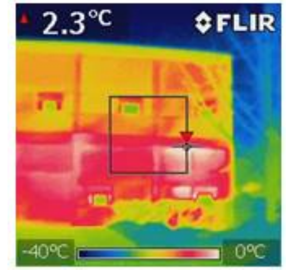
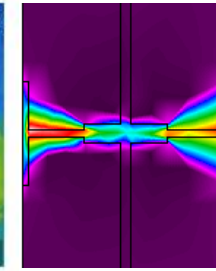
CAE 331/513
Building Science
Fall 2017





November 9, 2017
Infiltration and natural ventilation

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

Schedule changes for Spring 2018

- CAE 466 Building Electrical Systems Design to be added
  - Tuesdays and Thursdays 11:25 am - 12:40 pm (Snyder)

- CAE 463/524 Building Enclosure Design to be moved
  - Tuesdays 1:50 pm - 4:30 pm w/ an online section

- CAE 553 Measurements and Instrumentation
  - Tuesdays 5:00 pm - 7:40 pm

- CAE 550 Applied Building Energy Modeling
  - Wednesdays 10:00 am – 12:40 pm
  - *Prefer to move this to Wednesday nights?*

Last time

- Added filtration and deposition terms (for PM) into our indoor air mass balance
  - CADR
  - k_{dep}

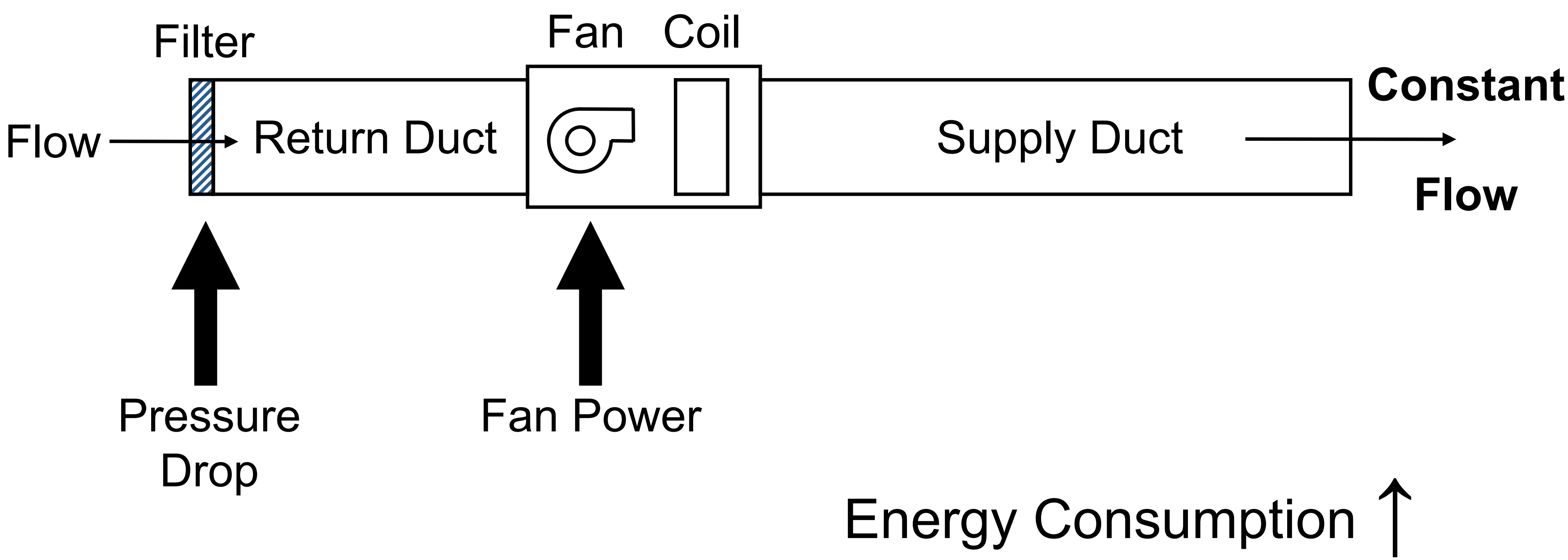
- Introduced particle filtration theory and types of HVAC filters

Pressure, flow, and energy relationships

- Higher efficiency filters usually have a higher pressure drop
  - Widely assumed to increase energy consumption

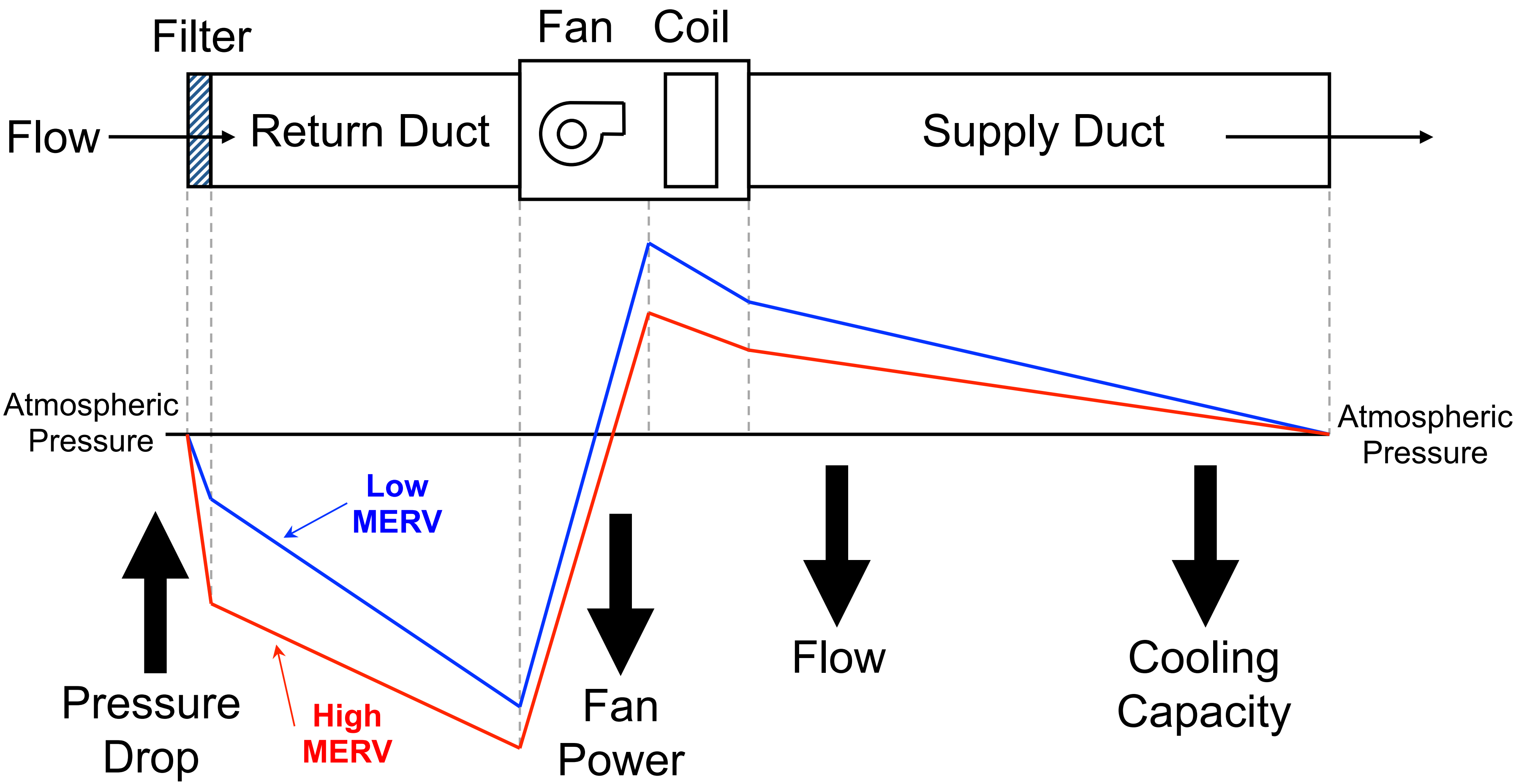
Energy consequences of filters

- In large commercial buildings with **variable speed fans**…



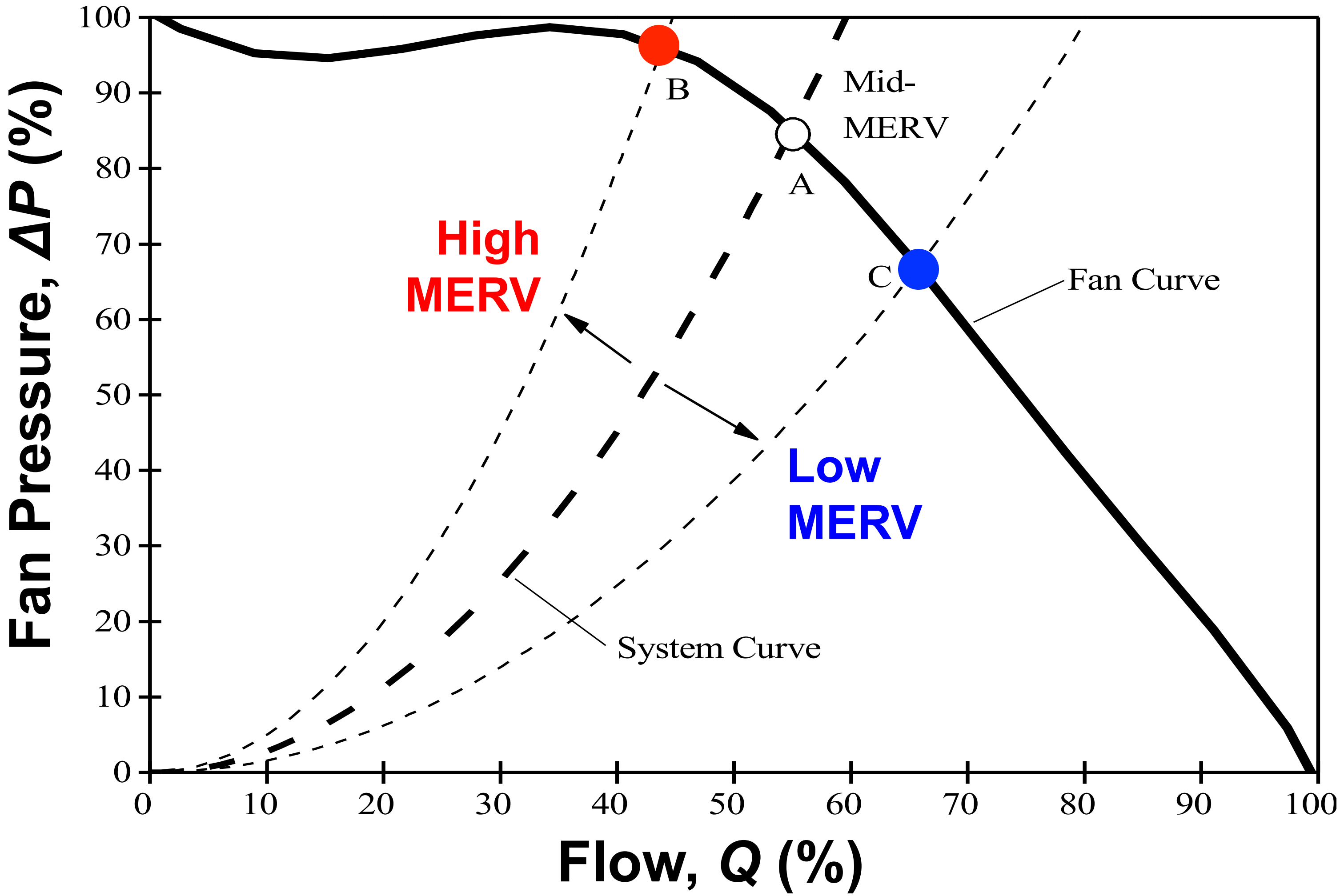
Residential and light-commercial buildings

PSC blower w/ constant speed fan



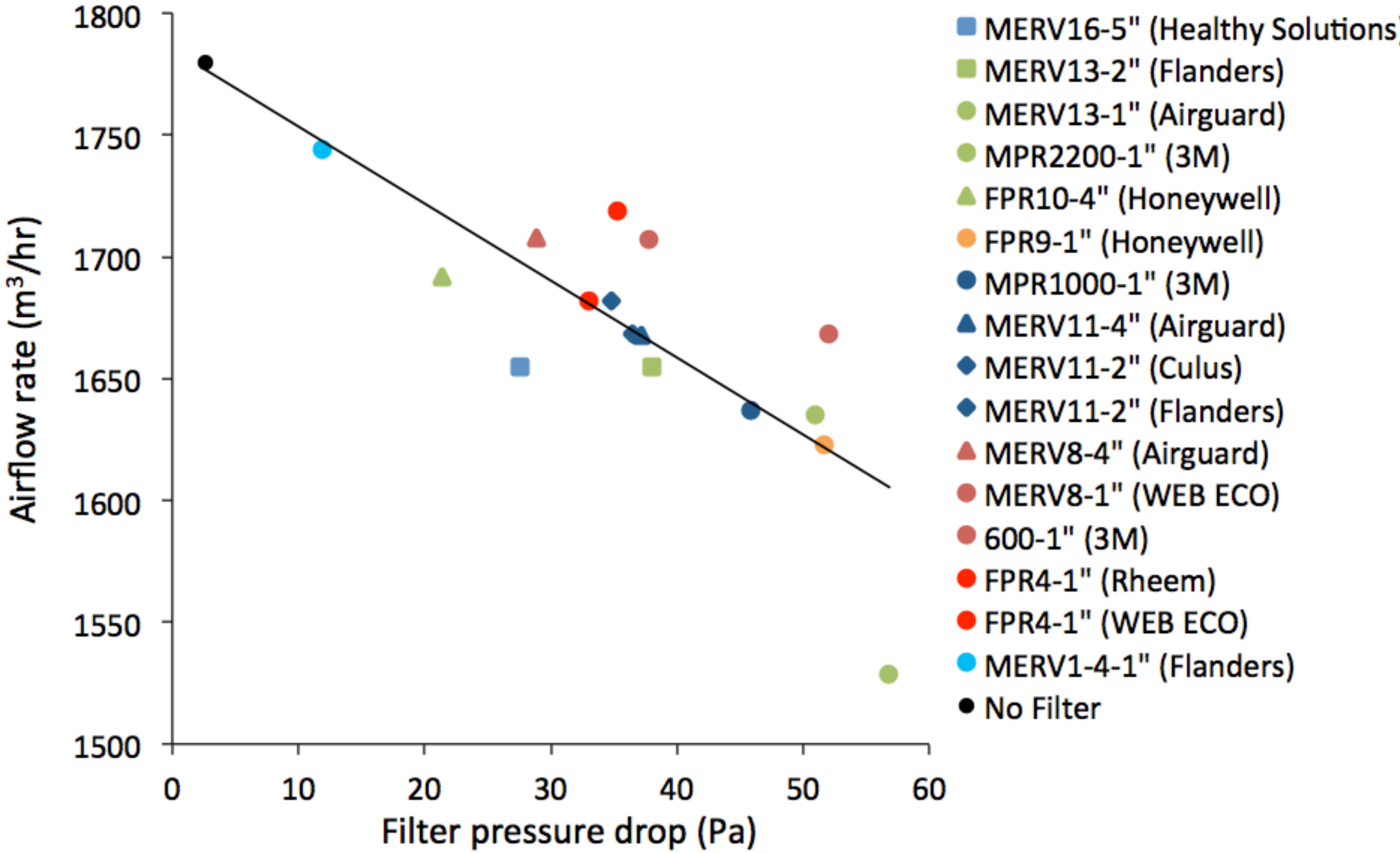
How does overall energy consumption change?

Fan and system curve interactions



Stephens et al., 2010 *HVAC&R Research*

Airflow rates and brand new filters



Data collected by: Torkan Fazli, PhD candidate, IIT CAEE

INFILTRATION AND NATURAL VENTILATION

What impacts air exchange rates?

Outdoor air exchange can be divided into two main categories:

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., *air 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 openings

- Given an opening (i.e., a leak, crack, or intentional 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 0.5 and 1.0 (depends on opening types)

- 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:
  - **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
  - **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 a function of temperature (so this is temperature driven)
  - **Mechanical air handling equipment (fans)**
    - Fans are used to supply, recirculate, exhaust, and otherwise balance pressures and flows in buildings

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

Wind pressures

- From velocity component of Bernoulli Equation:

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

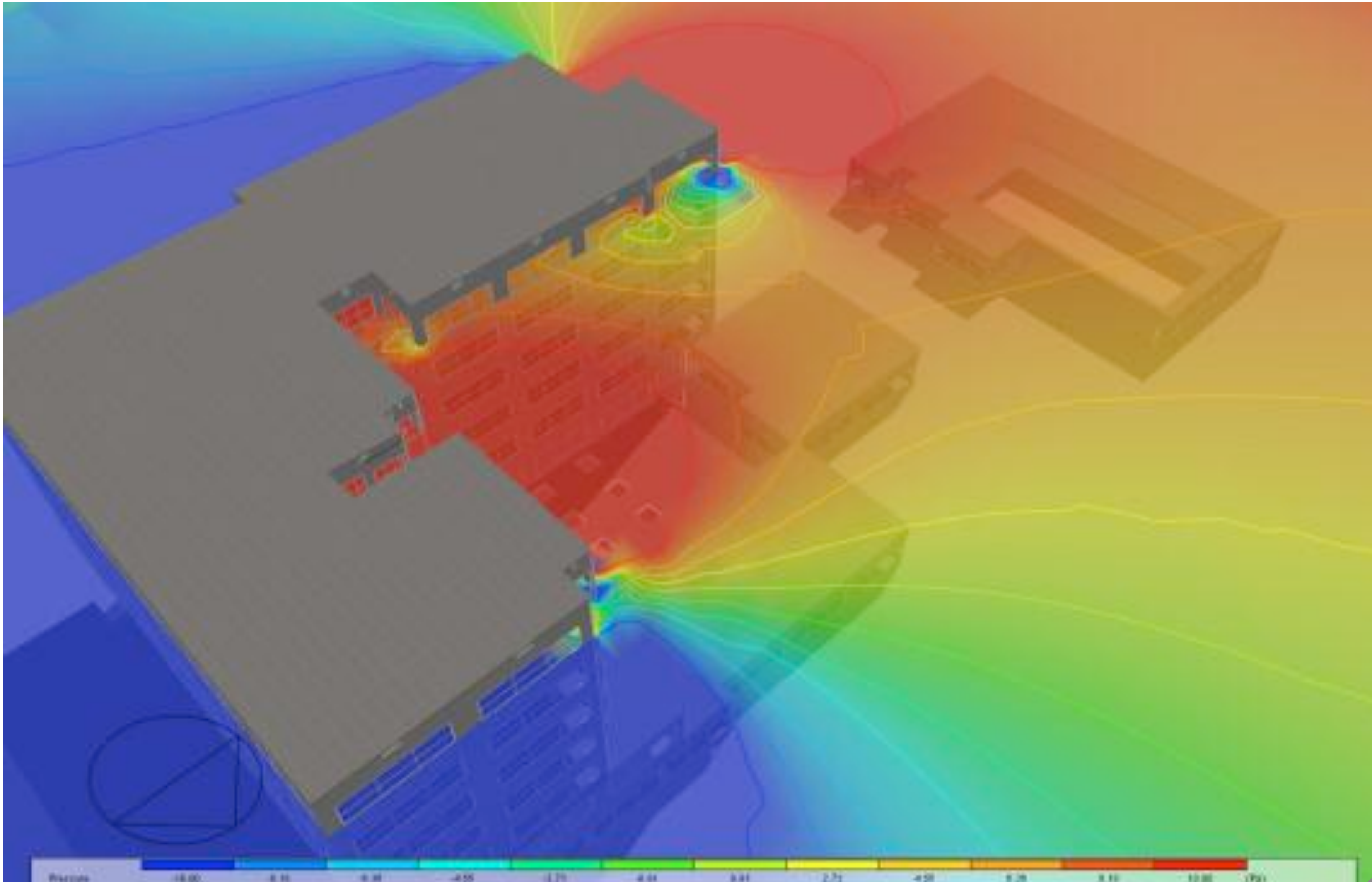
$P_{velocity}$ = wind velocity pressure; U_h = air velocity at building height, h; ρ_{air} = air density

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

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

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

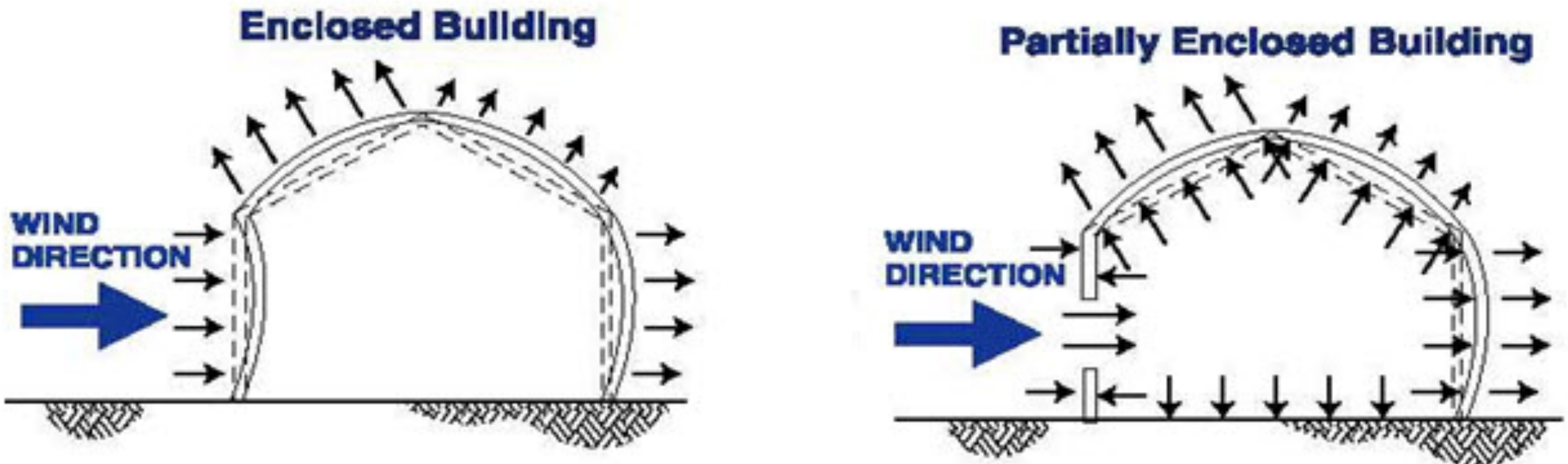
Wind pressure coefficients (C_p) vary around buildings



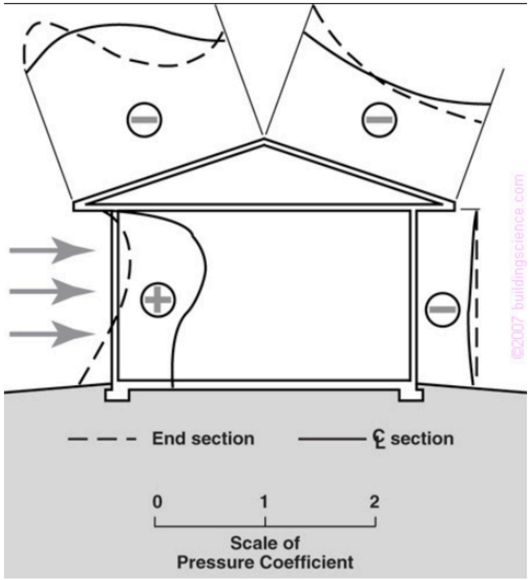
Wind pressure coefficients (C_p) vary around buildings

https://www.youtube.com/watch?v=gMkGM1D1QhY

Wind pressure coefficients (C_p) vary around buildings

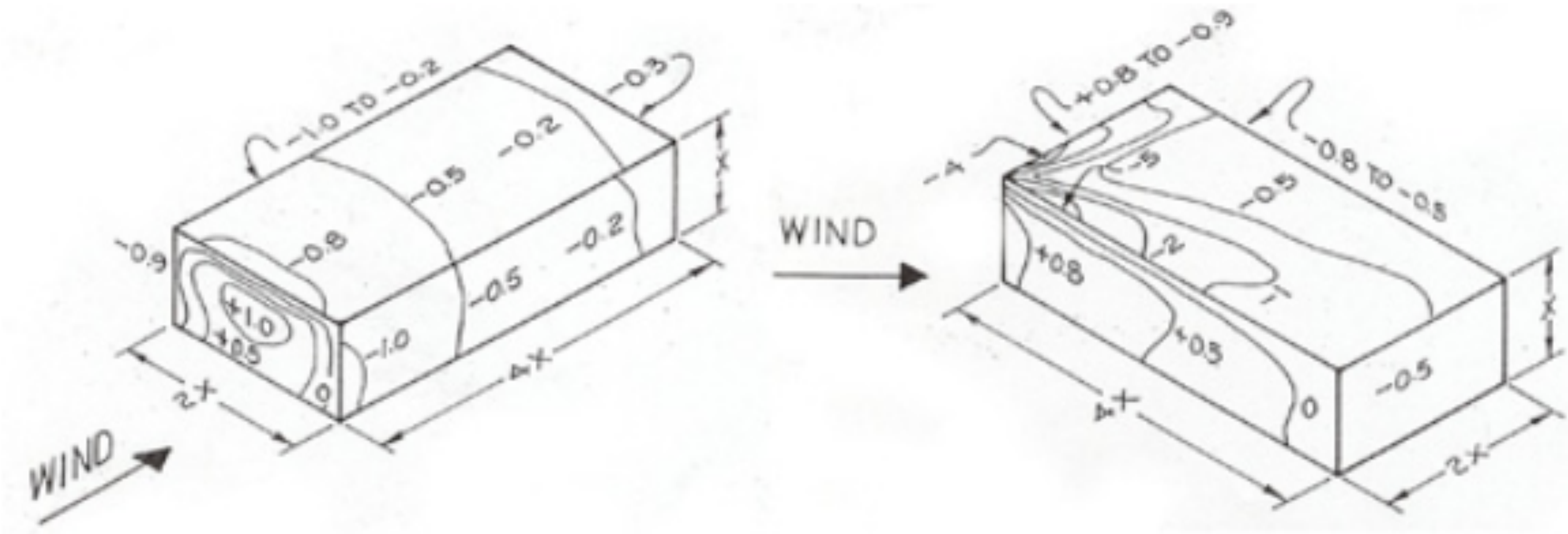


http://seblog.strongtie.com/wp-content/uploads/2013/02/Wind-Pressure-Figure.jpg



https://buildingscience.com/documents/digests/bsd-109-pressures-in-buildings

Wind pressure coefficients (C_p) vary around buildings



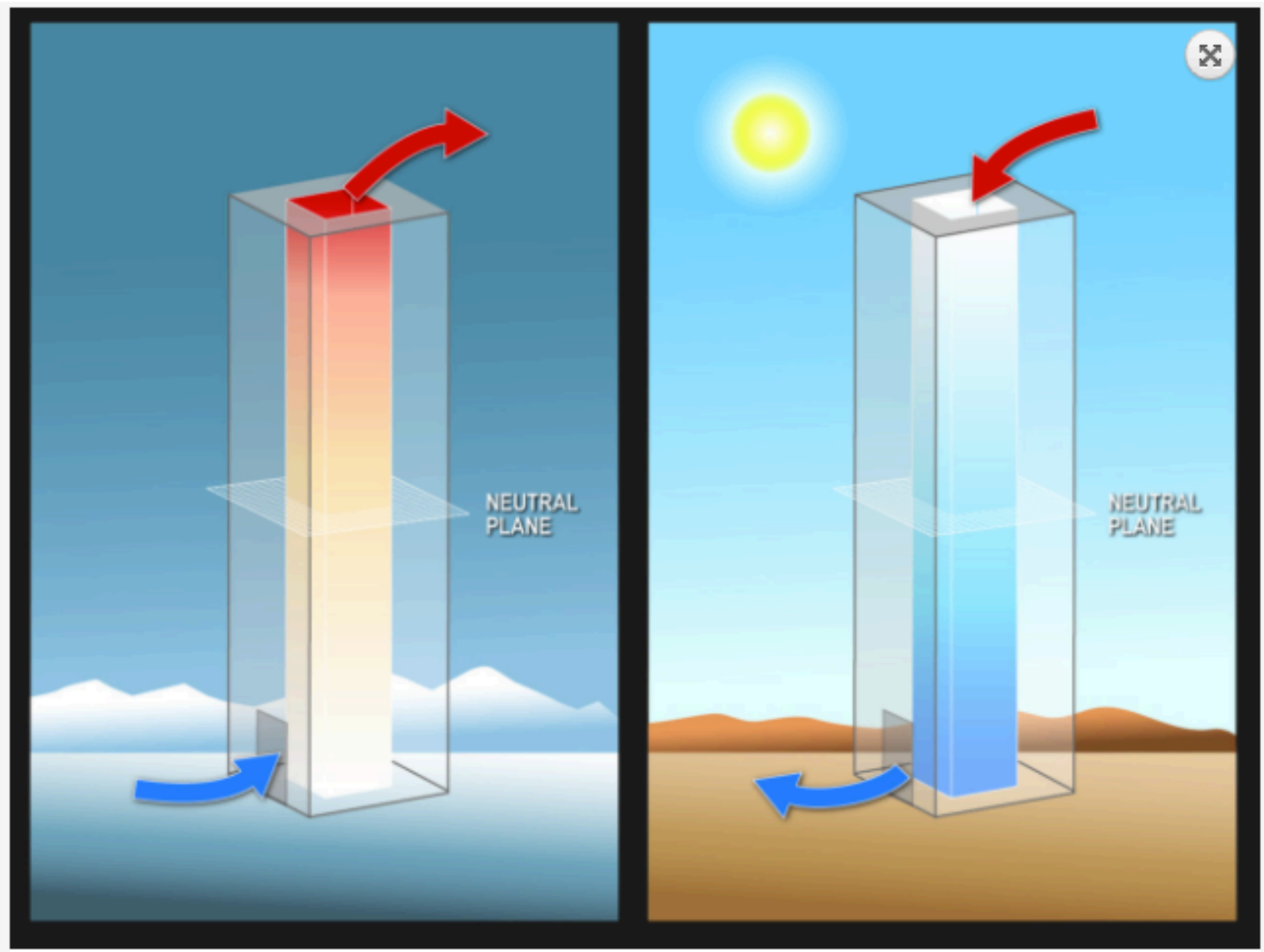
https://buildingscience.com/documents/digests/bsd-109-pressures-in-buildings

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 flows out through openings in the 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 is drawn in through openings in the top
    - Temperature differences usually lower in the summer time so the amount of flow is smaller

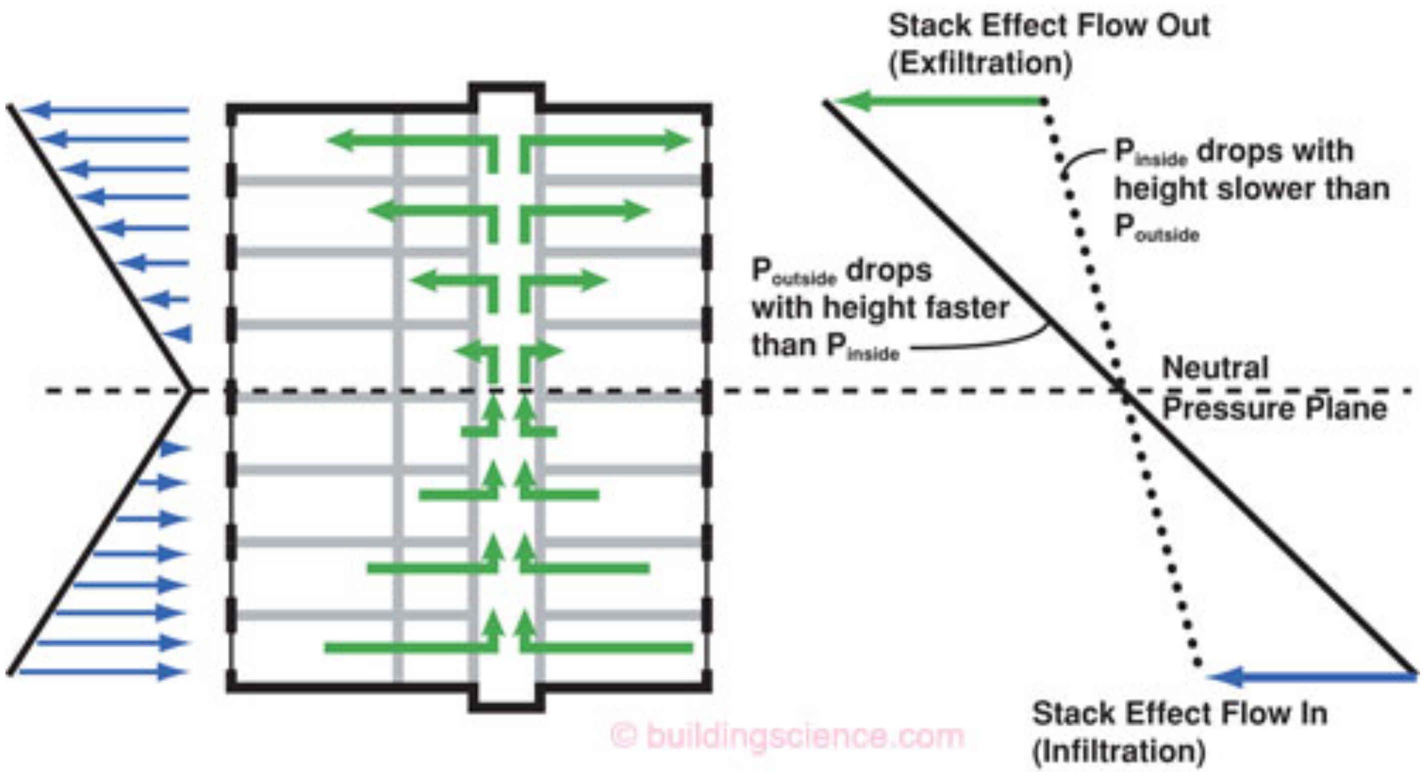
Stack effect



https://www.cppwind.com/blogs/get-to-know-a-flow-feature-the-stack-effect

Stack effect

- The stack effect is magnified in taller buildings



Stack effect equations

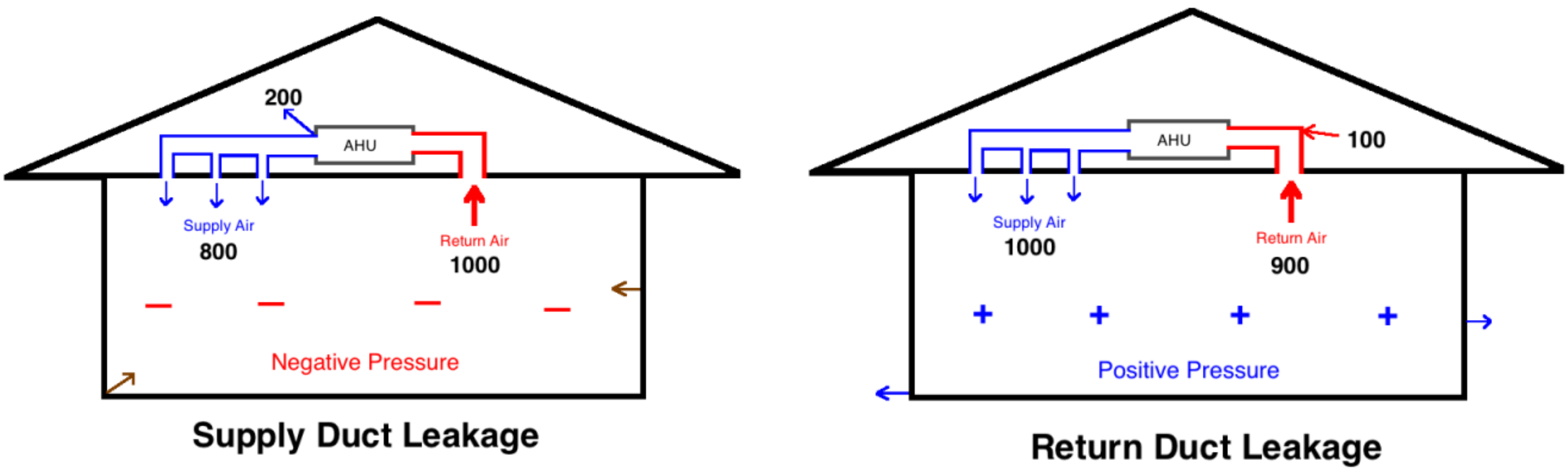
- Assuming temperature and barometric pressure are constant over the height of interest, the stack pressure decreases linearly as the separation above the reference point increases
- Neglecting vertical density gradients, the stack pressure difference across a horizontal leak at any vertical location is estimated by:

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

T_{out} = outdoor air temperature, K
T_{in} = indoor air temperature, K
ρ_{out} = outdoor air density, kg/m^3
ρ_{in} = indoor air density, kg/m^3
H_{NPL} = height of neutral pressure level above reference plane, m
H = height of point of opening, m

Mechanical system driving forces

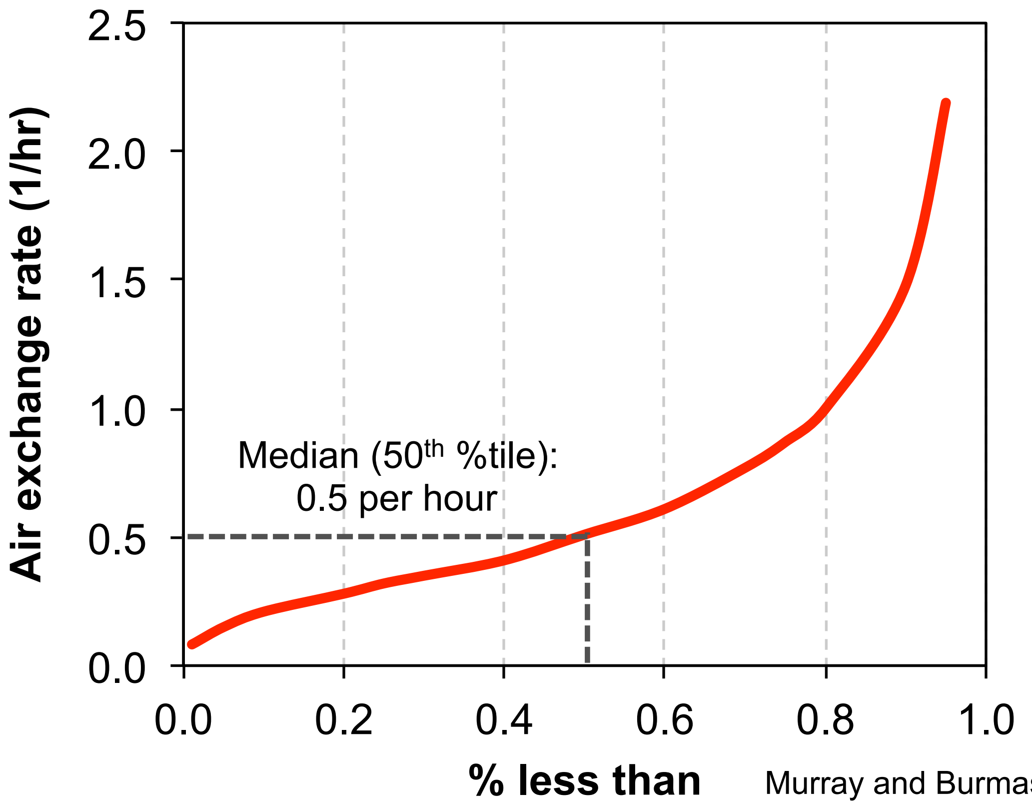
- Mostly relates to unbalanced leakage (e.g., duct leakage or unbalanced exhaust flows)



http://www.greenbuildingadvisor.com/blogs/dept/building-science/how-duct-leakage-steals-twice

What are typical air exchange rates (AERs) in homes?

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



Murray and Burmaster, **1995** *Risk Analysis*

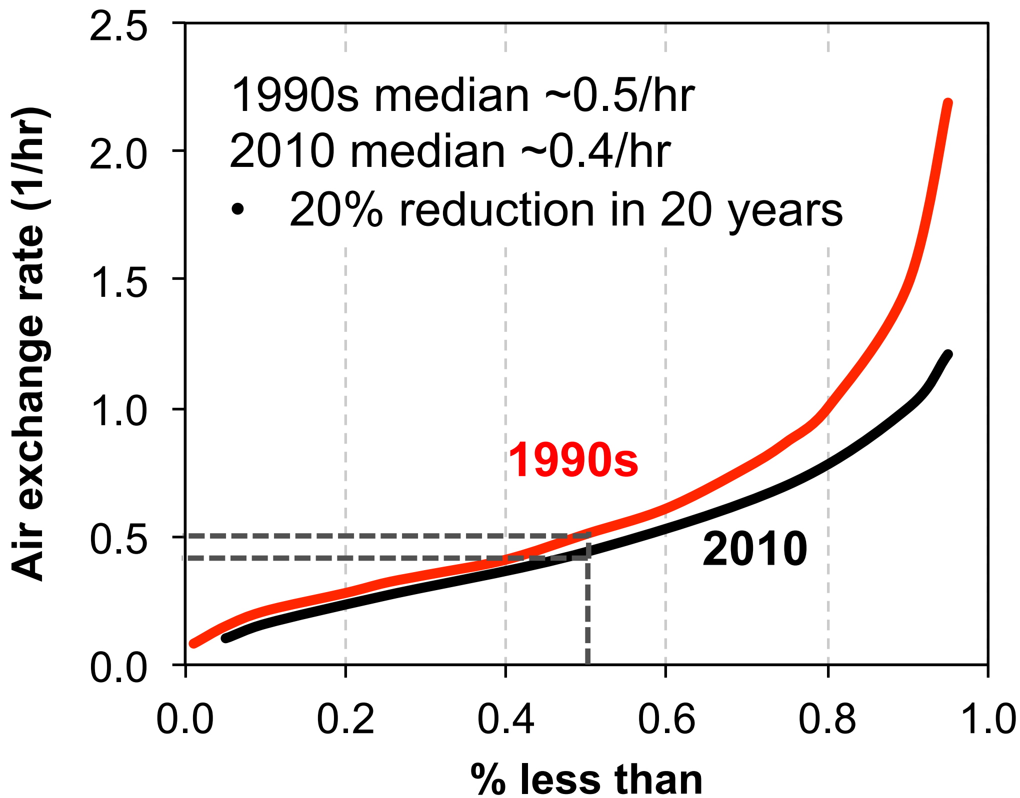
Mostly due to infiltration and window opening

In the past, we seldom used mechanical ventilation systems in single-family homes, but this is changing

- What do you think this curve looks like now?

What are typical air exchange rates (AERs) in homes?

- New distribution of AERs U.S. homes
  - Early 1990s and revisited in 2010 (Persily et al. 2010)

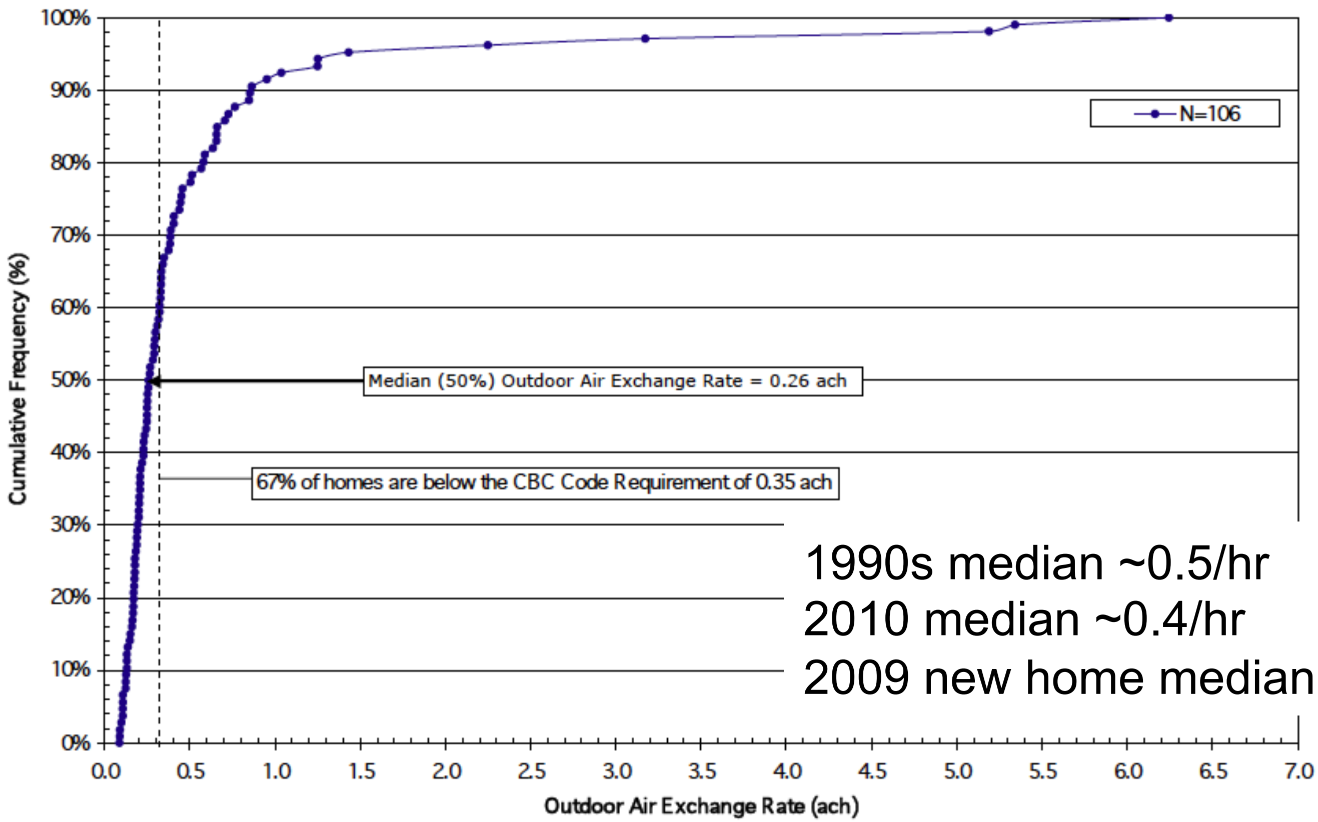


Murray and Burmaster, **1995** *Risk Analysis*
Persily et al. **2010** *Indoor Air*

- What about new homes?

What are typical air exchange rates (AERs) in homes?

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



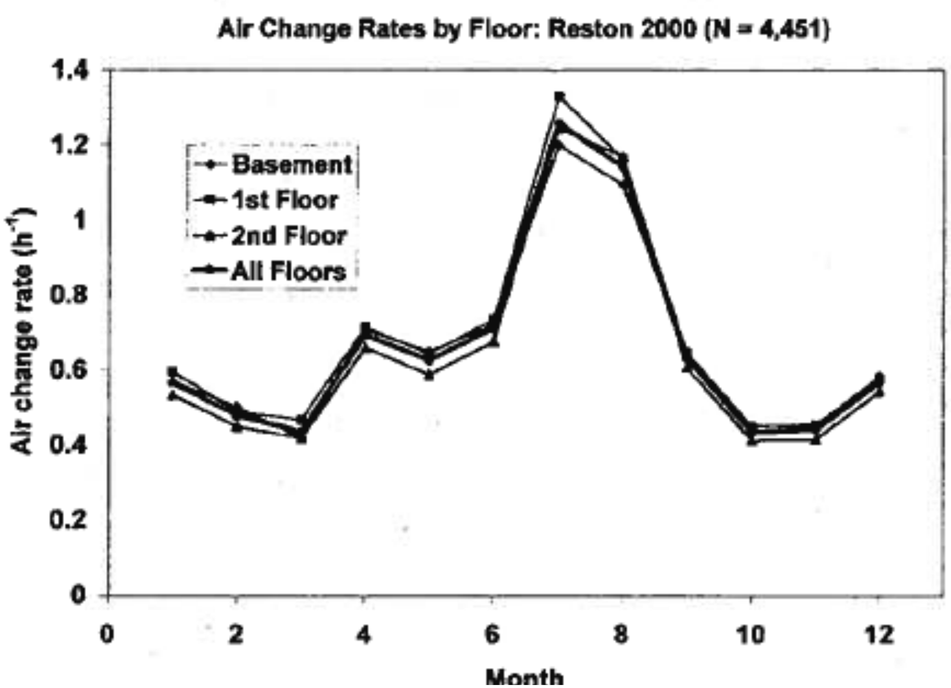
1990s median ~0.5/hr
2010 median ~0.4/hr
2009 new home median ~0.26/hr

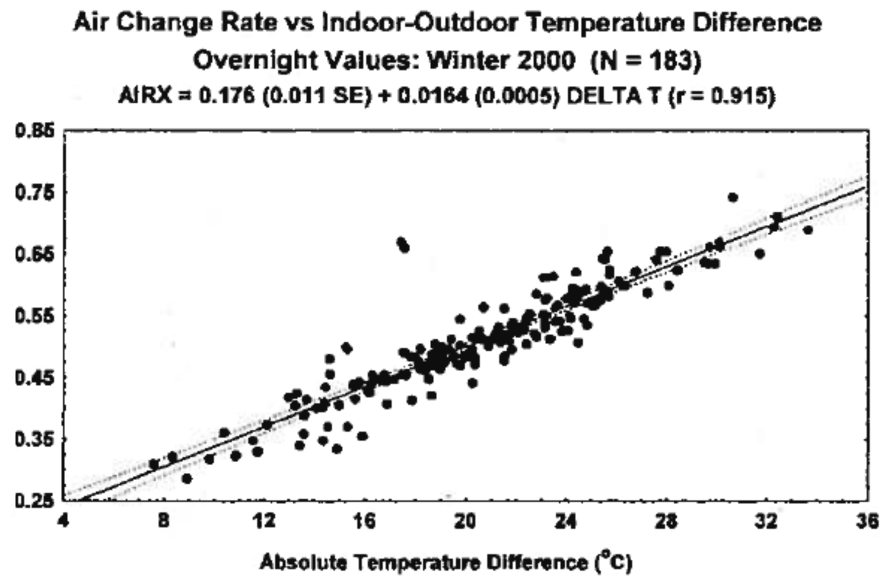
- Not uncommon for new homes to have AER = 0.05-0.20 per hour

Offermann et al. 2009 CEC PIER Report

Variation in infiltration AER with driving forces

- Air exchange rates differ both between buildings and within buildings
  - Differences vary by driving forces & building operation (e.g. windows/HVAC)
- 4600 AERs measured by automated SF_6 system in a house for 2 years:





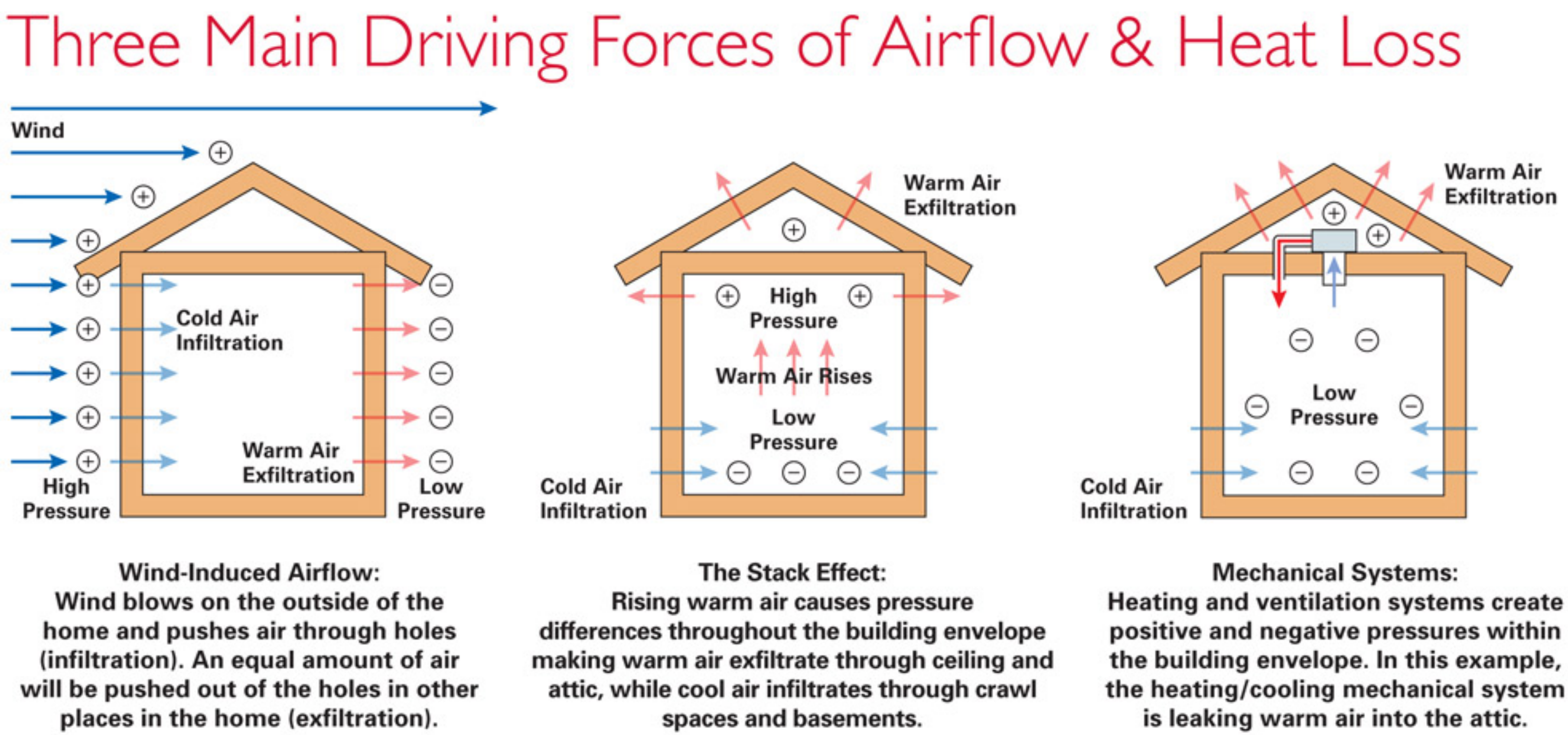
AERs can vary by I/O temperature within seasons

AERs in individual buildings can vary by season
- **Driving forces: temperature, wind speed**

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

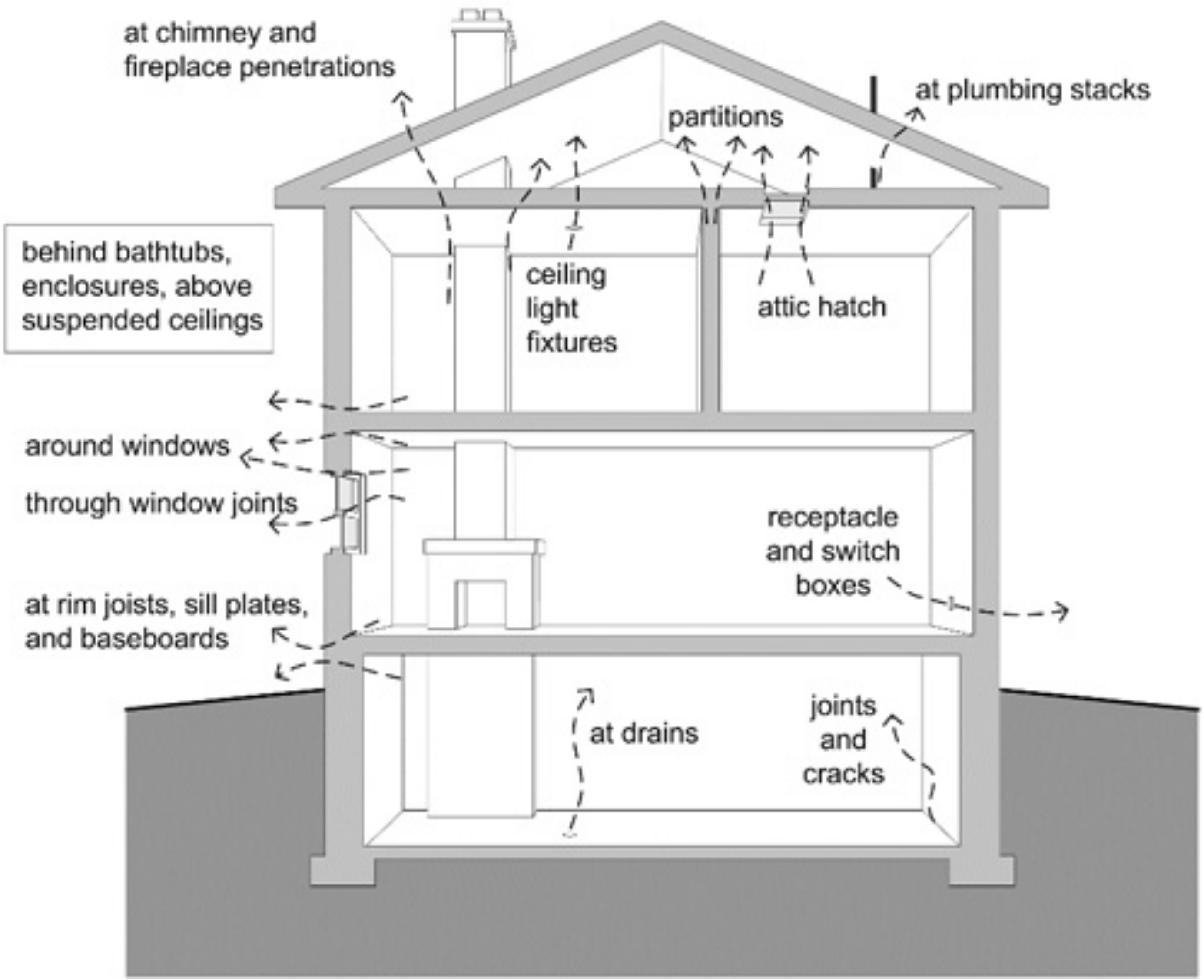
INFILTRATION

Driving forces of infiltration: Δ*P*



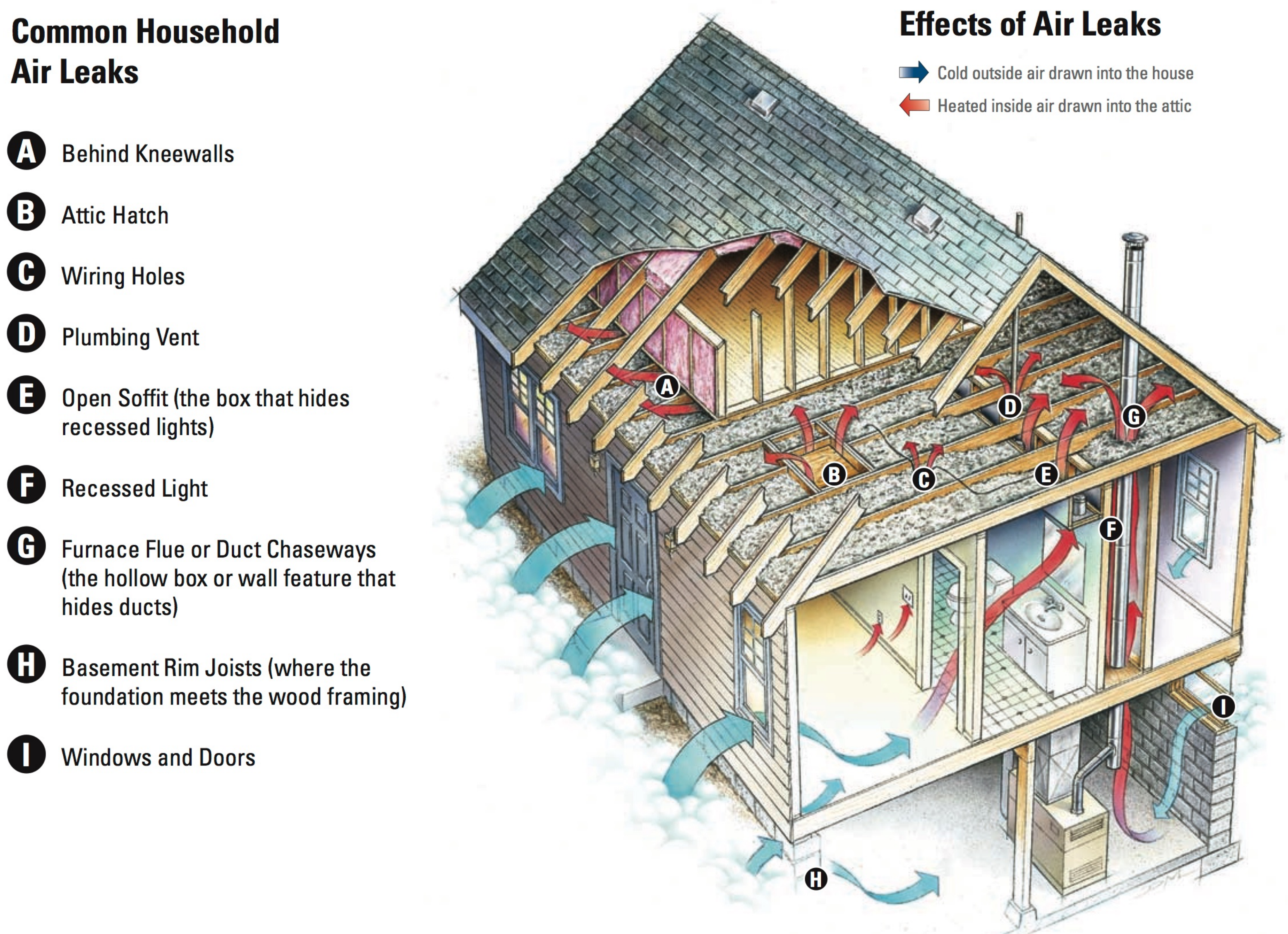
http://www.homepower.com/sites/default/files/articles/ajax/docs/4_HP126_pg40_Connor-2.jpg

Typical air leakage sites in residential buildings



http://buildingscience.com.678elmp02.blackmesh.com/sites/default/files/migrate/jpg/Figure_07_Typical_air_leaka.jpg

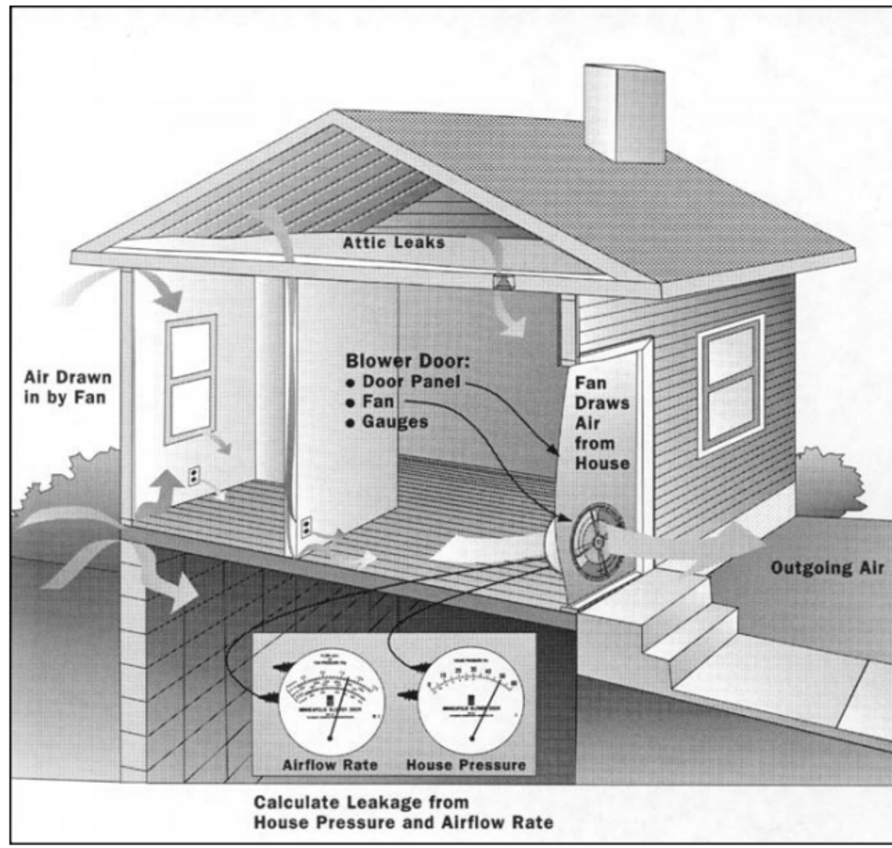
Stack effect in residential buildings



http://www.opalco.com/wp-content/uploads/2014/10/House-Image.jpg

Characterizing air leakage sites

- Q: How do we characterize air leakage sites in buildings?
- A: Blower door tests



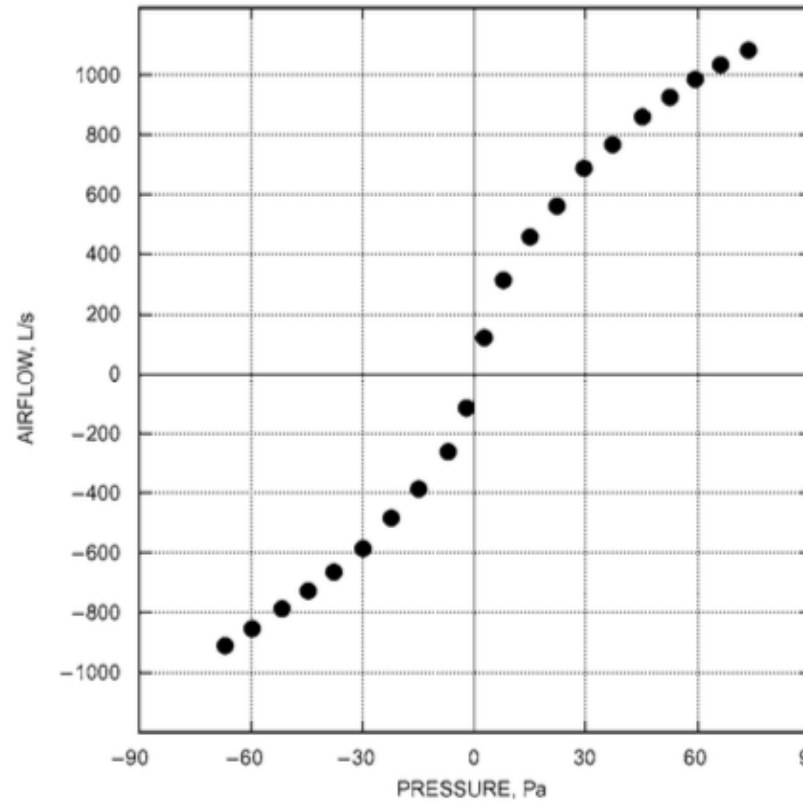
Characterizing air leakage sites

- Blower door test results:

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

- Effective leakage area:

$$A_L = 10000\,\dot{V}_{ref}\sqrt{\frac{\rho 2\Delta P_{ref}}{C_D}}$$



C = flow coefficient, CFM/Pa^n
ΔP = pressure difference between inside and outside, Pa
n = exponent, between 0.5 and 1.0 (usually around 0.65 for homes), dimensionless
A_L = effective air leakage area, cm^2
$\dot{V}_{ref}$ = airflow rate at reference pressure (e.g., 4 Pa), m^3/s
C_D = assumed equivalent discharge area (e.g., 1 or 0.6), dimensionless
ΔP_{ref} = assumed I/O reference pressure difference (e.g., 4 Pa), Pa

Simplified models of air infiltration

- Basic model for combining stack and wind driven flow

$$\dot{V} = \frac{A_L}{1000}\sqrt{C_s\left|T_{in} - T_{out}\right| + C_w U^2}$$

$\dot{V}$ = airflow rate, m^3/s
A_L = effective air leakage area, cm^2
C_s = stack coefficient, $(L/s)^2/(cm^4K)$
C_w = wind coefficient, $(L/s)^2/(cm^4(m/s)^2)$
U = average wind speed measured at the local weather station, m/s
T_{out} = outdoor air temperature, K
T_{in} = indoor air temperature, K

Simplified models of air infiltration

- Basic model for combining stack and wind driven flow

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 street from 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 immediately adjacent (closer than one house height): e.g., neighboring houses on same side of 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

Air infiltration modeling example

- Using a blower door test, you measure the effective leakage area of a 360 m^3 1-story suburban home in a densely populated neighborhood to be 450 cm^2
- Estimate the air exchange rate when it is 20°C (68°F) indoors and 0°C (32°F) outdoors and the wind speed is 6.7 m/s (15 mph)
  - What if the outdoor temperature drops to -18°C and the wind speed stays constant?
  - What if the outdoor temperature drops to -18°C and the wind speed increases to 13.4 m/s?

NATURAL VENTILATION

Natural ventilation

- Natural ventilation occurs through intentional openings:
  - Windows, doors, skylights
  - Roof ventilators
  - Stacks
  - Specially designed inlet or outlet openings

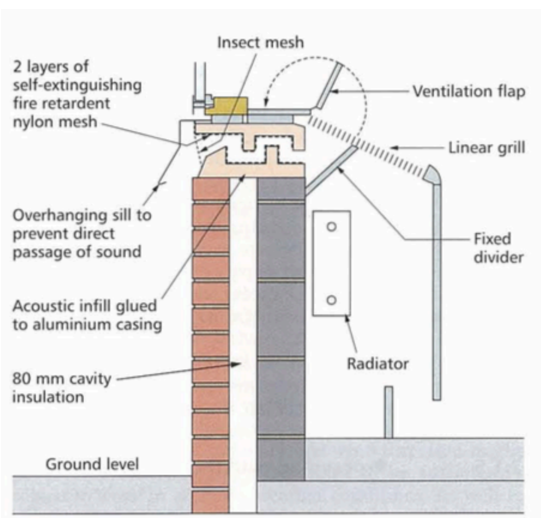
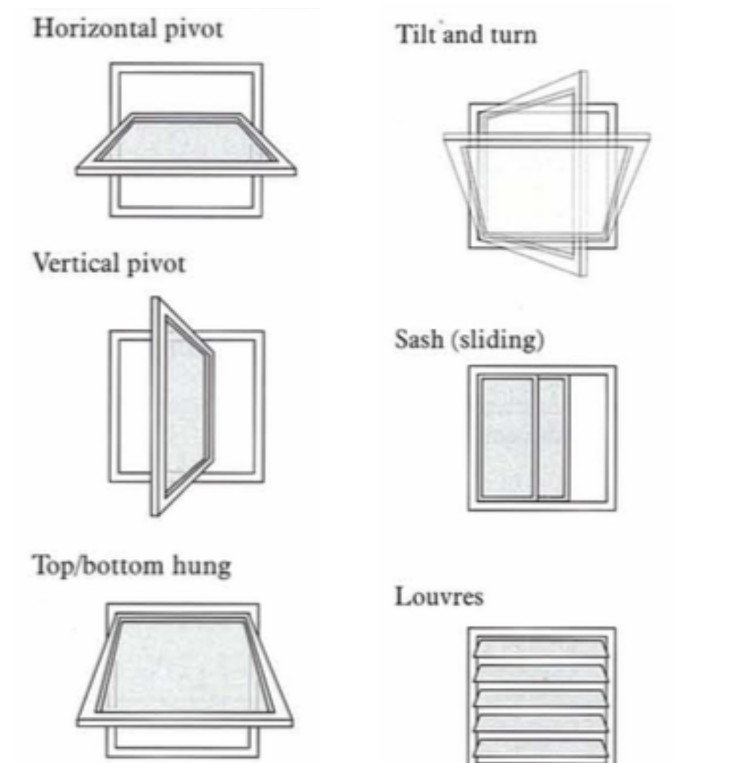


Figure 2.7 Ventilation opening with acoustic protection

Trickle ventilators

Passive inlets



Source: CIBSE Applications Manual A10
Natural ventilation in non-domestic buildings

Natural ventilation strategies

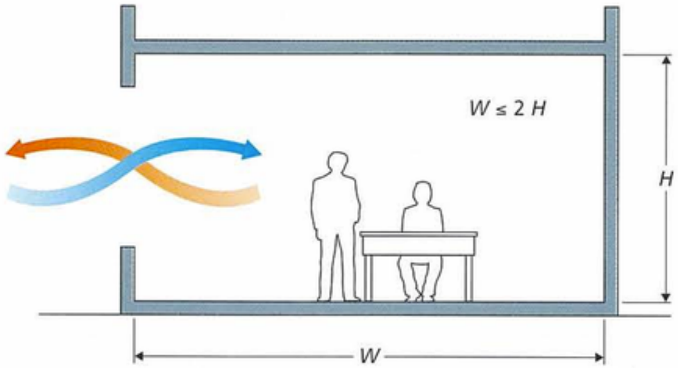


Figure 2.18 Single sided ventilation, single opening

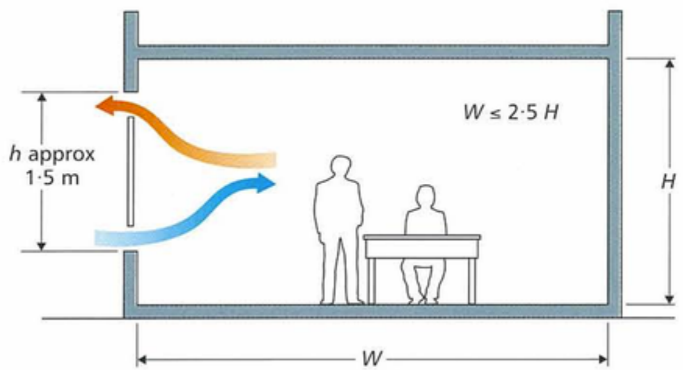


Figure 2.19 Single sided ventilation, double opening

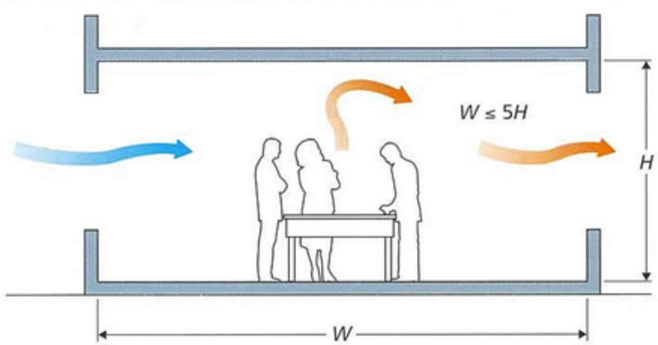


Figure 2.20 Cross ventilation

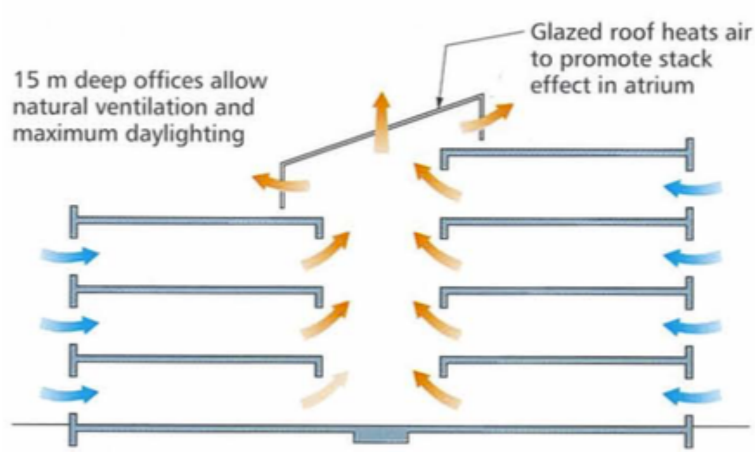


Figure 2.25 Atrium stack ventilation (Barclaycard Headquarters)

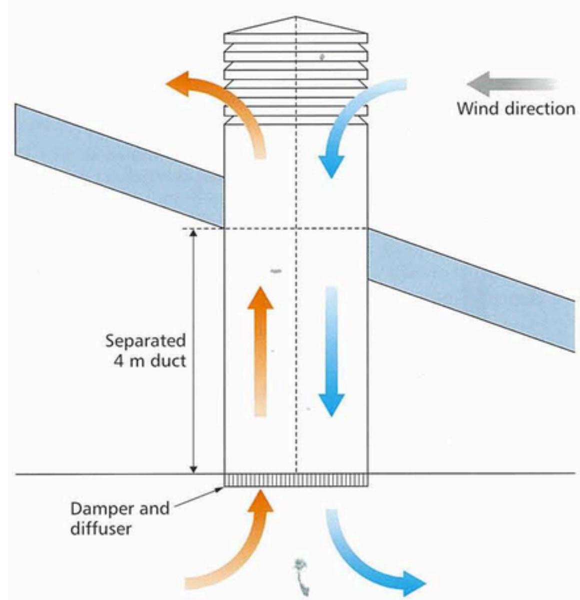
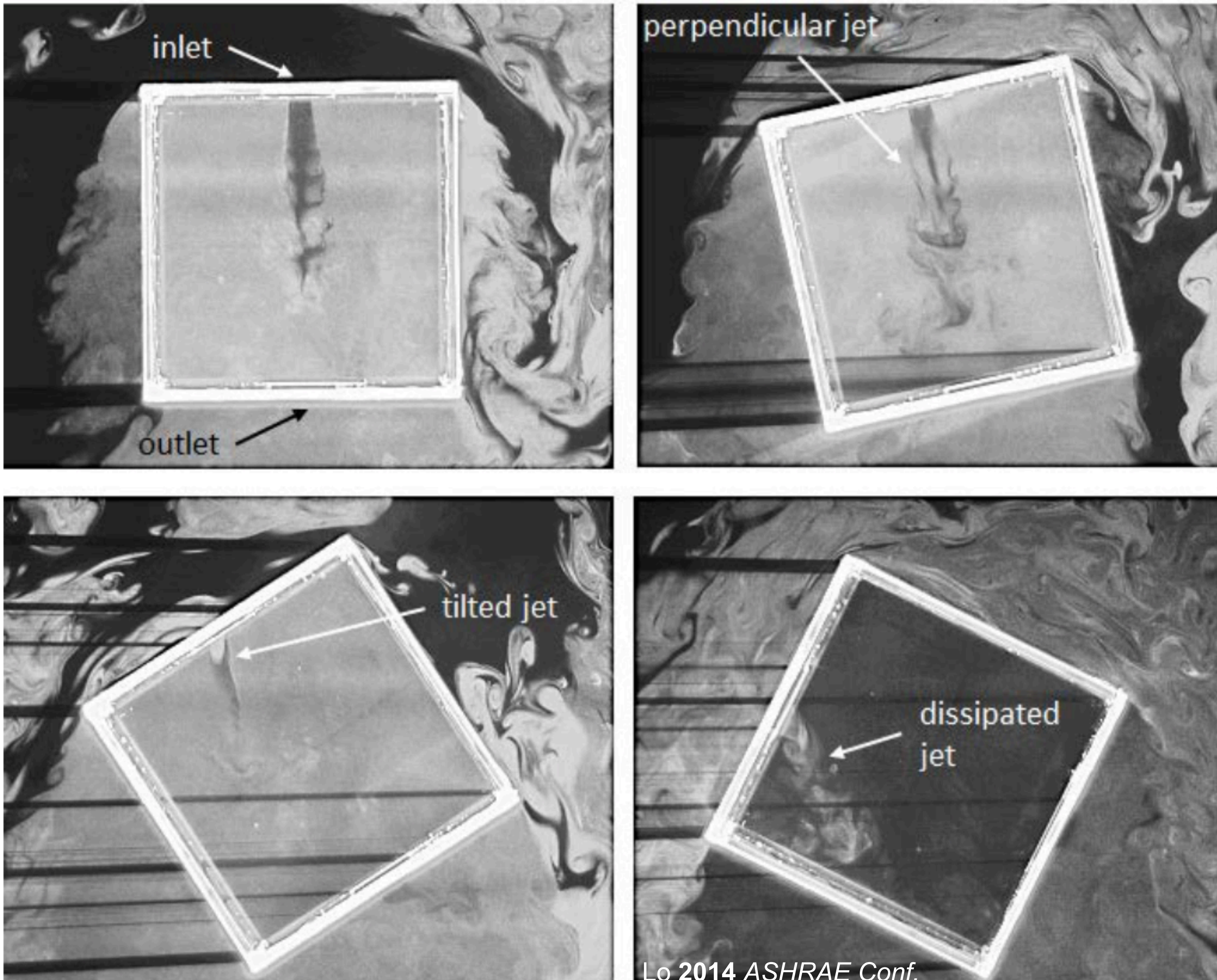


Figure 2.22 Roof-mounted ventilator

Natural ventilation flow dynamics



Lo **2014** *ASHRAE Conf.*

Natural ventilation equations

- Airflow through large intentional openings

$$\dot{V} = C_D A \sqrt{\frac{2\Delta P}{\rho}}$$

$\dot{V}$ = airflow rate, m^3/s
C_D = discharge coefficient for opening, dimensionless
[C_D depends on flow geometry of the opening and the Re of the flow]
A = cross-sectional area of opening, m^2
ρ = air density, kg/m^3
ΔP = pressure difference across opening, Pa

Natural ventilation equations

- Airflow caused by wind only

$$\dot{V} = C_v A U$$

$\dot{V}$ = airflow rate, m^3/s
C_v = effectiveness of openings, dimensionless
[C_v = ~0.5-0.6 for perpendicular winds and ~0.25-0.35 for diagonal winds]
A = free area of inlet openings, m^2
U = wind speed, m/s

Natural ventilation equations

- Airflow caused by thermal forces (buoyancy) only

$$\dot{V} = C_D A \sqrt{2g\left(H_{NPL} - H\right)\left(\frac{T_{in} - T_{out}}{T_{in}}\right)}$$

$\dot{V}$ = airflow rate, m^3/s
C_D = discharge coefficient for opening, dimensionless
A = cross-sectional area of opening, m^2
H_{NPL} = height of neutral pressure level above reference plane, m
H = height of point of opening, m
T_{out} = outdoor air temperature, K
T_{in} = indoor air temperature, K
g = acceleration due to gravity, 9.81 m/s^2

Note: If $T_{in} < T_{out}$, replace T_{in} with T_{out} and vice versa

Wind-driven natural ventilation example

- Consider the first floor of a house with two windows: one is 1 m^2 in area and orientated 20 degrees away from the normal of the prevailing wind direction and another is 1.5 m^2 in area on the opposite side of the room.

- If the local wind velocity is 6 m/s, determine the amount of ventilation air flowing into the room when both windows are wide open.
  - You can neglect infiltration due to stack effect since the indoor and outdoor temperatures are essentially the same
  - Assume an opening effectiveness of 0.6

- If the volume of the house is 360 m^3 (same as the last example), what is the air exchange rate?

When you have unequal inlet and outlet areas

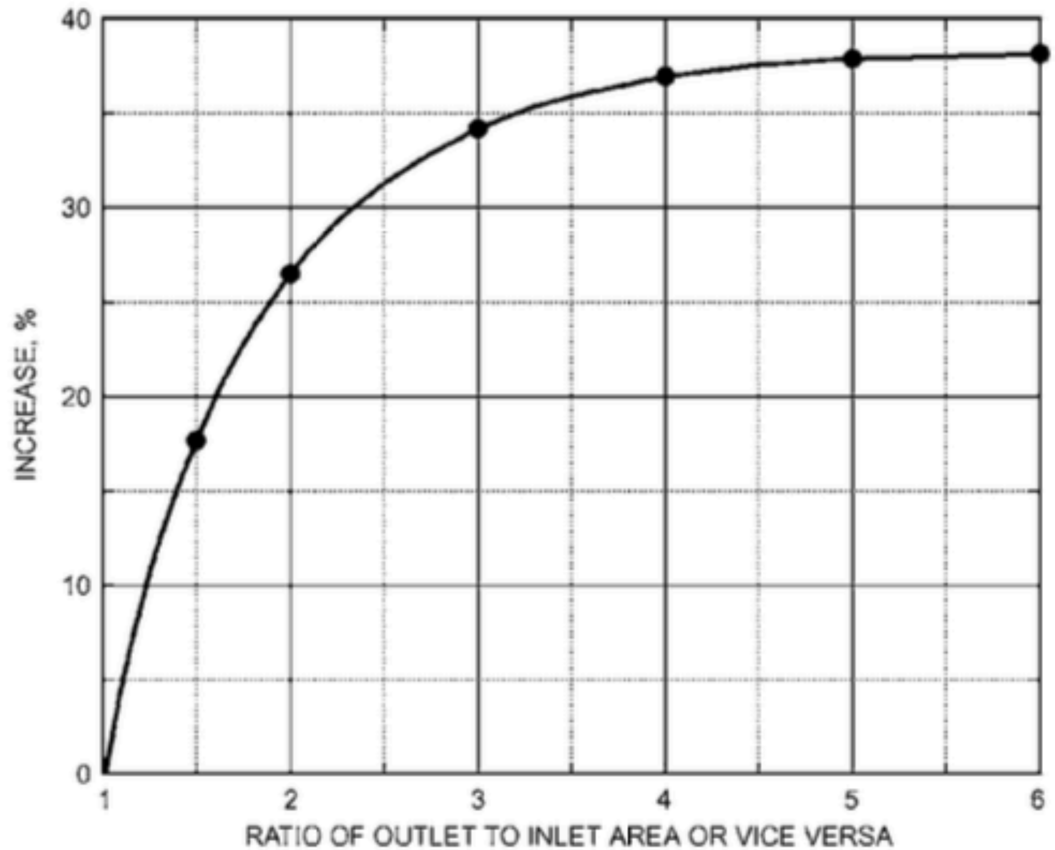
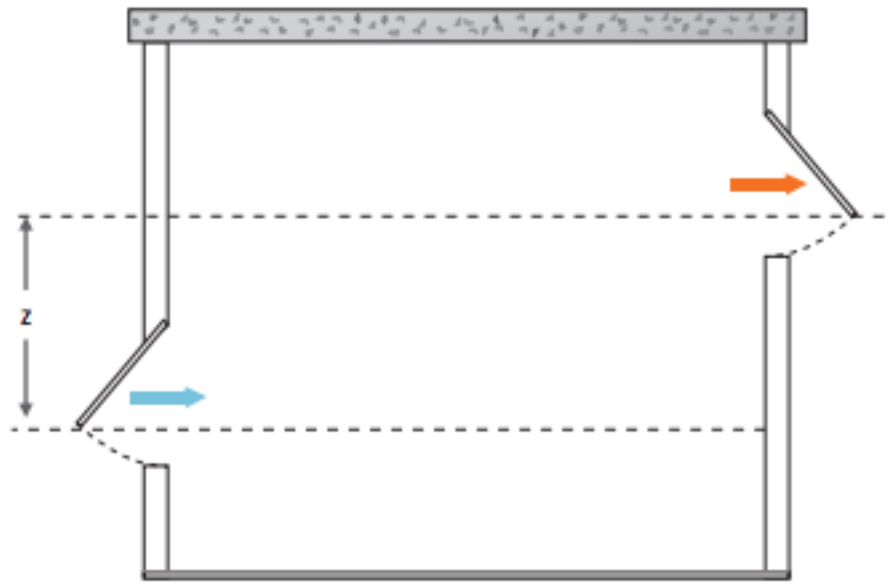


Fig. 8 Increase in Flow Caused by Excess Area of One Opening over the Other

Buoyancy-driven natural ventilation example

- Consider a 10 meter high atrium with openings to the outside at ground level and at roof level. The inside temperature is maintained at 25ºC and the outdoor temperature is 10ºC.
- Estimate the natural ventilation airflow rate due to stack effect pressure differences only if the area of both openings is 0.25 m^2
- If the volume of the house is 360 m^3 (same as the last example), what is the air exchange rate?



Next time

- Heating and cooling load calculations