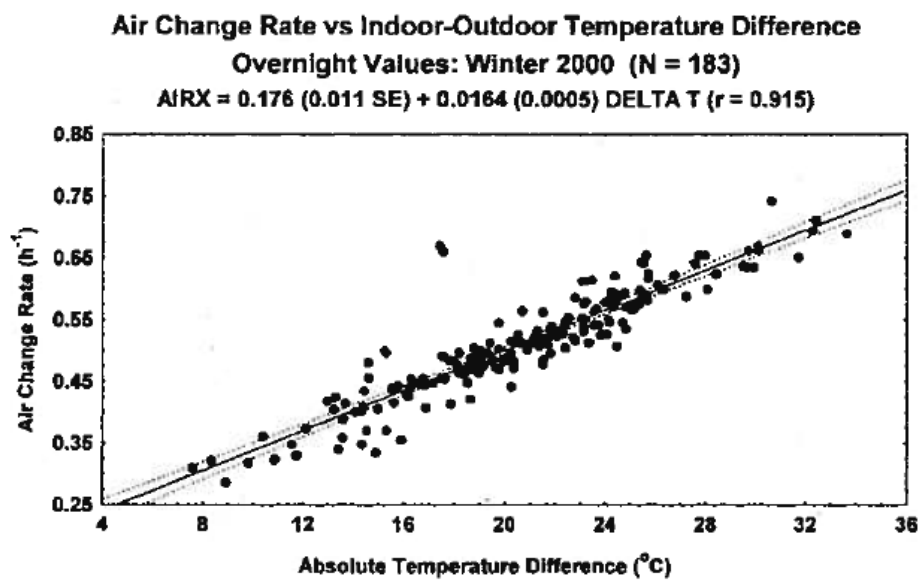
Wallace et al. 2002 *J Expo Anal Environ Epidem*

Variation in infiltration AER



AERs in individual buildings can vary by season

- **Driving forces: temperature, wind speed**



AERs can vary by I/O temperature within seasons

Wallace et al. 2002 *J Expo Anal Environ Epidem*

Modeling air leakage (infiltration only)

- There are several models for estimating infiltration rates in buildings
- One common model is the LBL Model for Air Leakage
  - aka Sherman-Grimsrud Model

$$\dot{V}_{\inf} = A_{leak}\sqrt{a_s \Delta T + a_w v_w^2} \quad \text{[L/s]}$$

A_{leak} = building equivalent leakage area [cm^2]

ΔT = interior-outdoor temp difference [K]

a_s = stack effect coefficient [$\frac{(\text{L/s})^2}{\text{cm}^4\text{K}}$]

a_w = wind coefficient [$\frac{(\text{L/s})^2}{\text{cm}^4(\text{m/s})^2}$]

v_w = wind speed [m/s]

LBL Air Leakage Model

Table 4 Basic Model Stack Coefficient C_s

	House Height (Stories)		
	One	**Two**	**Three**
Stack coefficient	0.000 145	0.000 290	0.000 435

Table 5 Local Shelter Classes

Shelter Class	Description
1	No obstructions or local shielding
2	Typical shelter for an isolated rural house
3	Typical shelter caused by other buildings across the street from the building under study
4	Typical shelter for urban buildings on larger lots where sheltering obstacles are more than one building height away
5	Typical shelter produced by buildings or other structures that are immediately adjacent (closer than one house height): e.g., neighboring houses on the same side of the street, trees, bushes, etc.

Table 6 Basic Model Wind Coefficient C_w

Shelter Class	House Height (Stories)		
	One	**Two**	**Three**
1	0.000 319	0.000 420	0.000 494
2	0.000 246	0.000 325	0.000 382
3	0.000 174	0.000 231	0.000 271
4	0.000 104	0.000 137	0.000 161
5	0.000 032	0.000 042	0.000 049

LBL model example problem

- You measure an effective leakage area of 449 cm^2 in a single story wood-frame building in a suburban neighborhood
  - Floor area of 120 m^2 and ceiling height of 3 m

- Estimate the air exchange rate of the building when it is 68°F inside and 32°F outside and a wind speed of 15 mph

- What if the outdoor temperature drops to 0°F?

- What if wind speed doubles to 30 mph (13.4 m/s)?