4.401/4.464 Environmental Technologies in Buildings

Christoph Reinhart

Lec 15 Ventilation

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Thermal Module

- [x] Thermal Mass & Heat Flow
- [x] Insulating Materials + Window Technologies
- [x] Shading + Integrated Façade Design
- [ ] Ventilation
- [ ] Internal Gains & Load Calculations
- [ ] HVAC for Small Buildings
- [ ] HVAC for Large Buildings
- [ ] Simulation Game

Weekly reading and tutorials

DIVA GH 8: DIVA/Archsim Single Zone

DIVA GH 10: Multi-Zone Thermal Modeling

DIVA GH 11: Natural Ventilation

Ventilation

Why do we ventilate buildings?

To breathe

To maintain indoor environmental quality

To control temperature & relative humidity

Terminology

According to the ASHRAE Handbook of Fundamentals, Chapter 27:

"Air exchange of outdoor air with the air already in a building can be divided into two broad classifications: ventilation and infiltration.

Ventilation air is air used to provide acceptable indoor air quality. It may be composed of forced or natural ventilation, infiltration, suitably treated re-circulated air, transfer air, or an appropriate combination. It includes the intentional introduction of air from the outside into a building and is further subdivided into natural ventilation and forced ventilation.

Natural ventilation is the flow of air through open windows, doors, grilles, and other planned building envelope penetrations.

Forced ventilation is the intentional movement of air into and out of a building using fans and intake and exhaust vents.

Infiltration is the flow of outdoor air into a building through cracks and other unintentional openings. Infiltration is also known as 'air leakage' into a building."

General Comments

- Infiltration and ventilation have to be controlled to provide thermal comfort and indoor air quality to building occupants.

- Indoor air quality issues relating to contaminants in the air (such as volatile organic compounds) will be addressed in a later lecture.

- Commercial buildings in the US tend to be ventilated using forced air. These buildings tend to be sealed (have no operable windows) and use economizer cycles to cool the air if desired. There always has to be a percentage of outside air of at least 10%.

- We will discuss different HVAC systems later this term.

How much fresh air do we need?

Ventilation/Infiltration Rates

- The amount of infiltration in a building is usually expressed in terms of air exchanges per hour (ACH), the number of times all air within a building is being exchanged with outside air over the course of an hour.

- Hygienic fresh air requirements per person are expressed in 'feet^3/minute person' or in 'liters/second person'. Typical fresh air supply requirements are:

15 ft^3/minute person or 10 liter/second person

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Blower Door Tests

- Are used to determine air leakage of building envelopes. Results are expressed in m^3/m^2h @ 50 Pa.
- There is a difference between ACH_{50} and ACH_{nat}. You want to reach an ACH_{50} <3.
- An ACH_{50}<1.5 means that your house requires mechanical ventilation.

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Infiltration Values - Residential

Energy efficient houses have been found to have an average ACH_{nat} of $0.5\ h^{-1}$ (range $0.02\ h^{-1}$ to $1.63\ h^{-1}$), compared to $0.9\ h^{-1}$ for 'normal new construction houses'.

Ventilation Losses

Energy loads on a building due to infiltration and ventilation are dependent on the amount of air changes per hour:

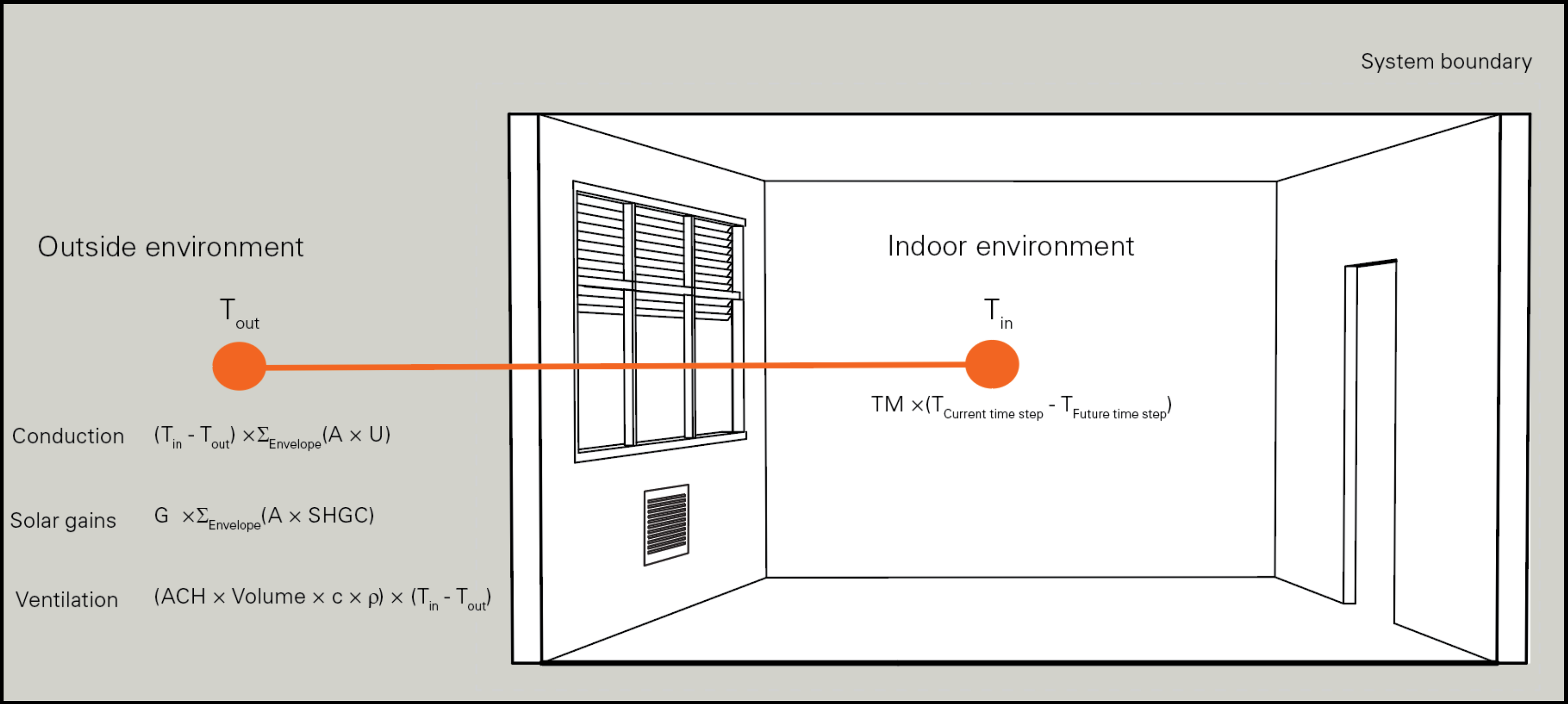
$$Q_{infiltration} = (ACH \times volume \times c \times \rho) \times (T_{inside} - T_{outside})$$

Where:

ρ = Density of Air 1.2 kg/m^3

c = Specific Heat Capacity of Air (20° C) ~ 1000 J/kg K

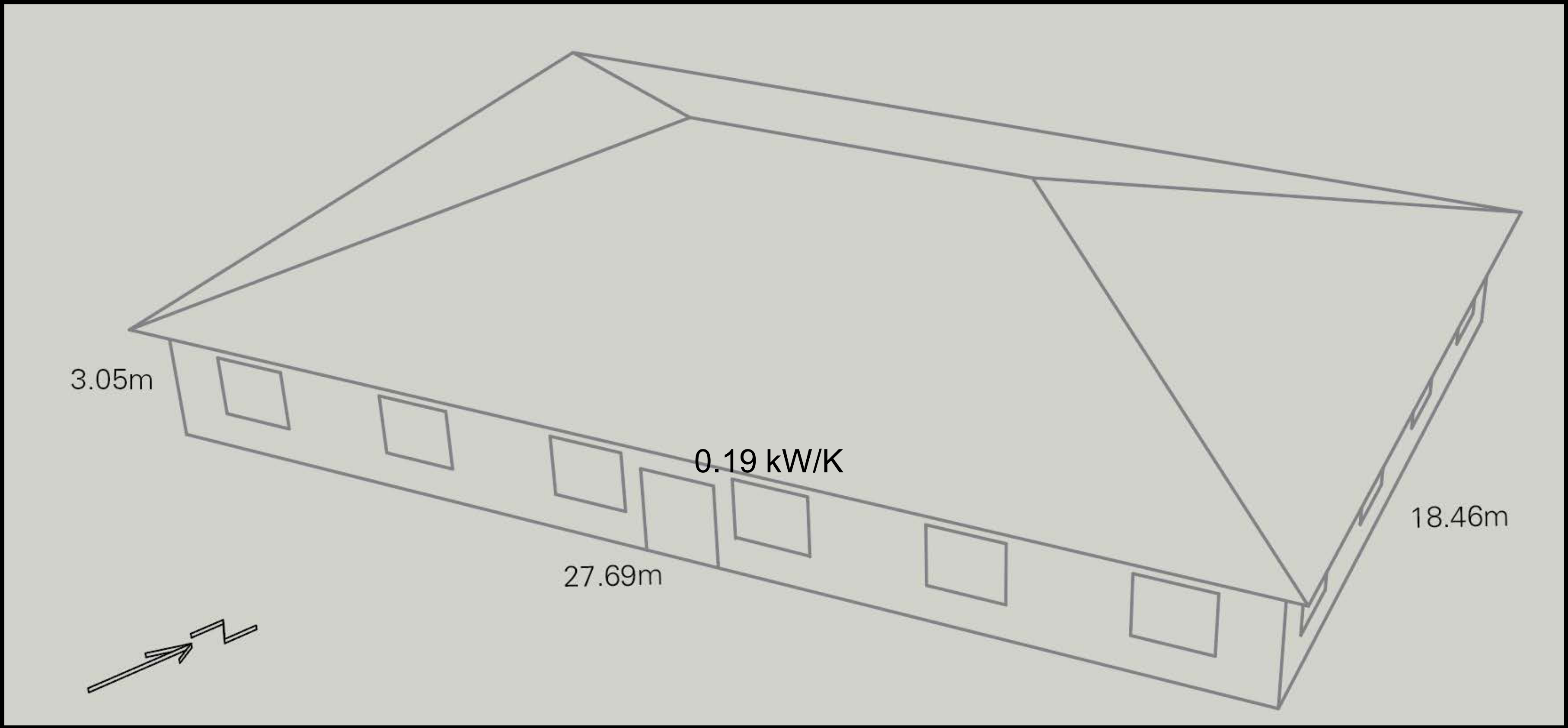
Heat Balance Equation



ACH = Air change per hour

Volume = Volume of air in conditioned space

US DOE Benchmark Small Office Building



Floor area: 511.1 m^2
Wall area: 225.7 m^2
Roof area: 511.1 m^2
Window area: 55.8 m^2

$TM_{\text{With concrete floor}}$ = 19.1 kWh/K

$\Sigma UA_{\text{Envelope}}$ = 11.6 kW

Ventilation Losses?

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Ventilation Losses for DOE Small Office

Energy loads on a building due to infiltration and ventilation are dependent on the amount of air changes per hour:

$$Q_{infiltration} = (ACH \times volume \times c \times \rho) \times (T_{inside} - T_{outside})$$

Where:

ρ = Density of air 1.2 kg/m^3

c = Specific Heat Capacity of Air (20° C) ~ 1000 J/kg K

For the US DOE Small Office Building:

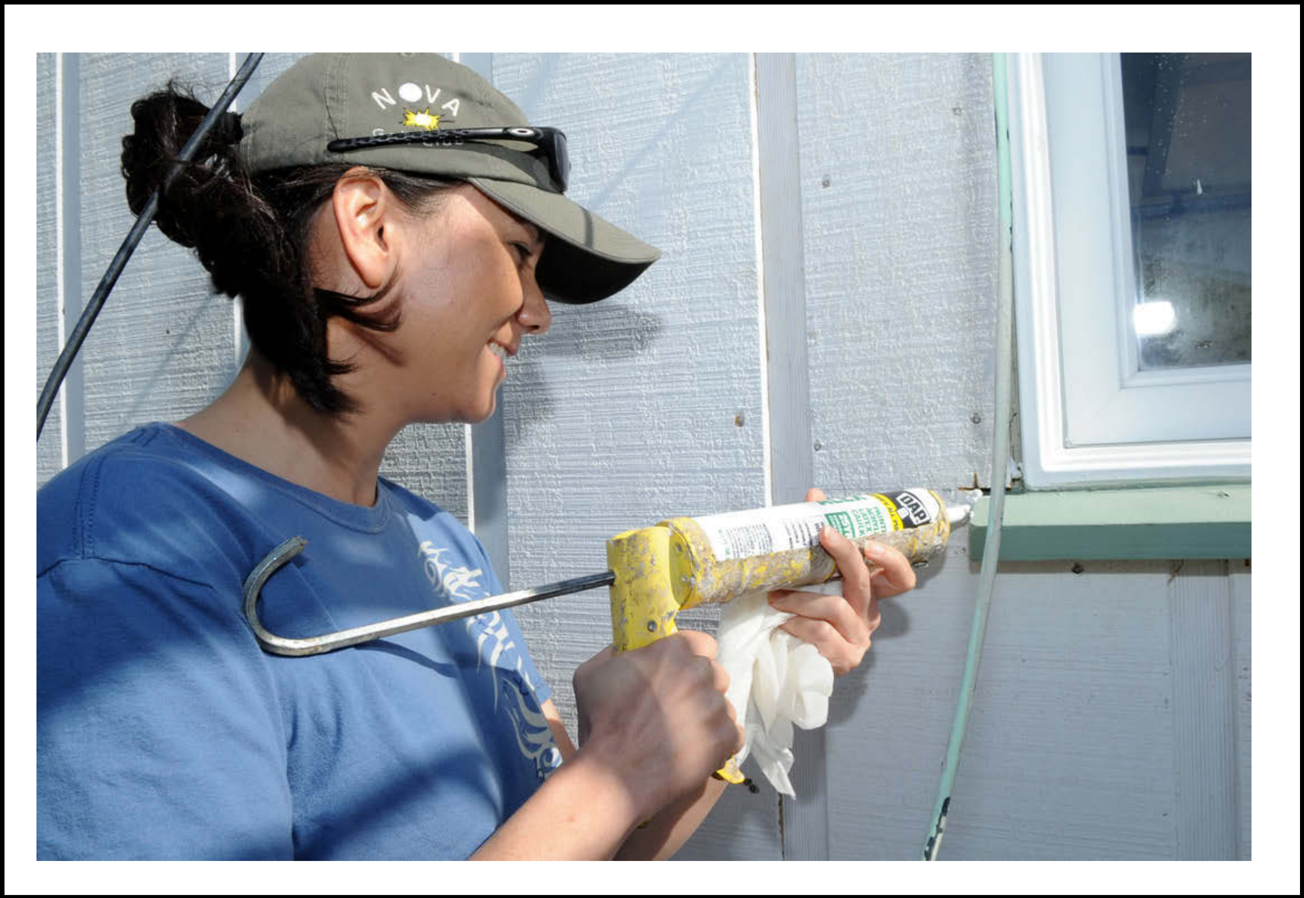
Assuming an ACH of 0.36/h and a volume of 1559 m^3

This is very low.

$$Q_{infiltration} = (0.36/h \times 1559\ m^3 \times 1000\ J/kgK \times 1.2\ kg/m^3 \times \Delta T$$

$$= 673{,}488680\ J/hK \times \Delta T = 0.2\ kW/K \times \Delta T$$

Residential Weatherization Techniques



Reduce cracks in window and door frames etc.

Public domain photo by Staff Sergeant Courtney Richardson, courtesy of US Air Force.

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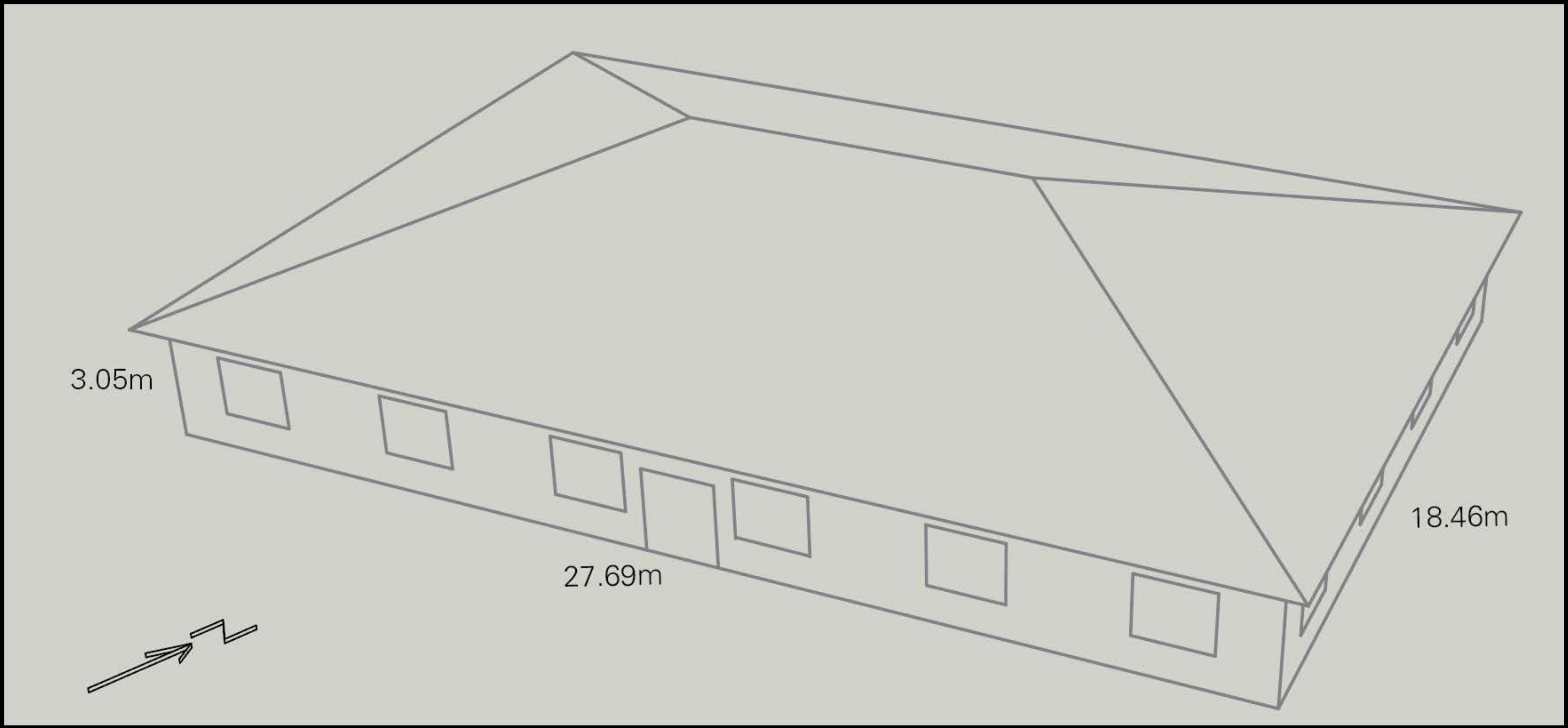
US DOE Benchmark Small Office Building



Floor area: 511.1 m^2
Wall area: 225.7 m^2
Roof area: 511.1 m^2
Window area: 55. 8 m^2

$TM_{\text{With concrete floor}} = 19.1$ kWh/K

$\Sigma UA_{Envelope} = 11.6$ kW

$ACH \times Vol \times c \times \rho = 0.2$ kW

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Do we need additional ventilation?

Assuming an ACH of 0.36/h, a volume of 1559 m^3 and 27 occupants, the fresh air supply per person [pp] is:

1559 m^3 x 0.36/h /27 pp= 20.1 m^3/h pp

A 1000 liter of air = 1m^3 of air

Fresh air per person = 20100 l/3600 s person ~ 6 l/s pp

There is insufficient fresh air in the non-weatherized building to provide the required hygienic ventilation to all occupants through infiltration when the windows are closed.

Sizing an Air Handling Unit

How much fresh air does a forced air system need to supply?

- ❑ 27 occupants need 20 x 10 l = 270 l/s = 0.27 m^3/s.

- ❑A 0.1 m^2 duct typically delivers around 0.13 m^3/s. This means that the building needs around 0.2 m^2 of supply ducts.

- ❑ A central, roof-mounted Air Handling Unit (AHU) requires roughly equally sized supply and return ducts, i.e. 2 x 0.2 m^2= 0.4 m^2.

Natural Ventilation

Excellent Reference

CIBSE manual AM10: Natural Ventilation in Non-domestic Buildings

ISBN 978-1903287569

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Why are we so excited about natural ventilation?

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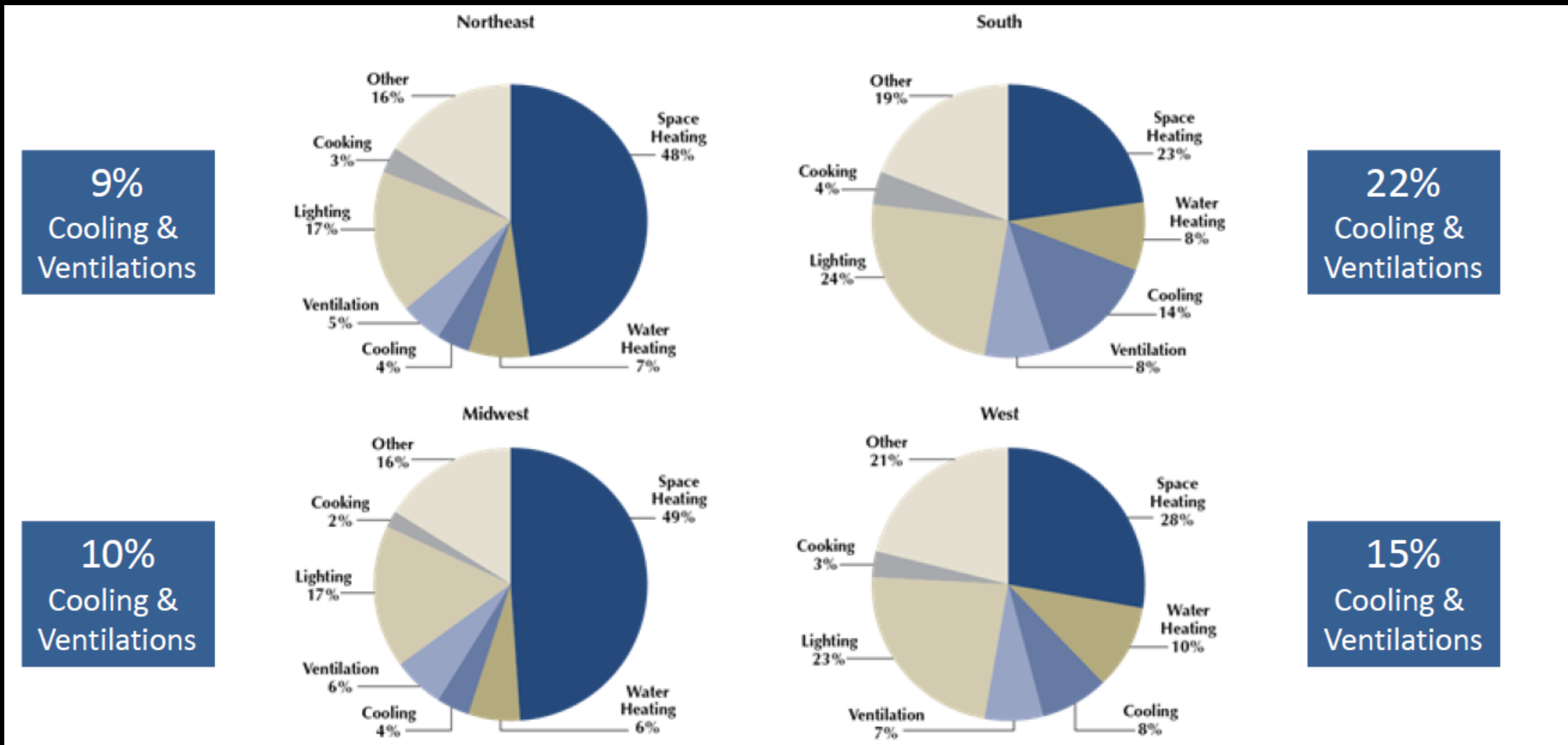
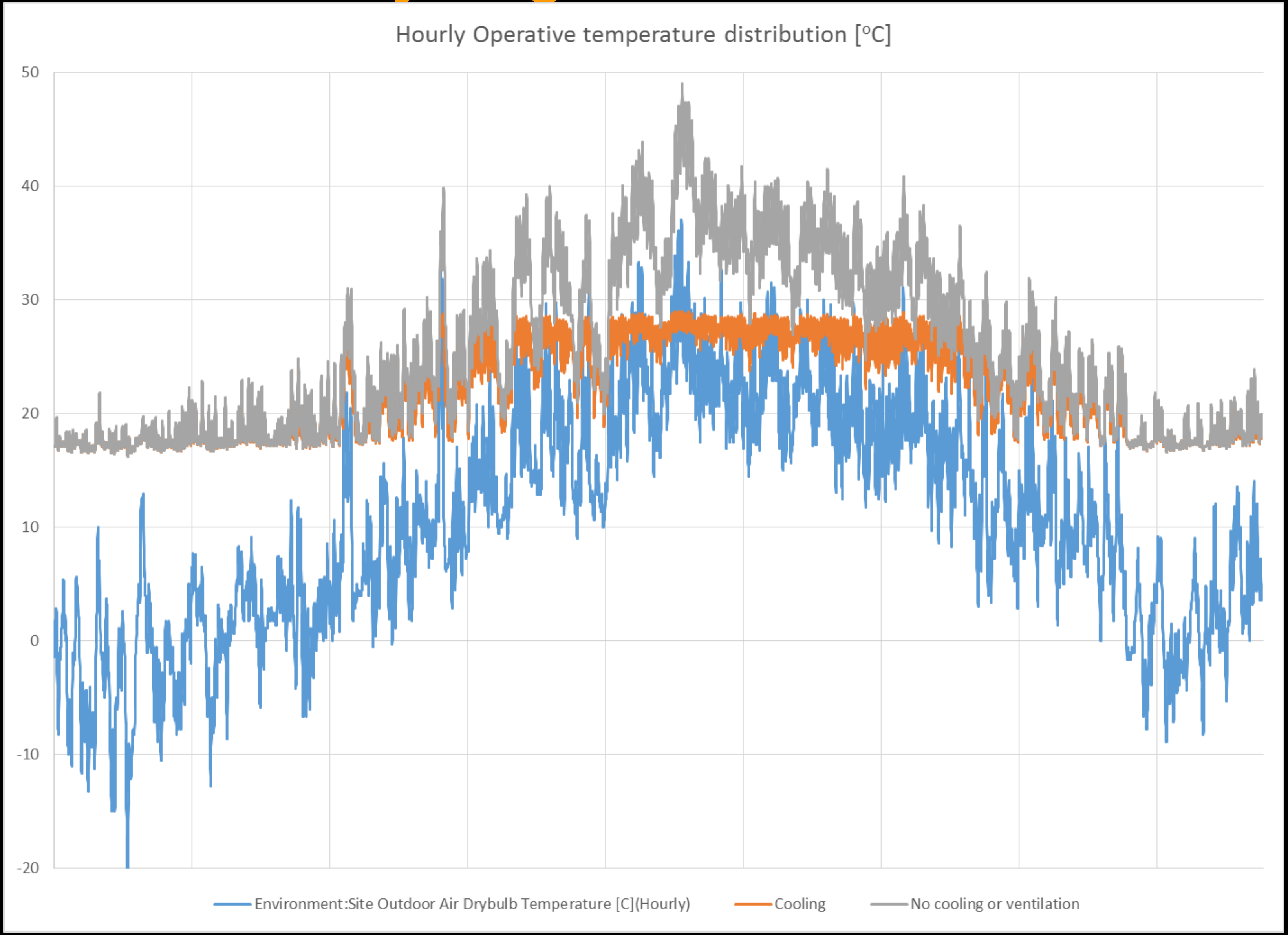
Energy Used for Cooling and Ventilation in US Commercial Buildings



Source: Energy Information Administration, Commercial Buildings Energy Consumption Survey 2009, "Building Characteristics," Table E1a. Available at:

Slide courtesy of Diego Ibarra. Used with permission.

Unfortunately, it gets a little warm…



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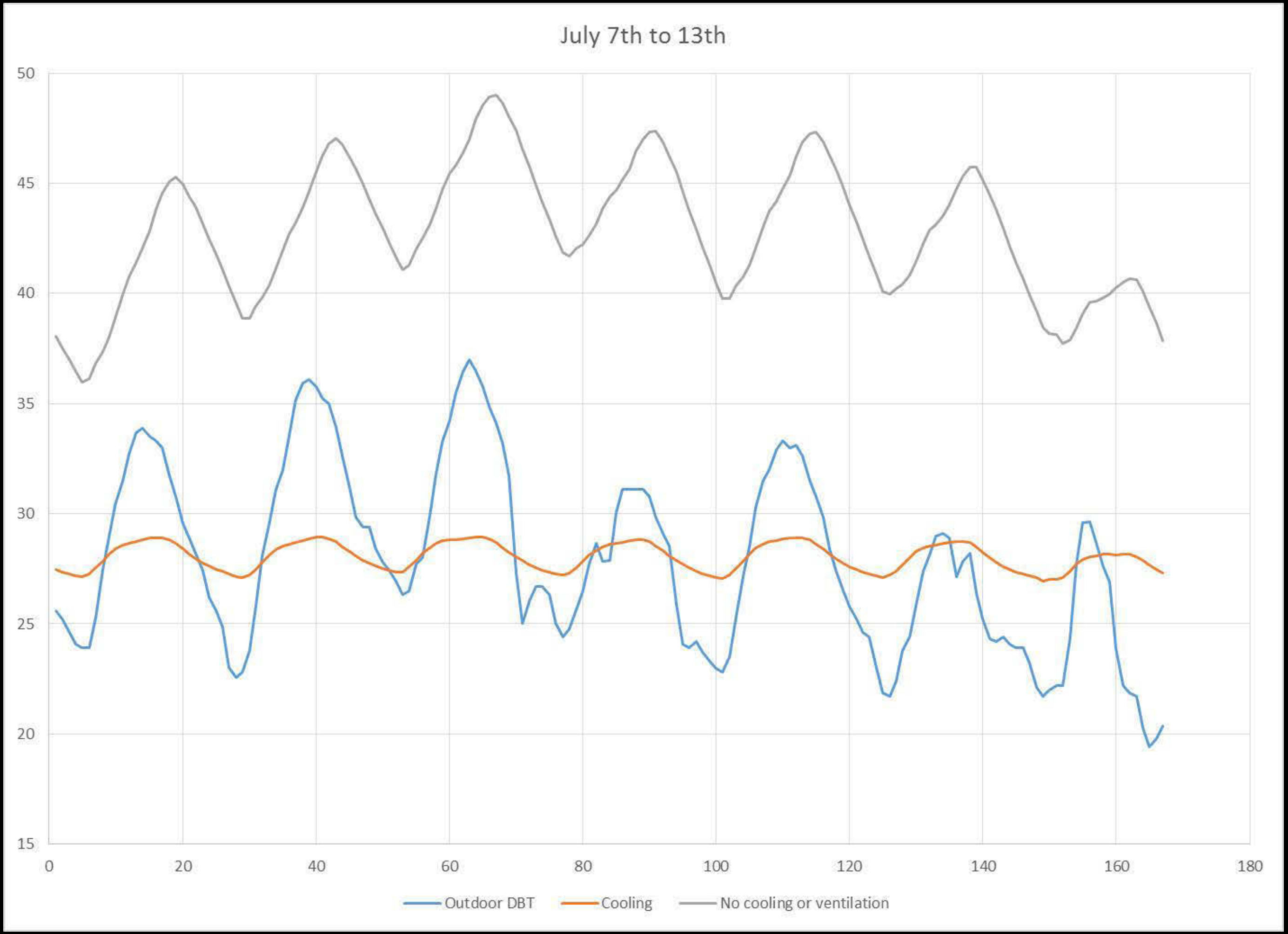
Summer Design Week (July 7th to 13th)



Of course, the reason why we do not simply discard our active cooling systems is that indoor temperatures rise. The figure compares temperatures in the New England Home with and without active cooling. In the no-cooling scenario the windows are permanently closed (no natural ventilation). At what point are the interior temperatures too high to be comfortable?

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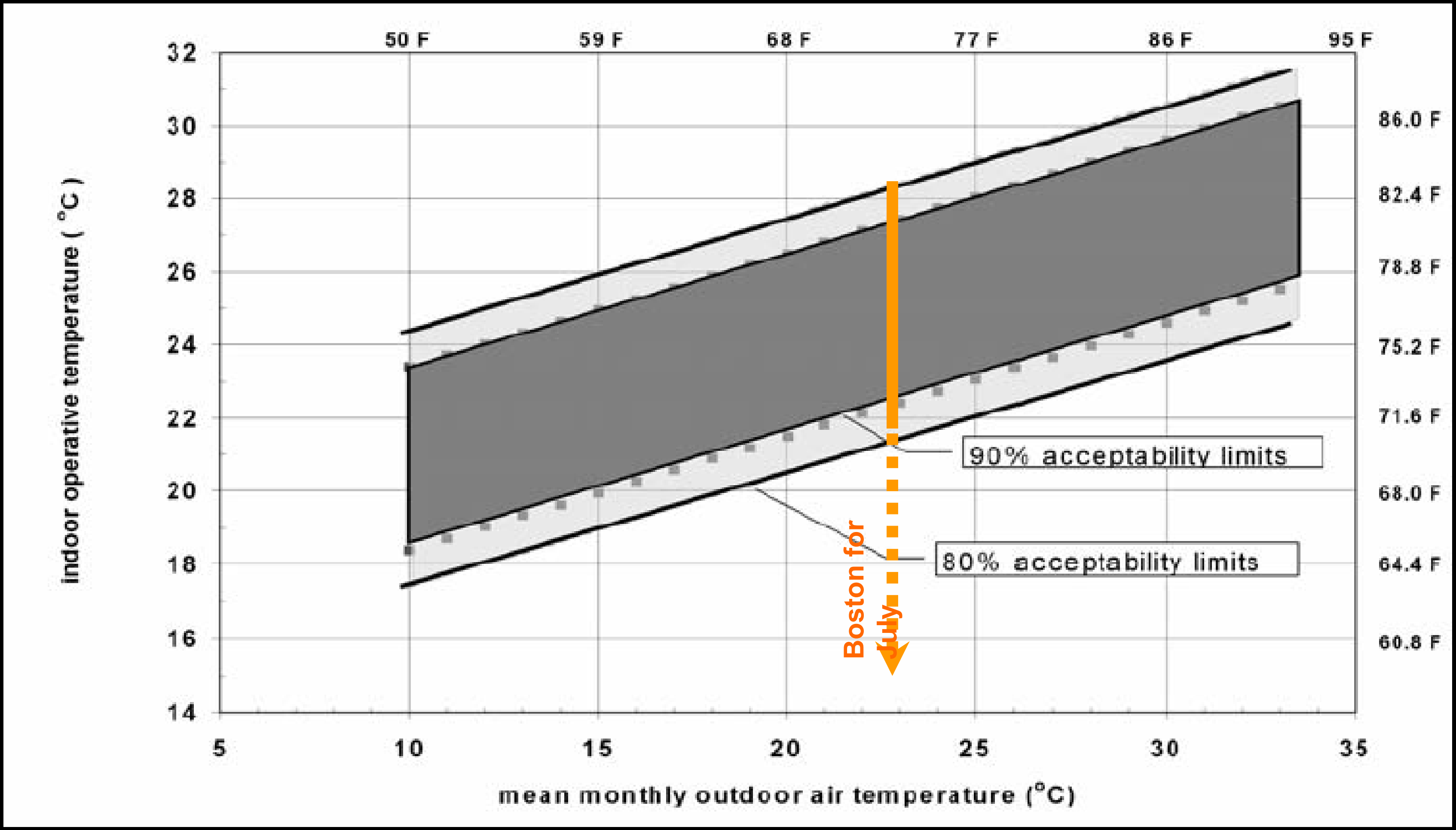
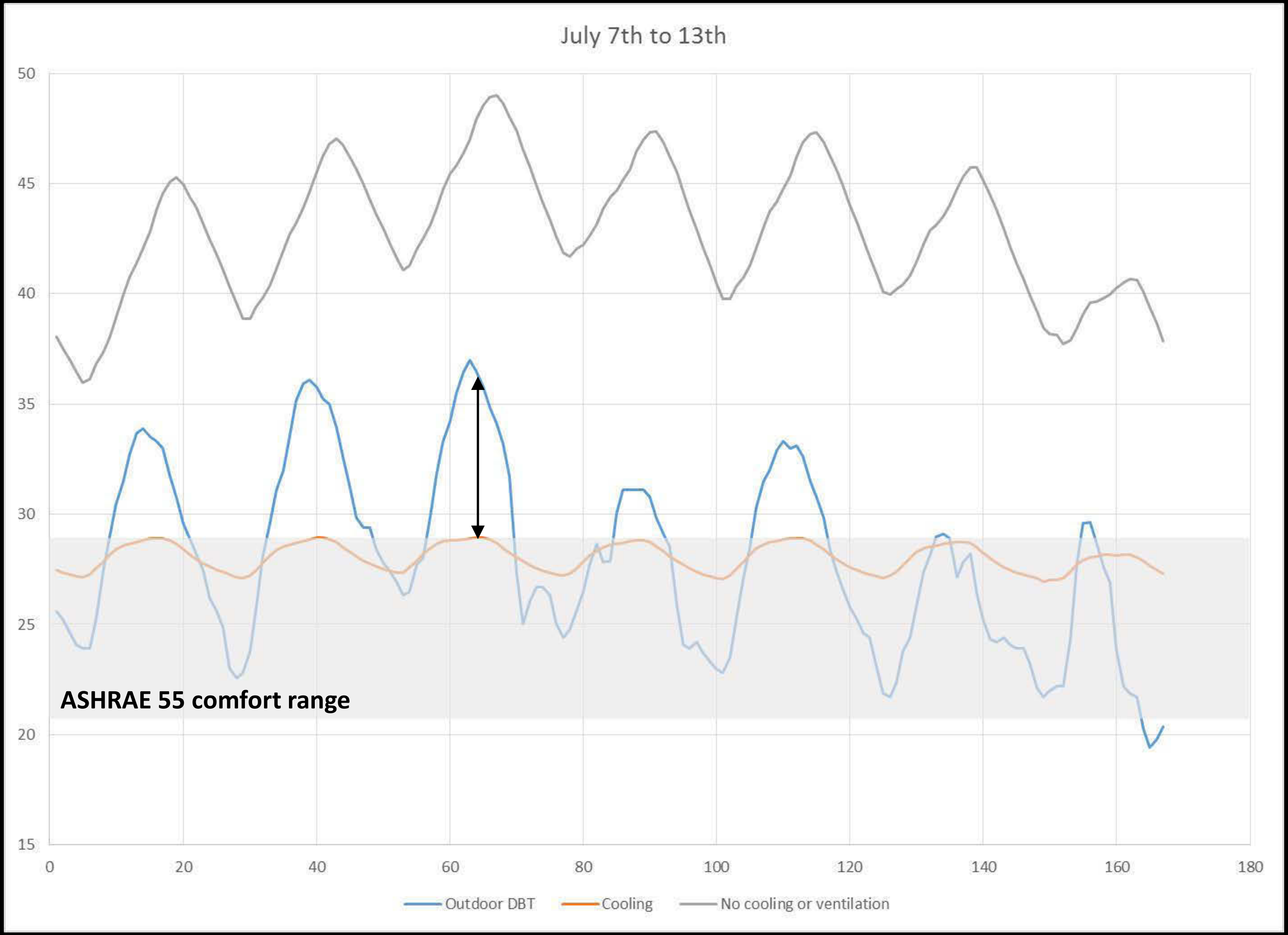
Acceptable Operative Temperature Ranges for Naturally Conditioned Spaces



The mean monthly temperature in Boston for the month of July is around 23° C. According to ASHRAE 55 this means that occupants are comfortable between 21° C and 28° C.

Can we reduce the inside temperature by opening the window?

Summer Design Week



The operative temperature for active cooling is just in the comfort range. The outdoor temperature is mostly above the comfort range so natural ventilation will not help during those situations.

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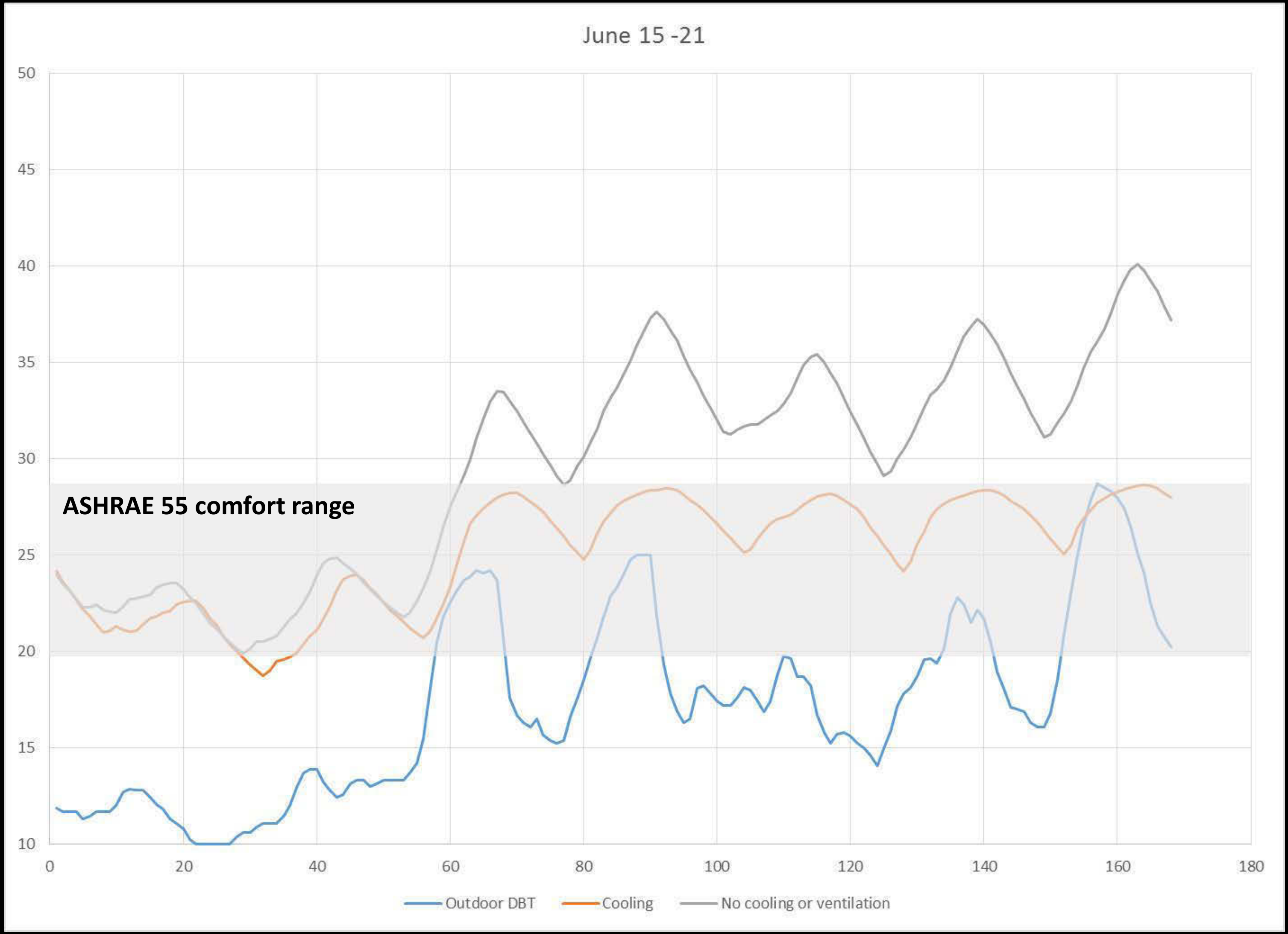
Typical Design Week



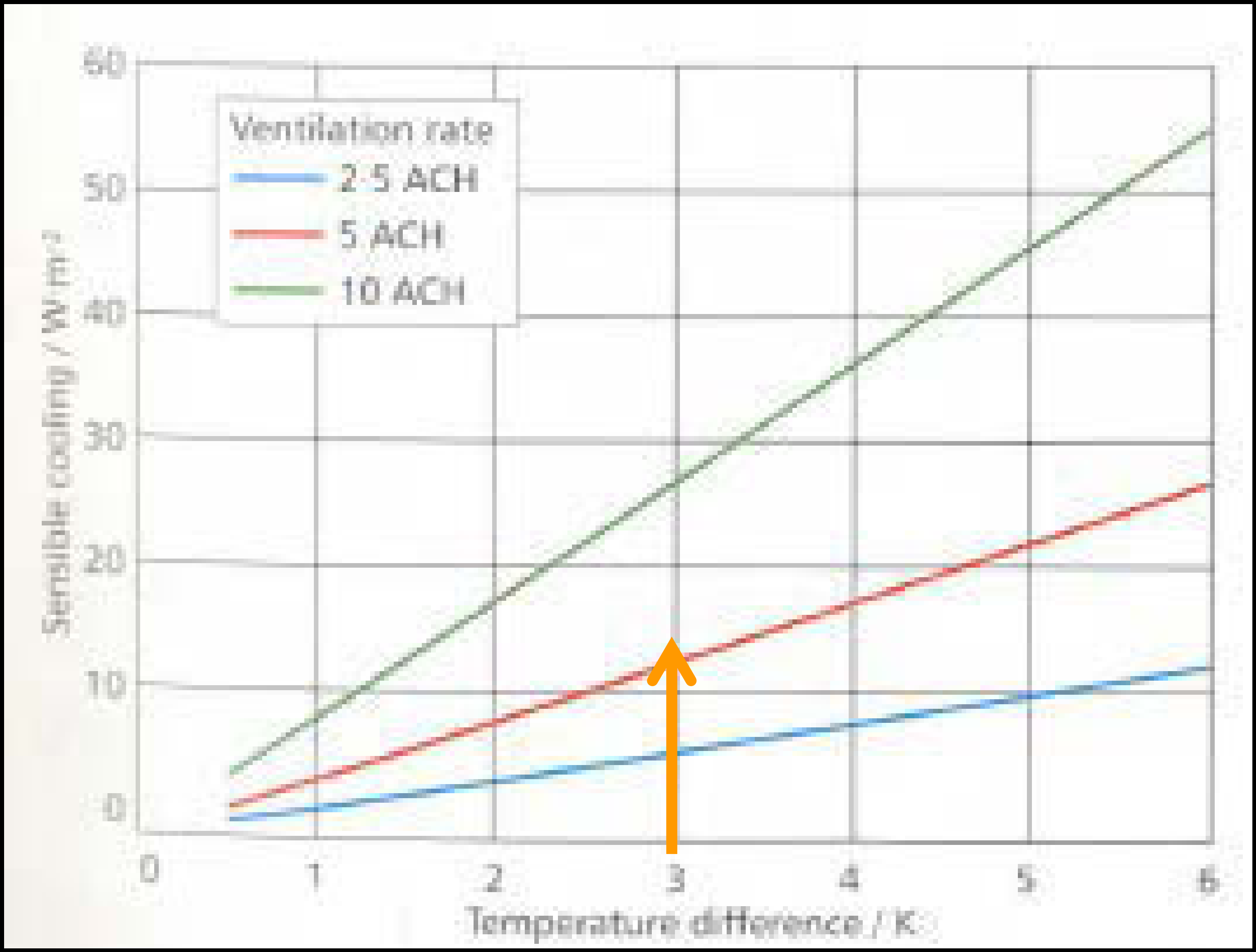
As a rule of thumb, we want the outside air at least 3 K below the maximum comfortable indoor temperature. During the typical summer week this is mostly the case, i.e. there is potential for natural ventilation during that week.

What is the required cooling load?

As will be established in Lecture 16, the mean hourly internal loads and solar gains are 2008 W and 6140 W, respectively. Given a floor area of 511 m^2, the typical load that has to be cooled away is:

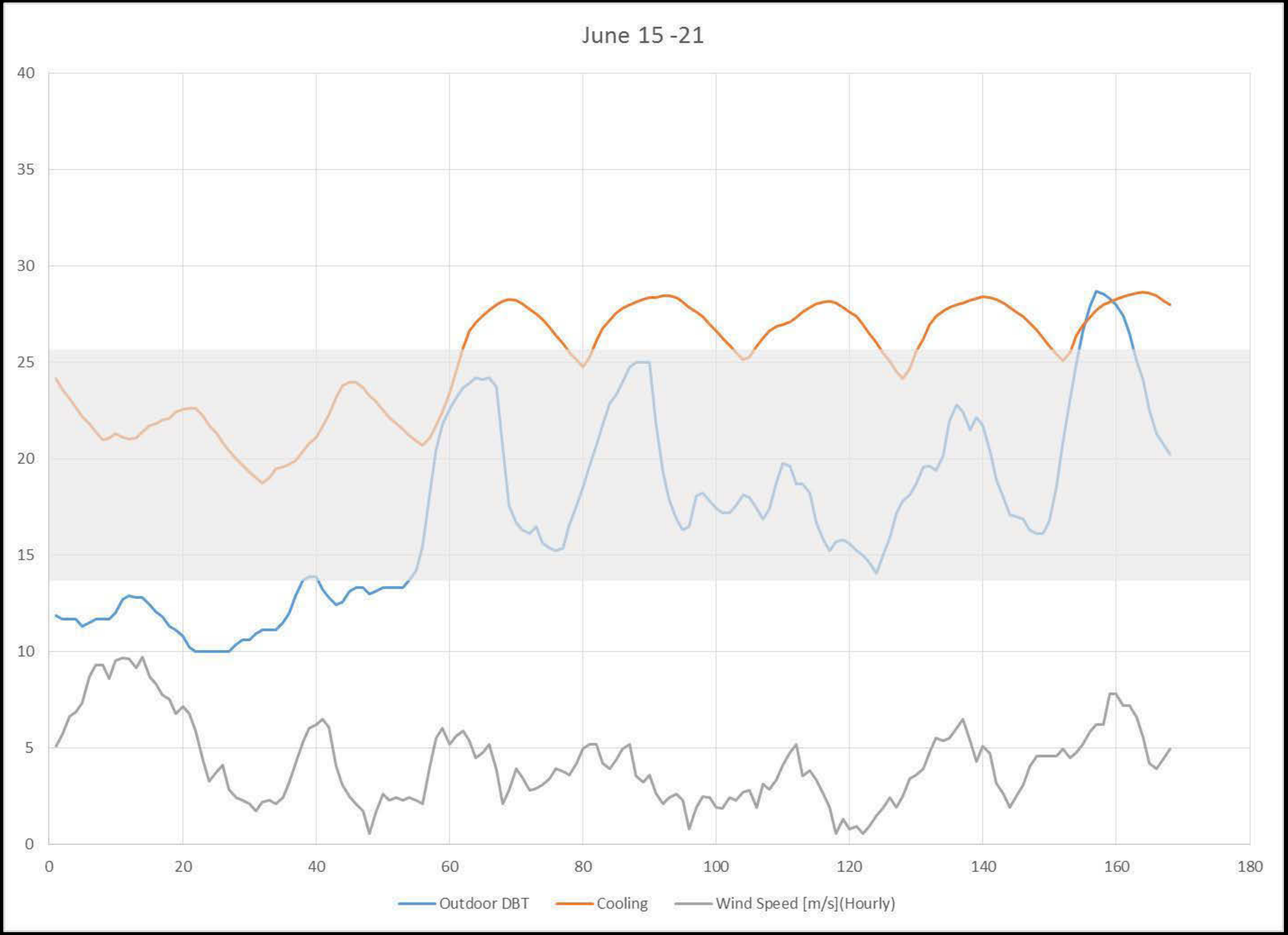
Average load = (2008 W + 6140 W)/511 m^2 ~ 16 W/m^2

Cooling From Natural Ventilation



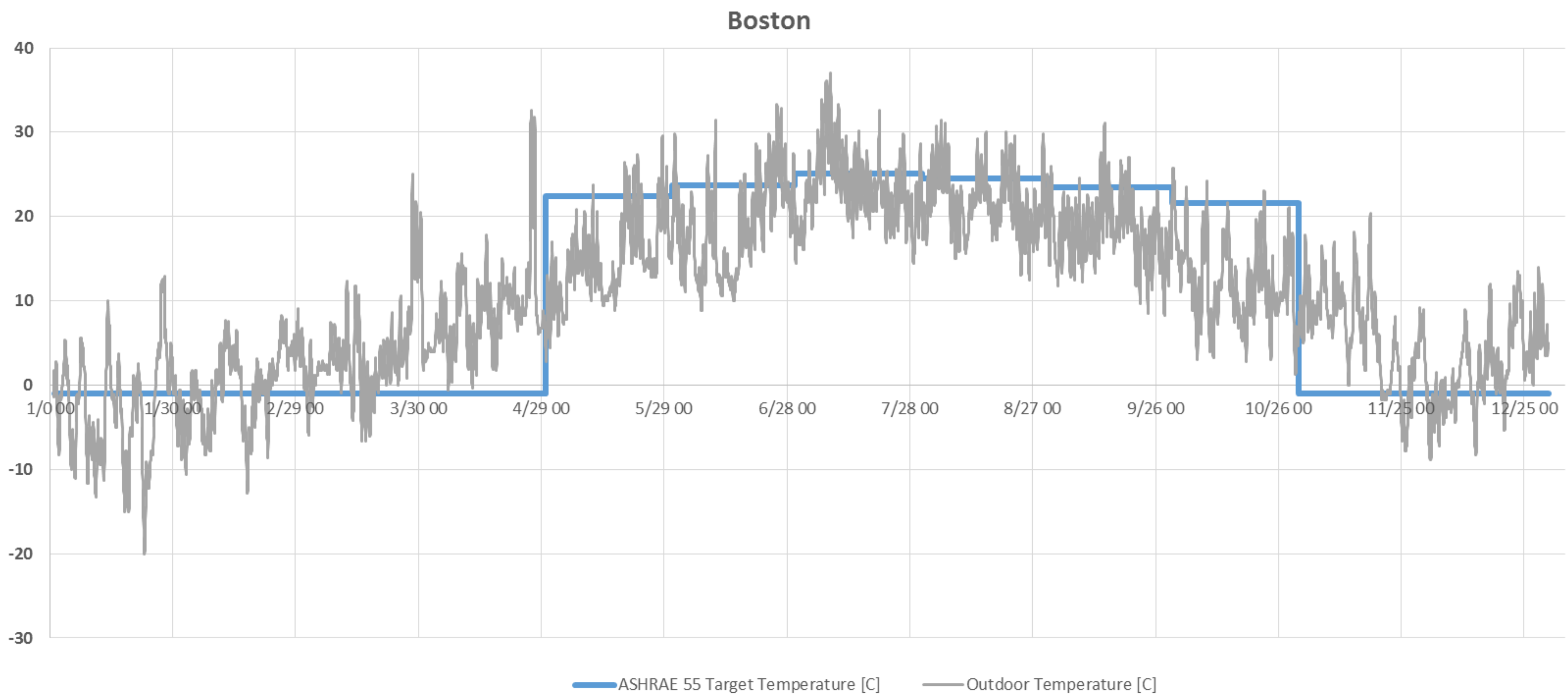
For a required cooling load of 16 Wm^{-2} and a temperature difference between inside and outside air (3K) the required air exchange rate is ACH ~6.

Potential for Natural Ventilation



There is some wind (5 m/s) when outdoor temperatures are high.

Outdoor Dry Bulb Air Temperature vs. ASHRAE 55 Maximum Indoor Temperature



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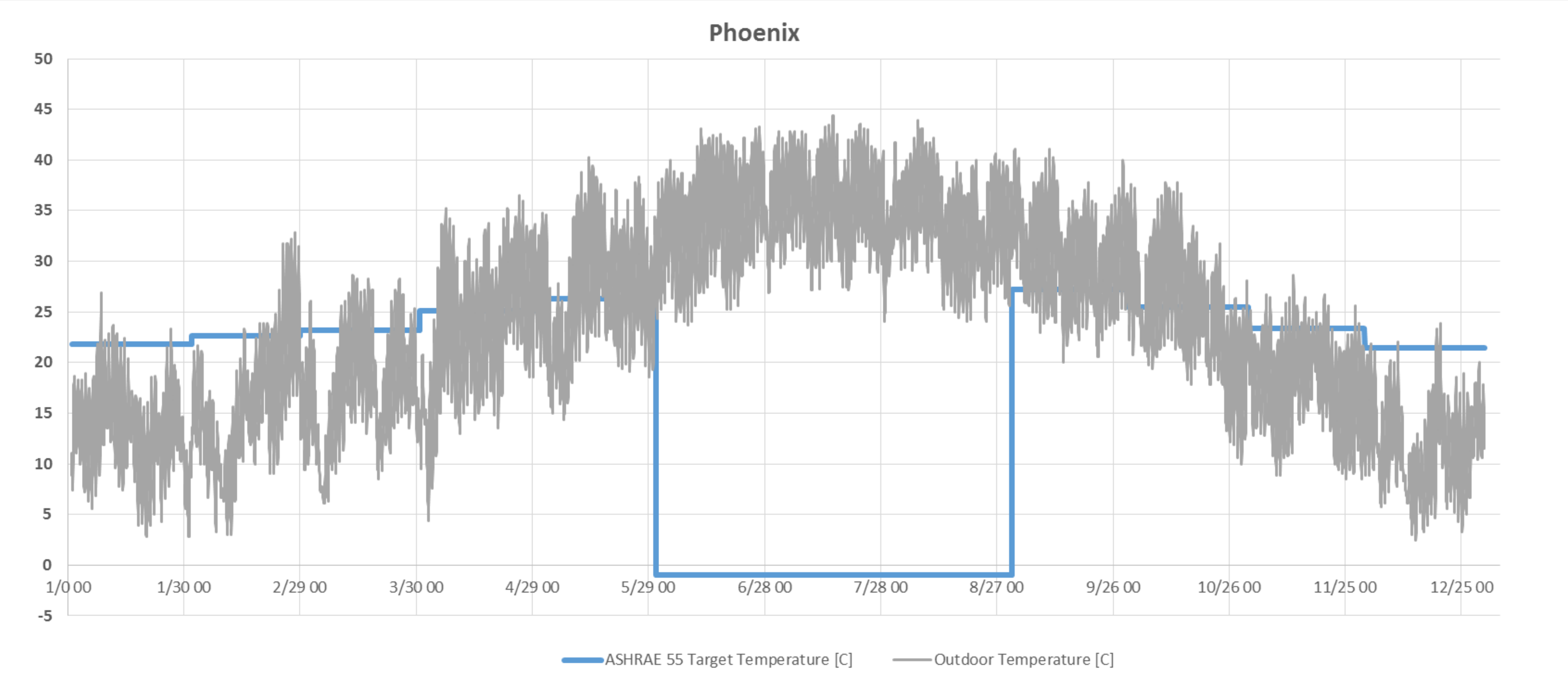
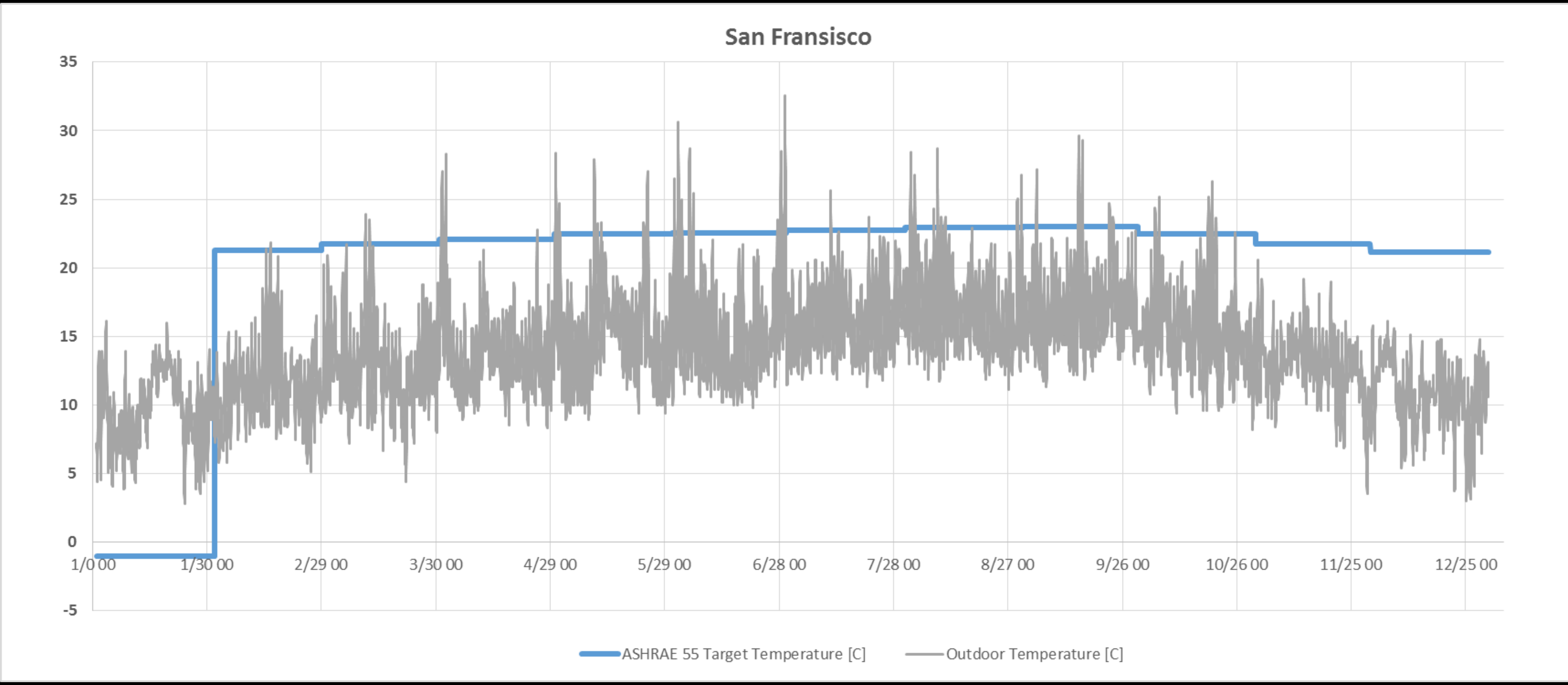
Outdoor Dry Bulb Air Temperature vs. ASHRAE 55 Maximum Indoor Temperature



Outdoor Dry Bulb Air Temperature vs. ASHRAE 55 Maximum Indoor Temperature



Do we want the outside air?

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Natural Ventilation

Based on the example it becomes apparent that we have to know the following:

Occupant Behavior: When are occupants opening and closing their windows and by how much?

Air Exchange Rate: What is the air exchange rate resulting from the occupants opening their windows? This air exchange rate depends on:

- ❑ Indoor Temperature
- ❑ Outdoor Temperature
- ❑ Window Arrangement
- ❑ Ambient Wind pattern (direction and speed)

Occupant Behavior – What do we know?

- Occupants open and close their windows *consciously* and *consistently*.

- The goal of opening the windows is to
  - create a connection to the outside (pleasant sounds, smells) and to
  - improve indoor environmental conditions (flush out VOCs, induce some air movement, replace inside air with fresh outside air).

Fachhochschule Bonn-Rhein-Sieg

Completed 1999, HMP Architekten. (Public domain photo courtesy of Stefan Knauf on Wikipedia.)

When the operable windows are opened the heating system shuts off.

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Syracuse Center of Excellence

Completed in 2010, Toshiko Mori Architect

Occupants get a visual signal when opening windows is adequate due to benign outdoor conditions (low traffic).

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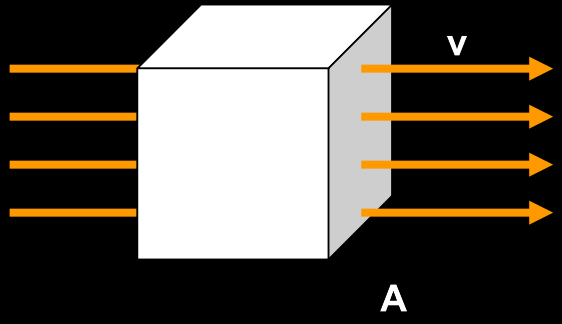
How do we get air to move?

Air Flow

Air flow or air movement is usually expressed through a volume flow rate, q. Typical units used are cubic feet per minute (cfm) and liters per second (L/s). Sometimes, the ventilation rate is also expressed on a per person or per unit floor area basis, such as cfm/p or cfm/ft^2.



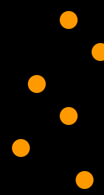
q = area * velocity

Note: When designing a ventilation system, the ventilation rates are required to determine the sizes of fans, openings, and air ducts.

What causes air flow?

Air flow is caused by a pressure difference. Air will flow from a zone of high pressure to a zone of low pressure.

$P_1 = P_2$



no flow

$P_1 > P_2$

air flow

Air Flow and Air Exchange Rate

Air flow, q , and air exchange rates, ACH, are closely related. The required air exchange rate during the typical summer week is 5 ACH.

The volume of the house is 1559 m^3 so

Required flow rate = 6 h^{-1} x 1559 m^3 ~2.6 m^3/s

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Driving Forces for Airflow in Buildings

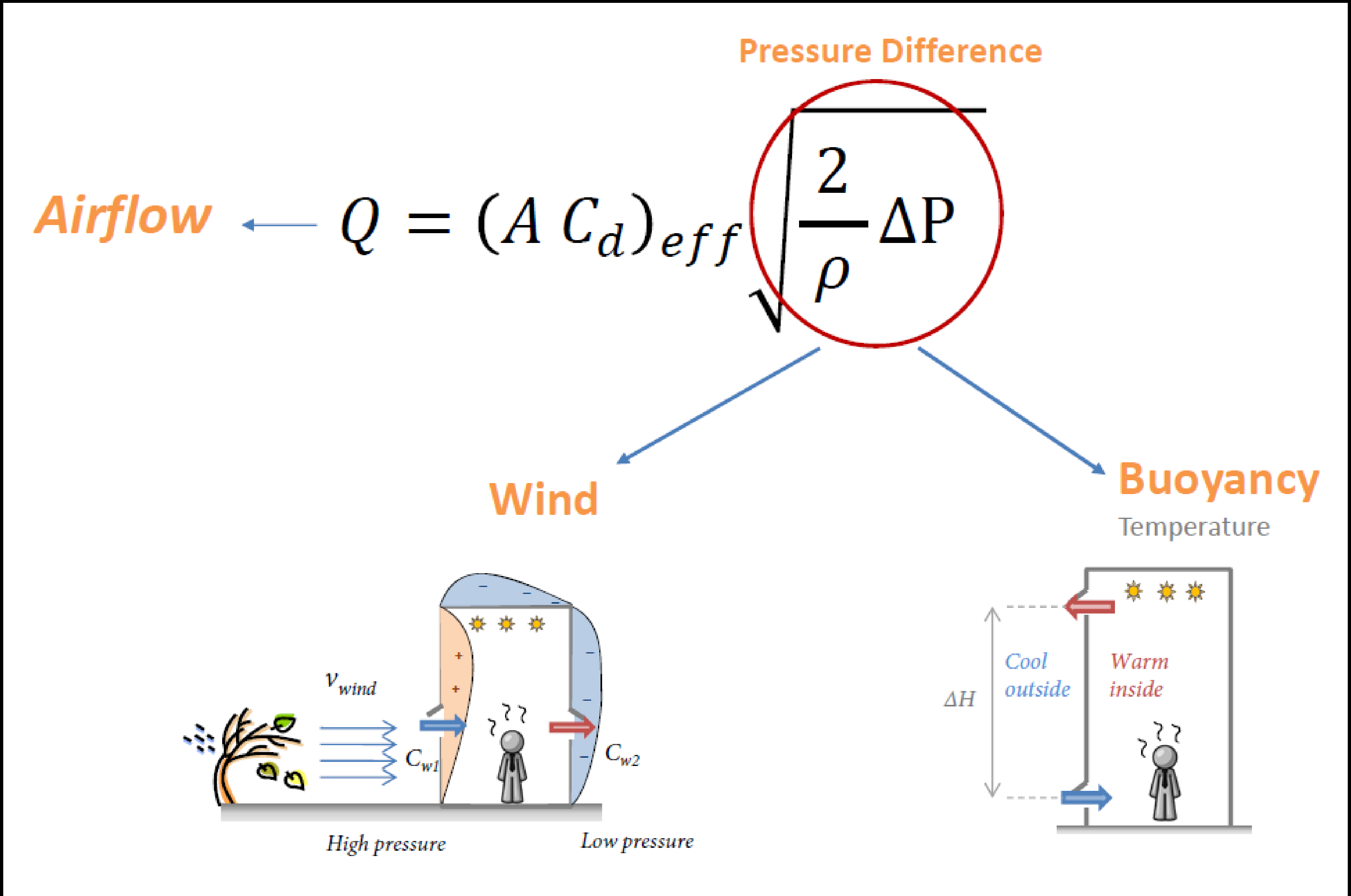
$$Q = (A\,C_d)_{eff}\sqrt{\frac{2}{\rho}\Delta P}$$

Airflow = **Area effective** X **Pressure Difference**

Area effective
- Opening Area [m^2]
- Discharge Coefficient [~0.6]

Pressure Difference inside and outside

Driving Forces for Airflow in Buildings



Slide courtesy of Diego Ibarra. Used with permission.

Driving Forces for Airflow in Buildings

Pressure Difference

Airflow ← $Q = (A\,C_d)_{eff}\sqrt{\frac{2}{\rho}\Delta P}$

Wind

$$Q_w = (AC_d)_{eff}\, v_W \sqrt{C_{w1} - C_{w2}}$$

Buoyancy

$$Q_B = (AC_d)_{eff}\sqrt{g\,2\,\Delta H\,\frac{\Delta T}{T_{in}}}$$

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Buoyancy

Hydrostatic Pressure

$P = h \times g \times \rho + P_a$ **hydrostatic pressure**

Where:

g = gravitational acceleration = 9.81 m/s^2

h = depth under water [m]

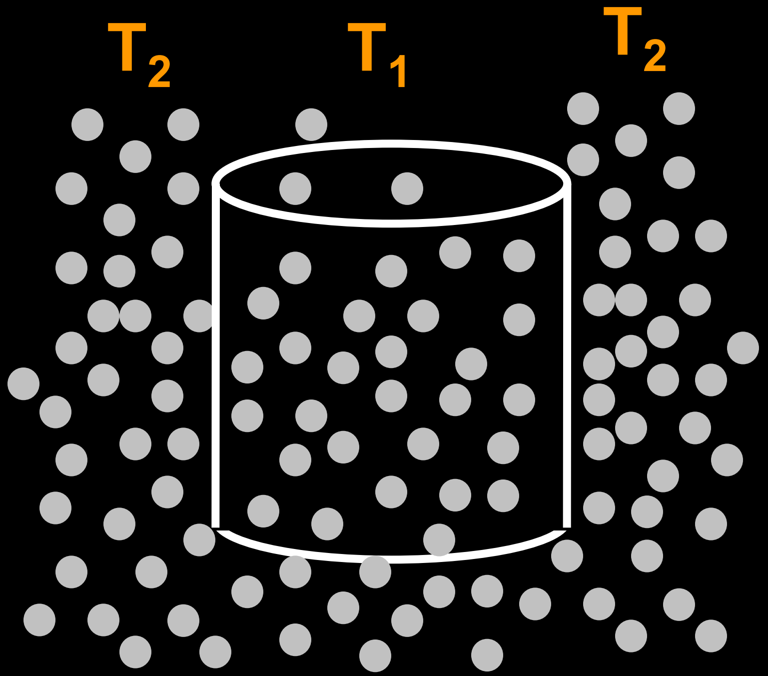
ρ = density of water kg/m^3

P_a = Atmospheric Pressure

- Think of a diver under water.
- Same as water, the weight of the atmosphere also exerts pressure on objects at sea level.

Air Flow - Stack Effect (Chimney Effect)

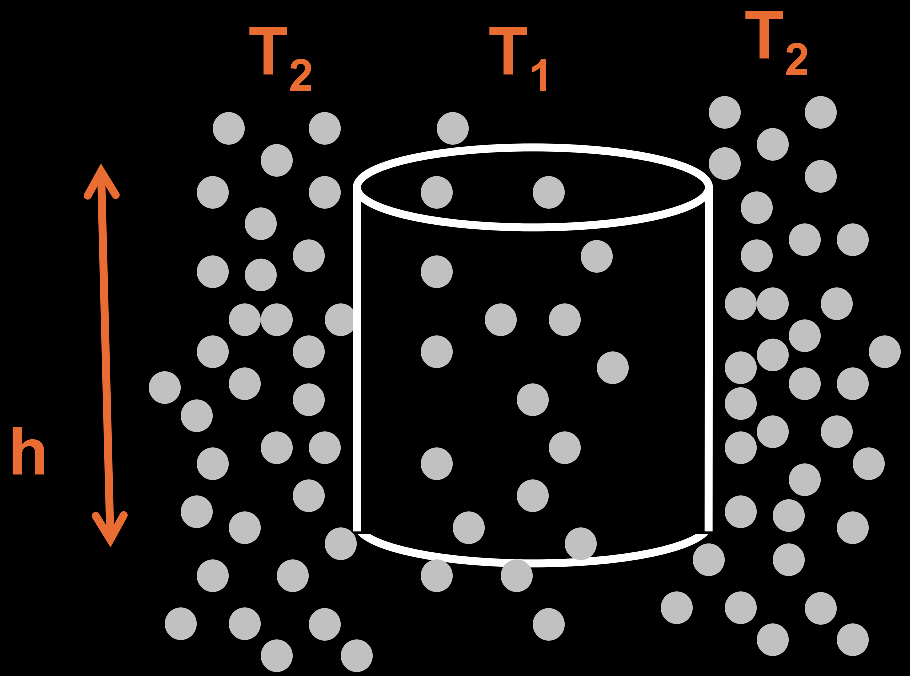
$T_2 = T_1$



What happens to the air in the cylinder?

Air Flow - Stack Effect (Chimney Effect)

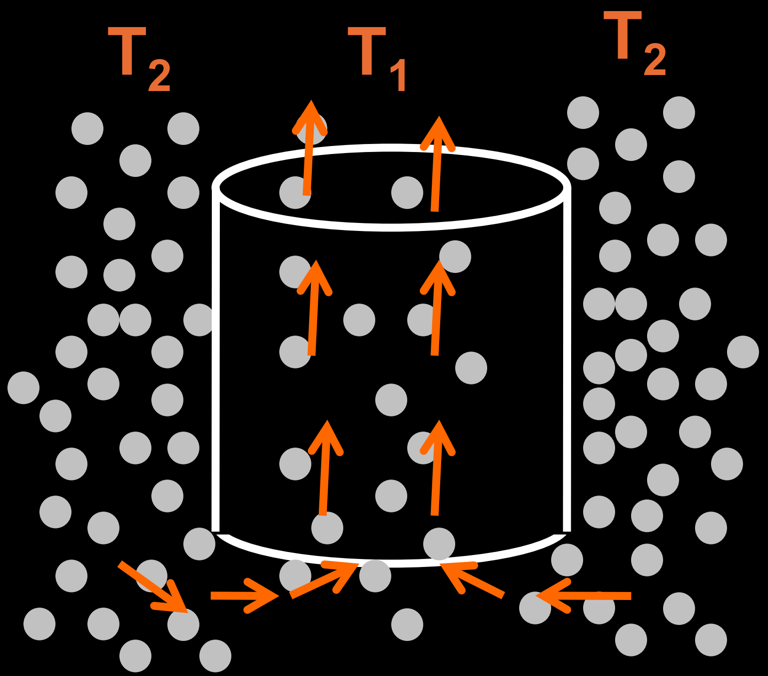
$T_2 < T_1$



Warm air has a lower density than colder air (more particle movements => less particles per space).

Air Flow - Stack Effect (Chimney Effect)

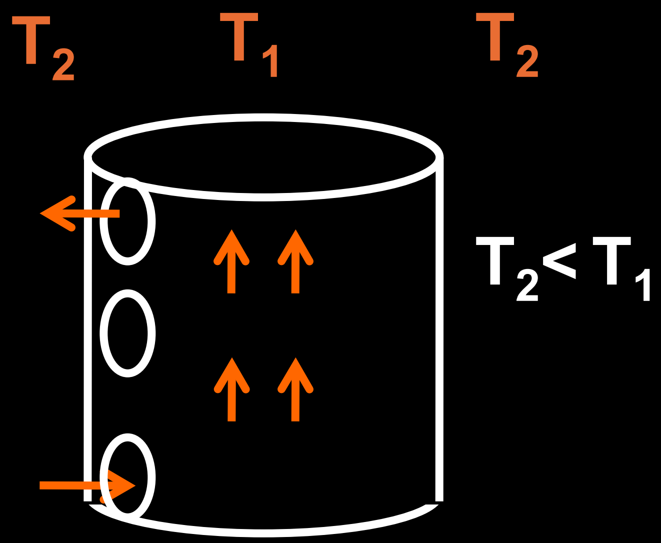
$T_2 < T_1$



In a cylinder with heated inside air the warmer/lighter inside air rises and the cooler/heavier air flow in through the bottom opening.

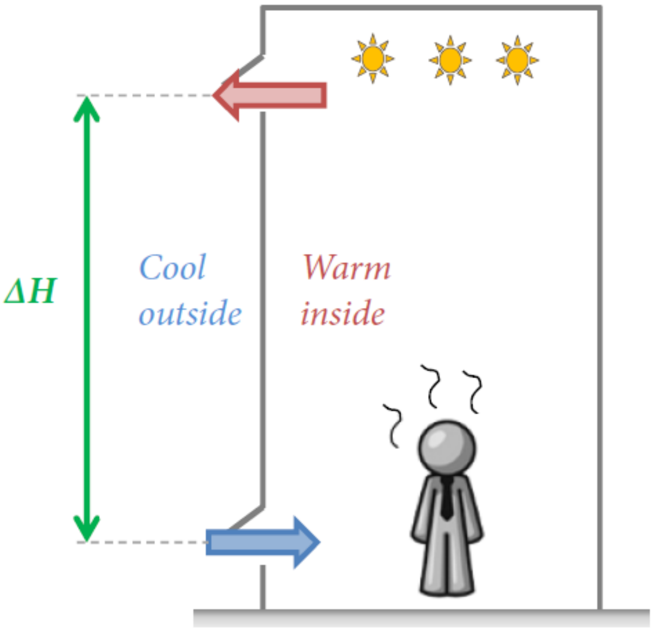
Air Flow - Stack Effect (Chimney Effect)

Now think of the cylinder as a building. There will be one height at which there is no pressure difference between the outside and the inside. This is called the neutral pressure level.



During the winter the inside temperature is higher than the ambient temperature and the base of the building is depressurized whereas the top is pressurized. During the summer the relationship is reversed. As a consequence basements draw in cool air in the winter. During the summer moist air from the main living areas is pushed into the basement, which tends to be cooler than the rest of the house, which may in turn lead to condensation. The consequence is that dehumidifiers are often needed in basements in air-conditioned buildings.

Stack Ventilation



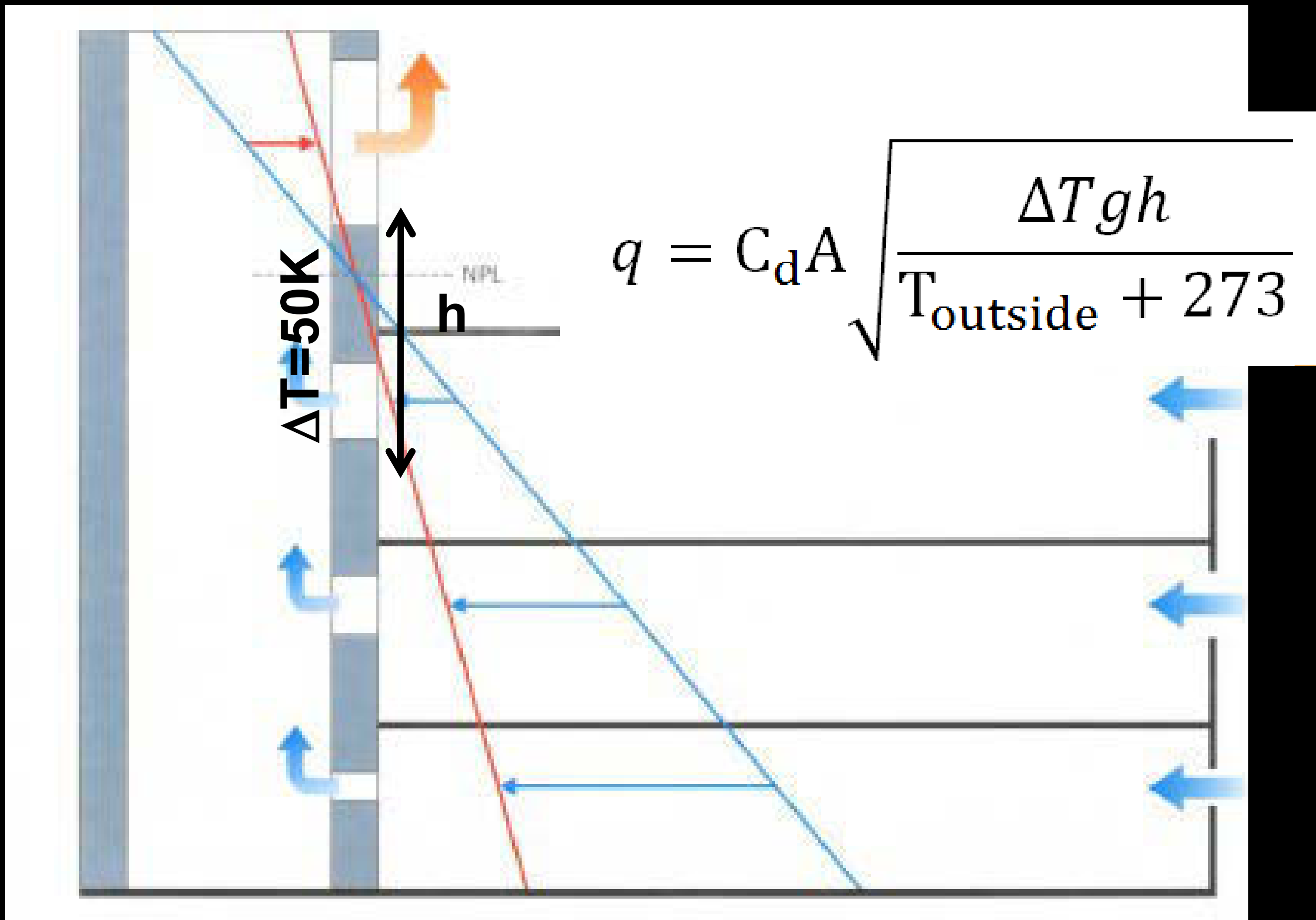
Basic strategies

1. Maximize distance between inlet and exhaust (i.e. shafts, tall windows, vertically spaced openings)
2. Maximize inlet and exhaust area, minimize obstructions
3. Maximize heat gains inside <u>*unoccupied spaces*</u> using a solar chimney

$$Q_B = (AC_d)_{eff} \sqrt{g\, 2\, \Delta H \frac{\Delta T}{T_{in}}}$$

$$Flowrate \sim A_{openings/obstructions} \sqrt{\Delta H * \textbf{heat gains}}$$

Principle of a Solar Chimney



$$q = C_d A \sqrt{\frac{\Delta T g h}{T_{outside} + 273}}$$

- ❑ Superheat the air in the solar chimney.
- ❑ Increase the height difference between air intake and exhaust.
- ❑ Move the neutral pressure level up.
- ❑ An effective stack is twice as tall as the tallest space it is ventilating.
- ❑ Stack can be interior (atrium) or exterior (chimney).

BRE Environmental Building

Architecture: Feilden Clegg Bradley Studios
Image deleted due to copyright restrictions.

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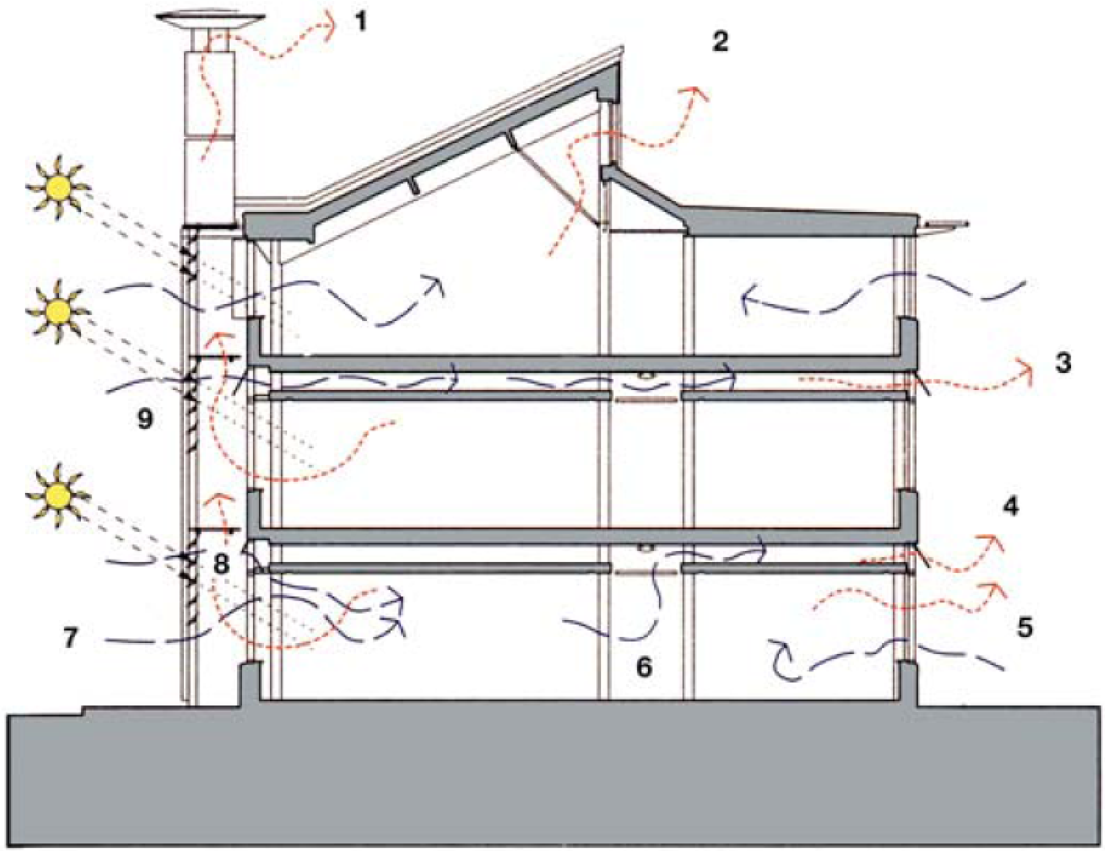
BRE Environmental Building

Office cross-section

1 Stack ventilation for hot still conditions
2 High level BMS controlled ventilation
3 Night time purge through slab
4 Cross-ventilation bypass over cellular offices
5 Cellular office single sided ventilation
6 Corridor cross over zone
7 Low level manually operated windows
8 High level motorised windows
9 Motorised external glass shading louvres



Architecture: Feilden Clegg Bradley Studios.
Image courtesy of Feilden Clegg Bradley Studios. Used with permission.

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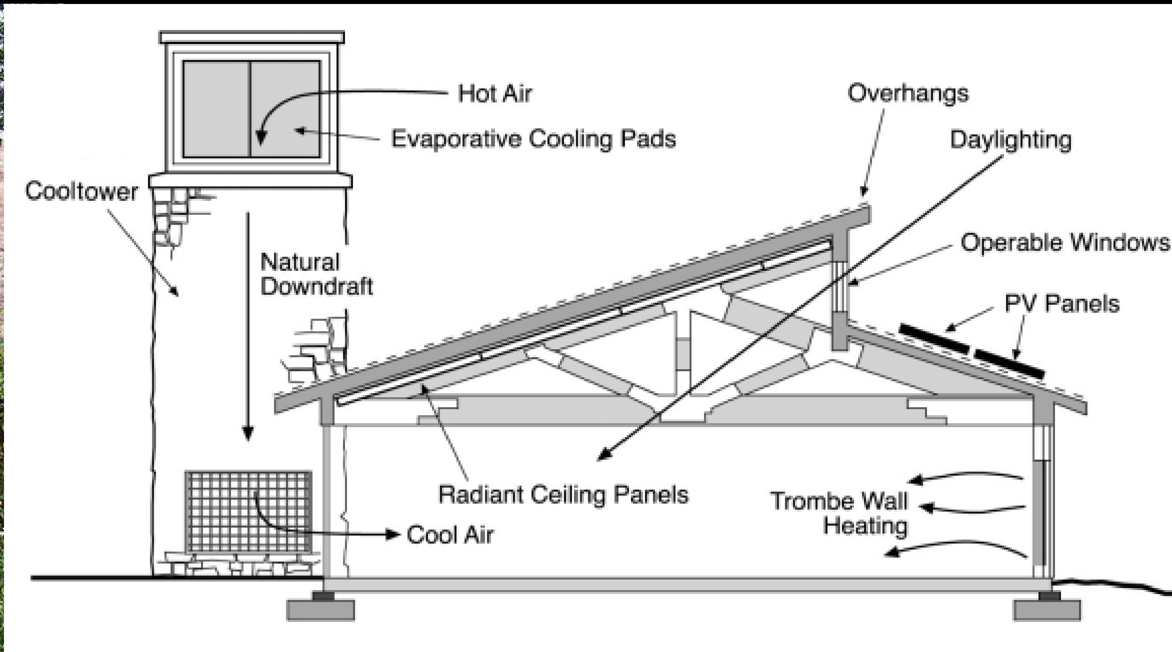
Evaporative Downdraft Cooling Tower



Visitor Center, Zion National Park (environmental design by NREL)
Left: photo courtesy of J. Stephen Conn on Flickr. License: CC BY-NC.
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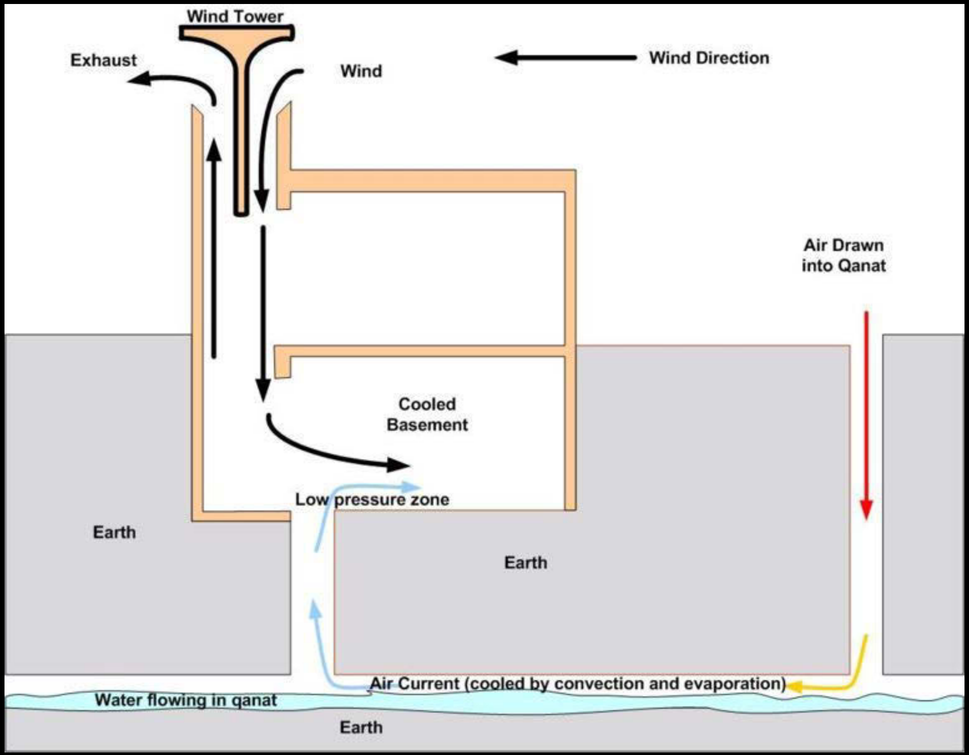
Wind Catcher



Wind Tower and Qanat

Wind catcher in Dowlat-abad, Yazd, Iran

- Open the leeward side for updraft (works together with stack effect)
- Open the windward side for downdraft (works against the stack effect)
- Qanat (water reservoir) further cools and humidifies the air

Calculation Procedures

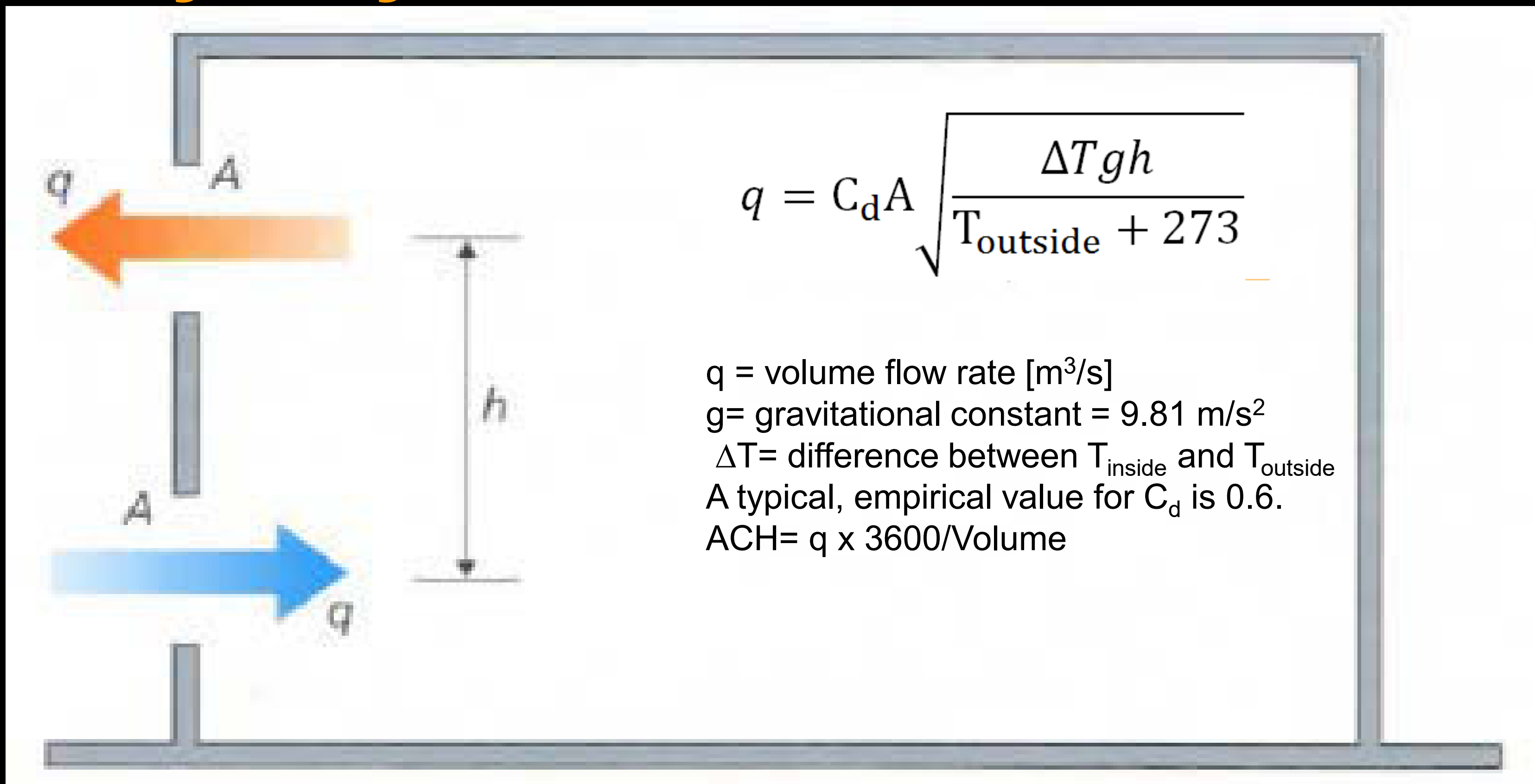
The previous slides have shown that following the air exchange rate is a key component in defining the cooling load of a natural ventilation concept.

There are a series of different calculation procedures that can be used to estimate air exchange rates in naturally ventilated spaces:

- ❑ Envelope flow models (semi-empirical models)
- ❑ Computational fluid dynamics (CFD)
- ❑ Combined thermal and ventilation models
- ❑ Physical scale models

In the following slides, several envelope flow models are presented.

Air Flow – Single sided, two vents, buoyancy driven

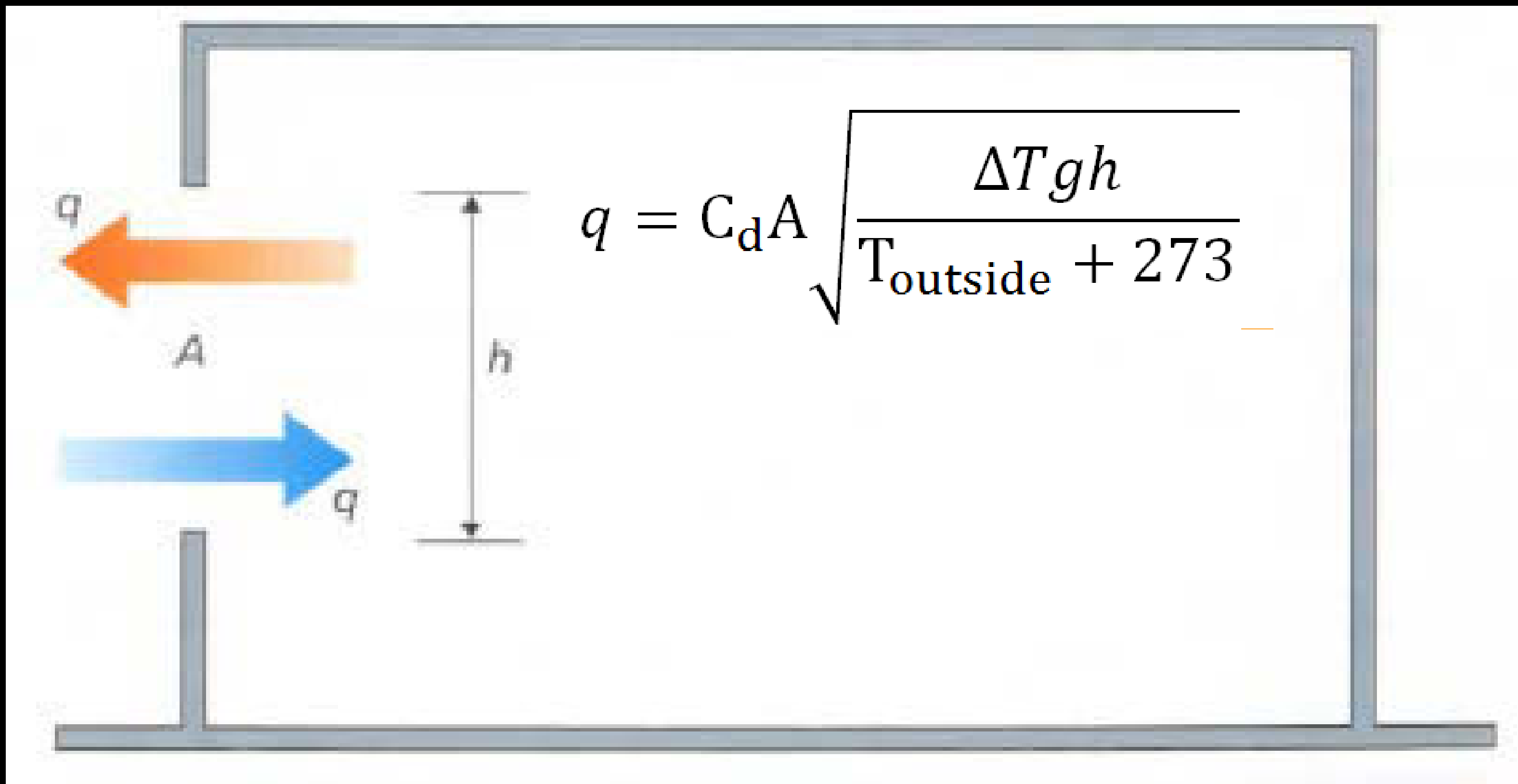


$$q = C_d A \sqrt{\frac{\Delta T g h}{T_{outside} + 273}}$$

q = volume flow rate [m^3/s]
g= gravitational constant = 9.81 m/s^2
ΔT= difference between T_{inside} and $T_{outside}$
A typical, empirical value for C_d is 0.6.
ACH= q x 3600/Volume

The concept only works if it is warmer inside than outside and if (in a side-vented space) the room depth is less than about 2.5 times the window head height. In a space with vents on both sides the depth may be increased up to 5 times the window head height.

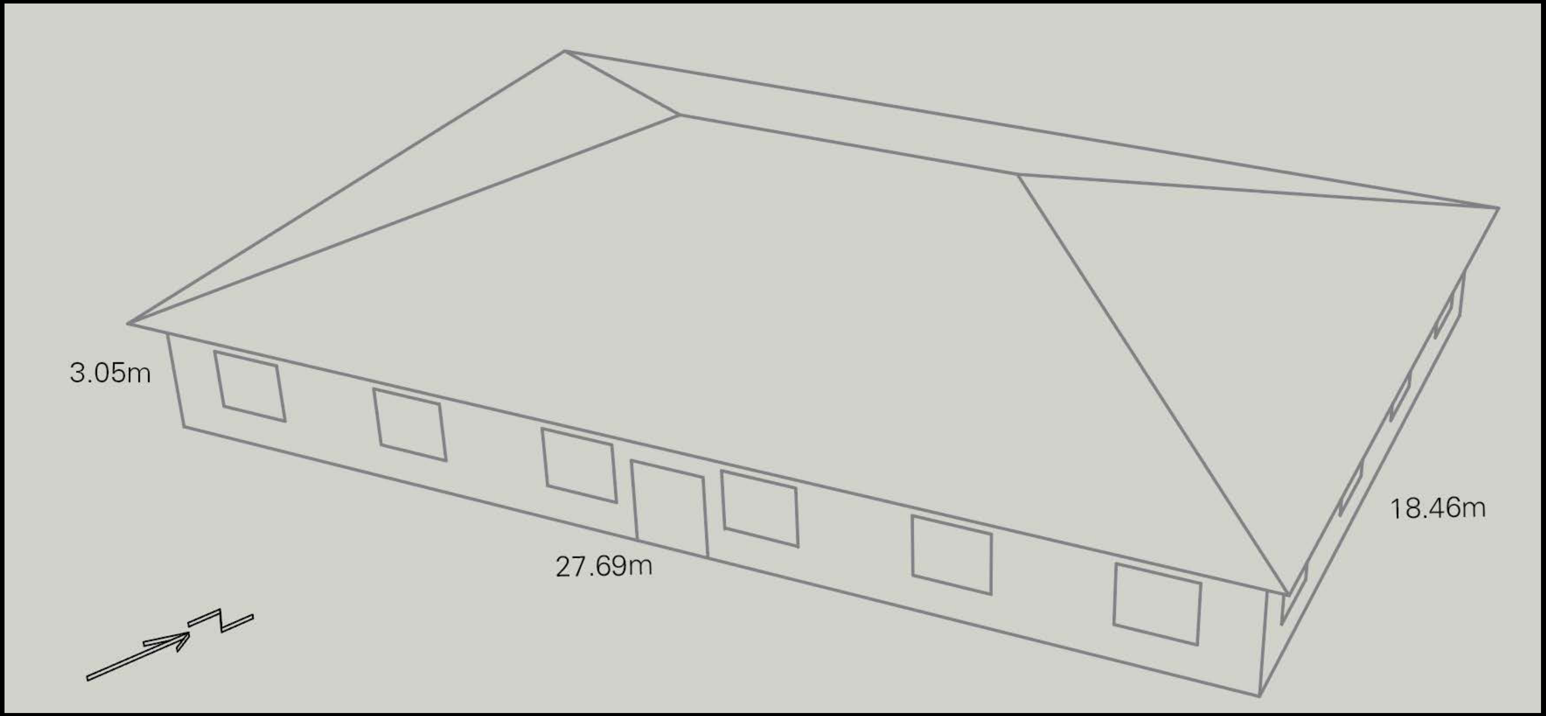
Air Flow – Single sided, single vent, buoyancy driven



$$q = C_d A \sqrt{\frac{\Delta T g h}{T_{outside} + 273}}$$

A typical value for C_d is 0.25 as air only enters through parts of the window. This is an empirical formula.

Example – DOE Benchmark Building



Assuming

$T_{outside}$ = 27° C

T_{inside} = 24° C

$A_{windows}$ = 2.4 m^2

C_d = 0.25

$$q = C_d A \sqrt{\frac{\Delta T g h}{T_{outside} + 273}}$$

q = 0.25 x 55.8 m^2 x sqrt(3K *9.81 ms^{-2} x 1.5 m/297K)

=5.4 m^3s^{-1}

ACH = 5.4 m^3s^{-1} x 3600 s/h / 1559 m^3

= 12.5 h^{-1}

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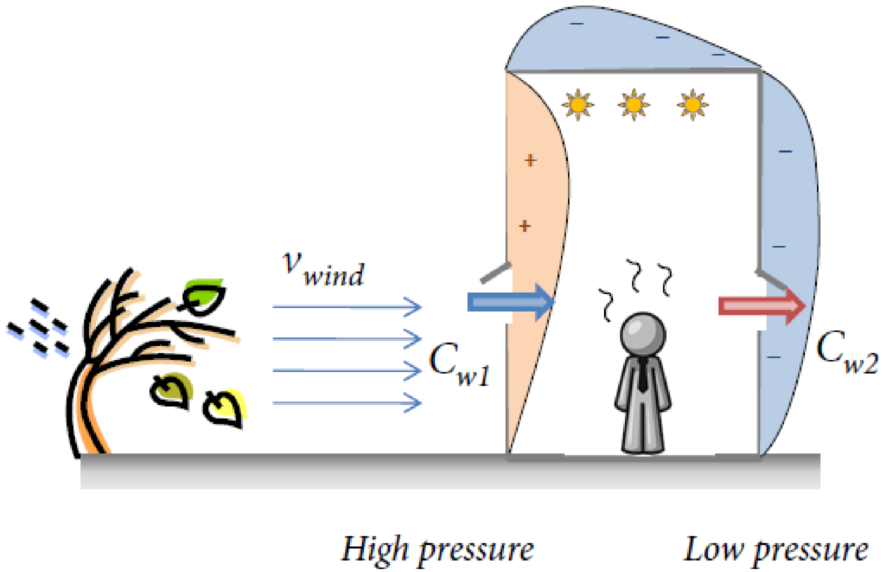
Wind

Wind Driven Ventilation



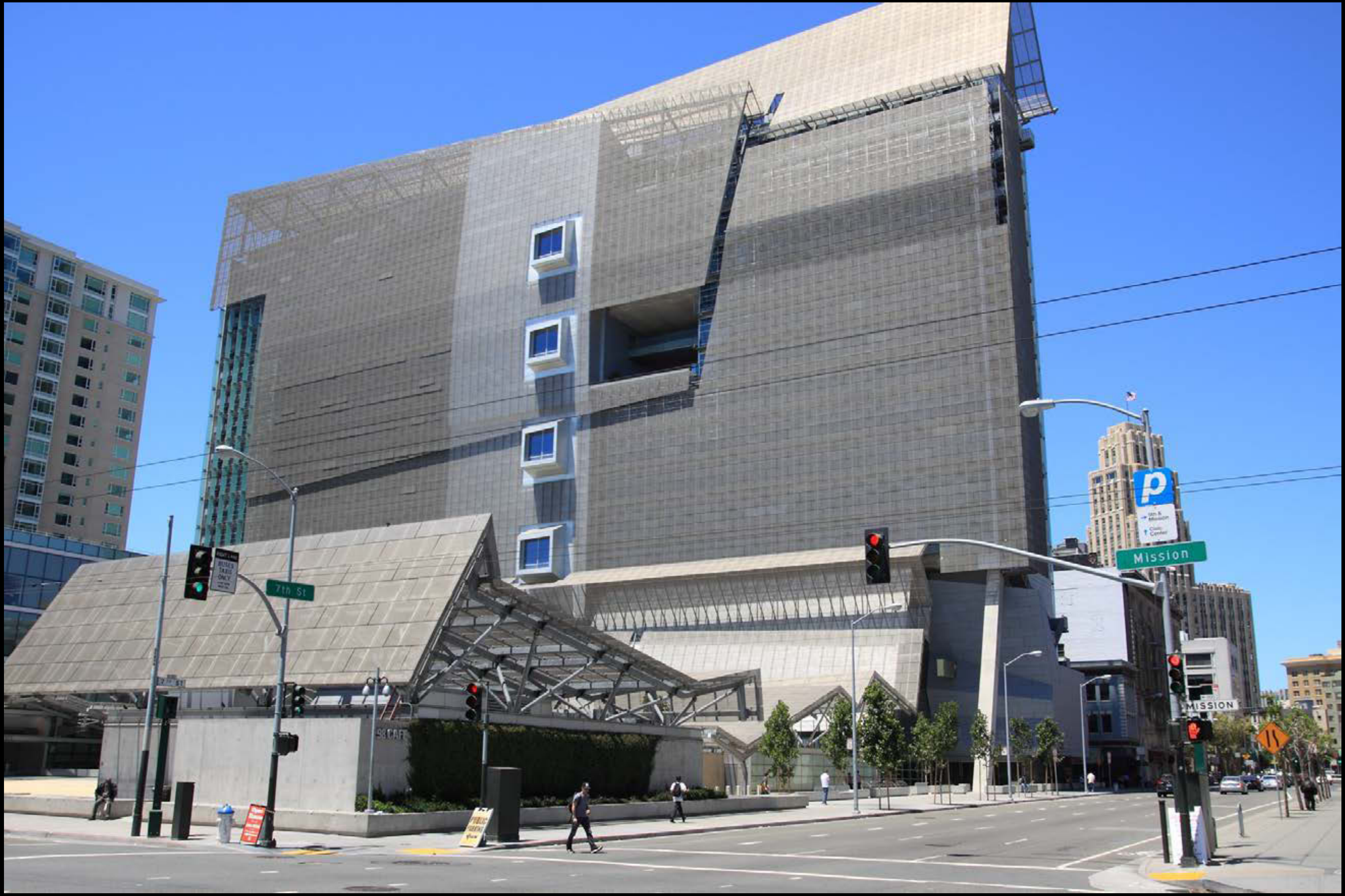
Basic strategies

1. Maximize exposure to wind
2. Maximize inlet and exhaust area
3. Minimize obstructions

$$Q_W = (AC_d)_{eff}\, v_W \sqrt{C_{w1} - C_{w2}}$$

$$Flowrate \sim A_{openings/obstructions}\, v_{wind} \sqrt{(C_{w1} - C_{w2})}$$

Wind Driven Ventilation- Case Studies



Thom Mayne - Federal Building - San Francisco

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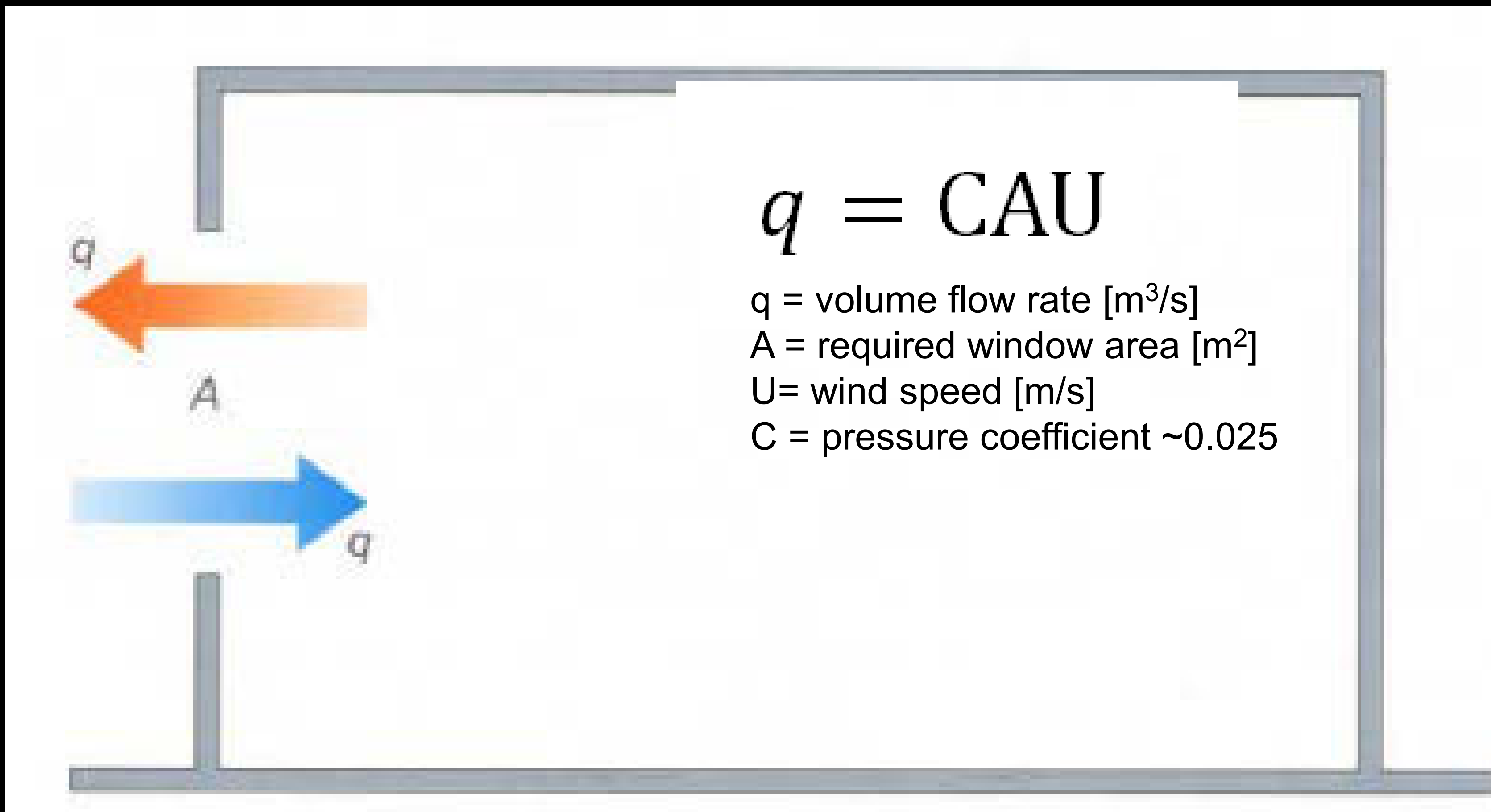
Wind Driven Ventilation- Case Studies

Carrilho da Graça G.; Linden P. F.; McConahey E.; Haves P. , 2003, "DESIGN AND TESTING OF A CONTROL STRATEGY FOR A LARGE, NATURALLY VENTILATED OFFICE BUILDING," Building Simulation 2003, Eindhoven, The Netherlands, pp. 399-407

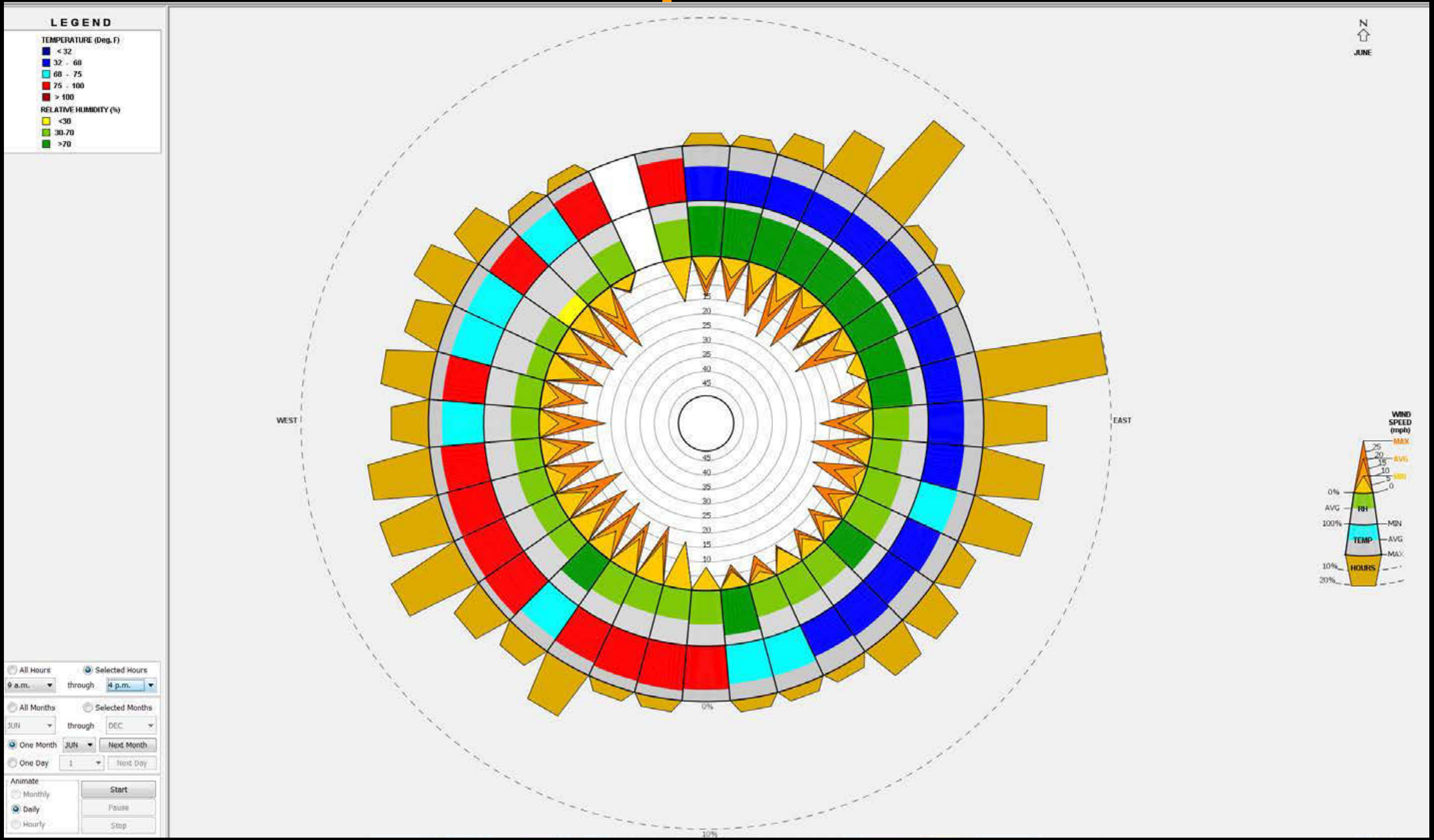
Air Flow – Single sided, single vent, wind driven



$$q = CAU$$

q = volume flow rate [m^3/s]
A = required window area [m^2]
U= wind speed [m/s]
C = pressure coefficient ~0.025

Mean outside wind speed & direction



The wind is primarily coming from west and east.

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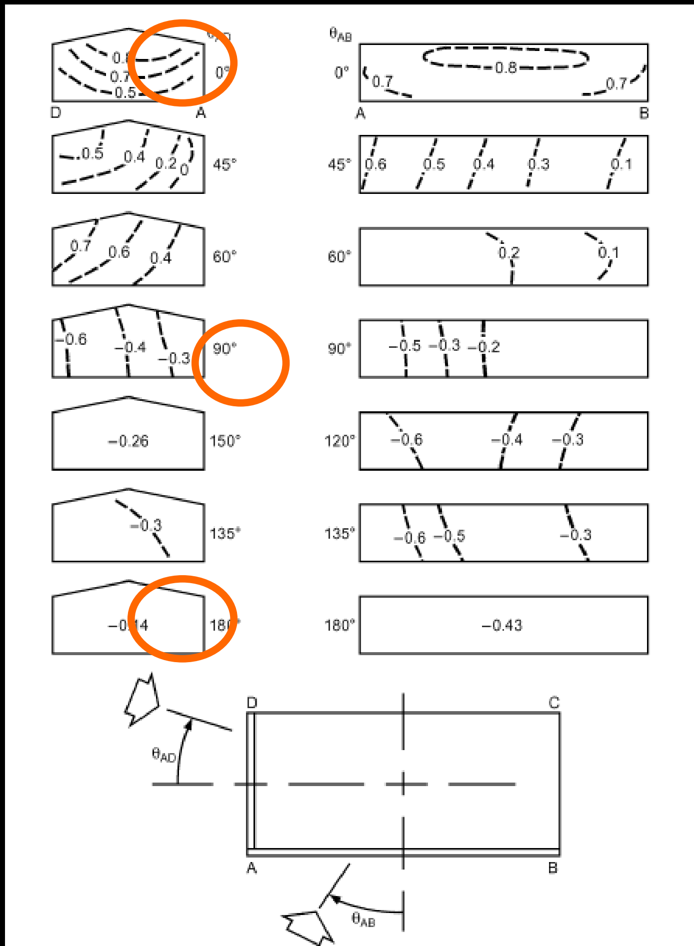
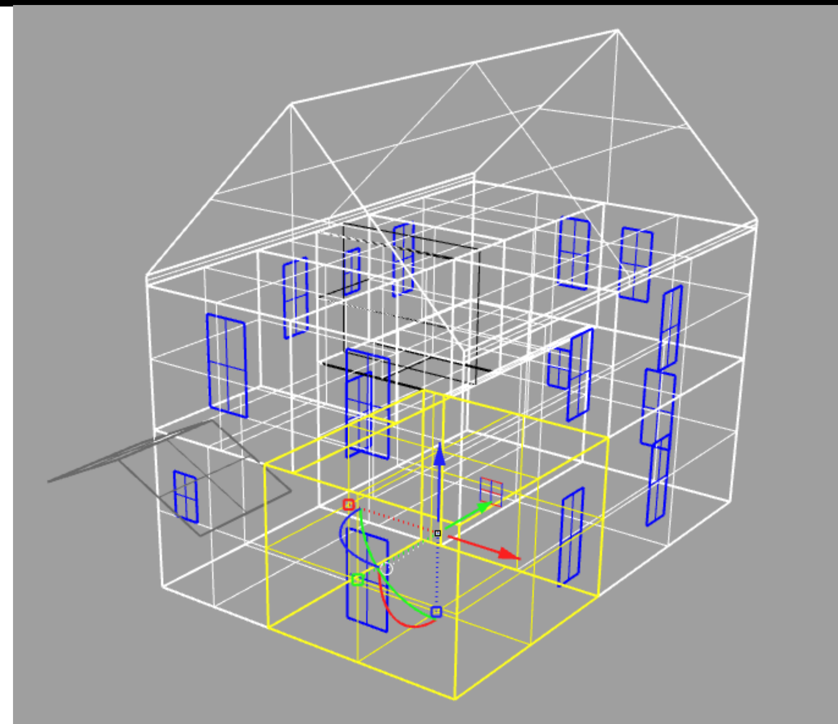
Local Pressure Coefficients





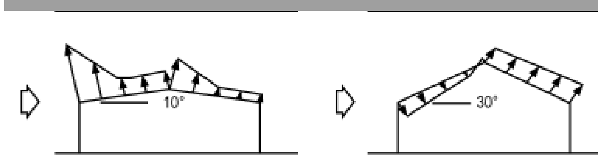


Fig. 8 Local Roof Pressure Coefficients for Roof of Low-Rise Buildings (Holmes 1986)

Wind from west

$C_{East} = -0.3$

$C_{North} = -0.14$

$\Delta C = 0.16$

Wind from east

$C_{West} = 0.5$

$C_{North} = -0.3$

$\Delta C = 0.8$

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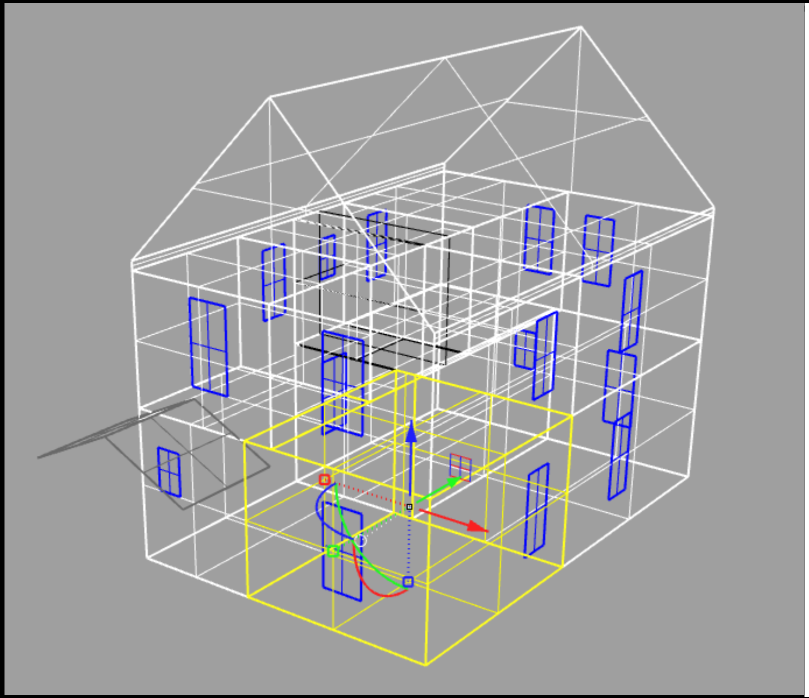
Example – New England Home



$$q = \mathrm{CAU}$$

Wind from West

q = 0.16 x 1.2 m^2 x 7ms^{-1}

= 1.3 m^3s^{-1}

ACH = 3.12 m^3s^{-1} x 3600 s/h / 53 m^3

= 91 h^{-1}

Wind from East

q = 0.8 x 1.2 m^2 x 7 ms^{-1}

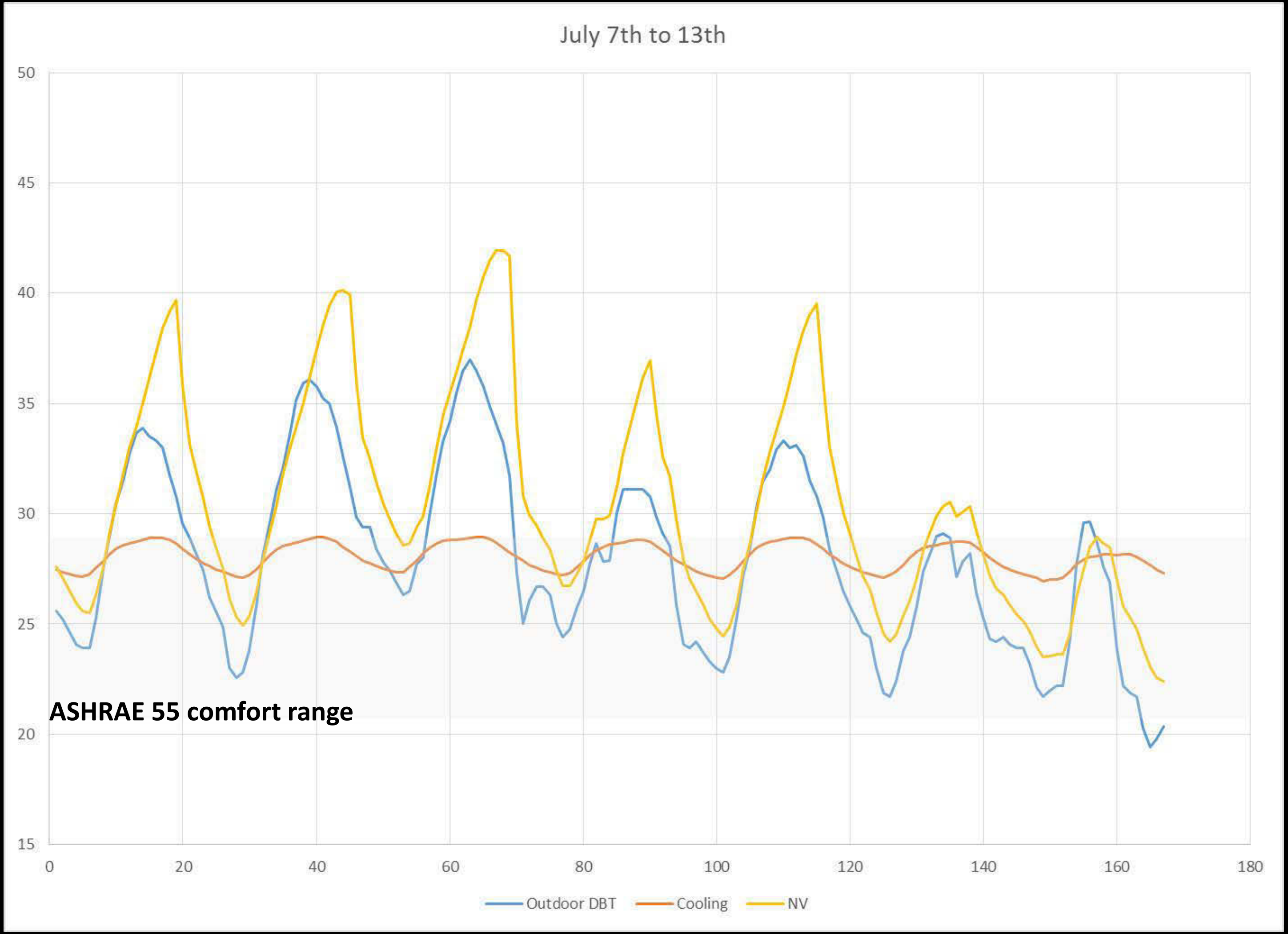
= 6.7 m^3s^{-1}

ACH = 3.12 m^3s^{-1} x 3600 s/h / 53 m^3

= 456 h^{-1}

If there is wind there is plenty of air exchange.

Simulated Natural Ventilation Summer Design Week



NV cannot maintain thermal comfort during the summer design week since the outside air is too hot.

Wind vs. Stack Effect

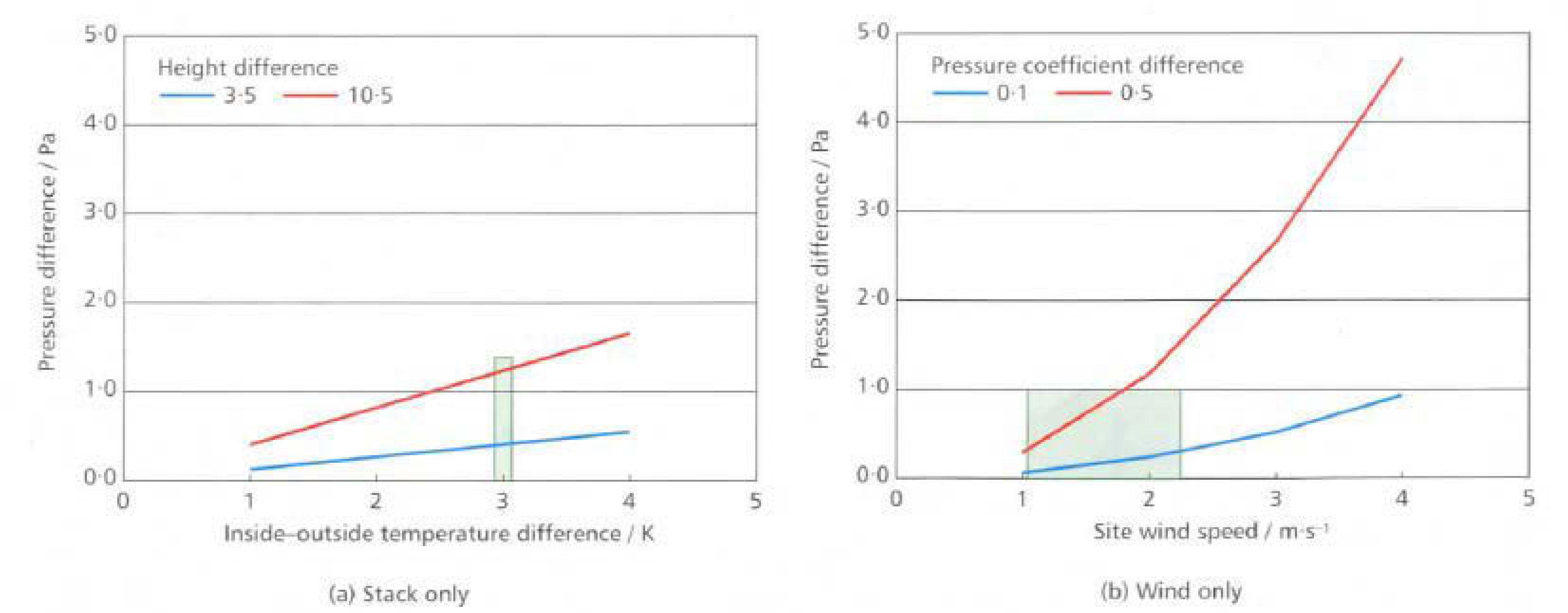


Figure 2.10 Relative driving pressures

- Wind tends to be an order of magnitude larger than buoyancy.
- Stack does not rely on wind and therefore can take place on still, hot summer days when it is most needed. Stack is a relatively stable air flow (compared to wind) and offers greater flexibility in choosing areas of air intake. It relies on temperature differences (inside/outside).
- Stack may incur extra costs (ventilator stacks, taller spaces).
- Both effects are difficult to predict in urban settings due to microclimatic effects.

Barriers to the application of natural ventilation

During design

- ❑ Building and fire regulations
- ❑ Need for acoustic protection
- ❑ Designing a naturally ventilated building requires more work but can reduce mechanical system (design fee on a fixed percentage of system's cost)
- ❑ Increased risk for design team (occupant behavior)
- ❑ Difficult to predict pattern of use
- ❑ Devices for shading, privacy & daylighting may hamper the free flow of air
- ❑ Problems with automatic controls in openings

During operation

- ❑ Occupants not understanding the system
- ❑ Safety concerns
- ❑ Noise from outdoors
- ❑ Dust and air pollution
- ❑ Solar shading covering the openings

Questions?

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