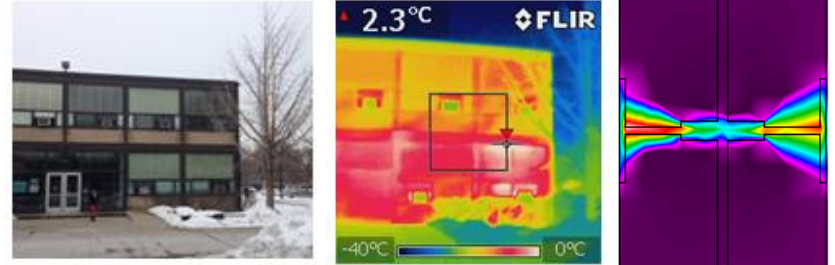


CAE 331/513

Building Science

Fall 2017



September 19, 2017
Human thermal comfort

Built
Environment
Research

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

Quick plug: Thurs Oct 5 2017 4-7 pm

Bridge the divide: envelope and HVAC design integration

Thursday, October 5, 2017 - 4-7 p.m. (registration at 3:30 p.m.)

DIRTT, Chicago, IL

Cost: \$15; \$10 AIA Chicago or USGBC Illinois members

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As a result of this event, you will be able to:

- Explain how occupant comfort and energy performance interact.
- Describe high performance thermal envelope design strategies.
- Discuss tools that predict façade comfort implications and energy impacts.
- Explain design strategies and approaches to improve envelope and HVAC performance.

Who should attend?

Architects, building owners, developers, mechanical and electrical engineers, project managers, general contractors, energy efficiency specialists, commissioning authorities, and anyone involved and interested in high-performance building design.

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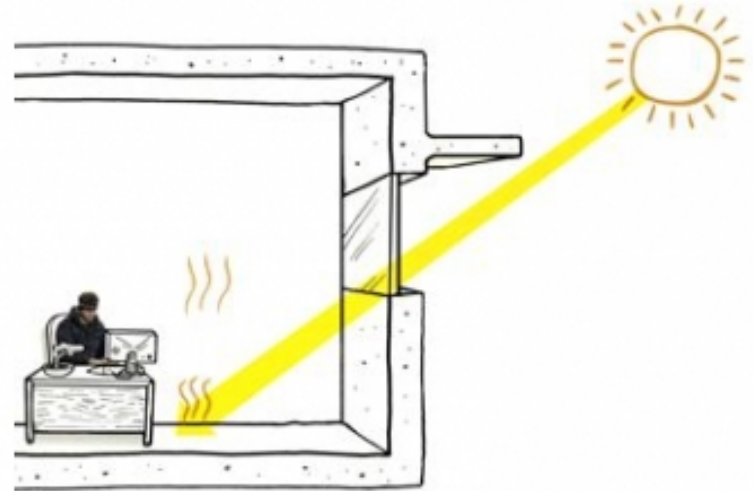
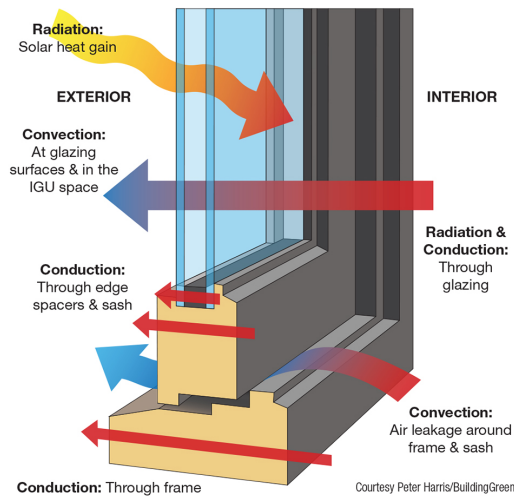
Registration is \$10 w/ promo code: **OCT5PARTNER**

<http://seventhwave.org/comfort-zone>

Schedule updates

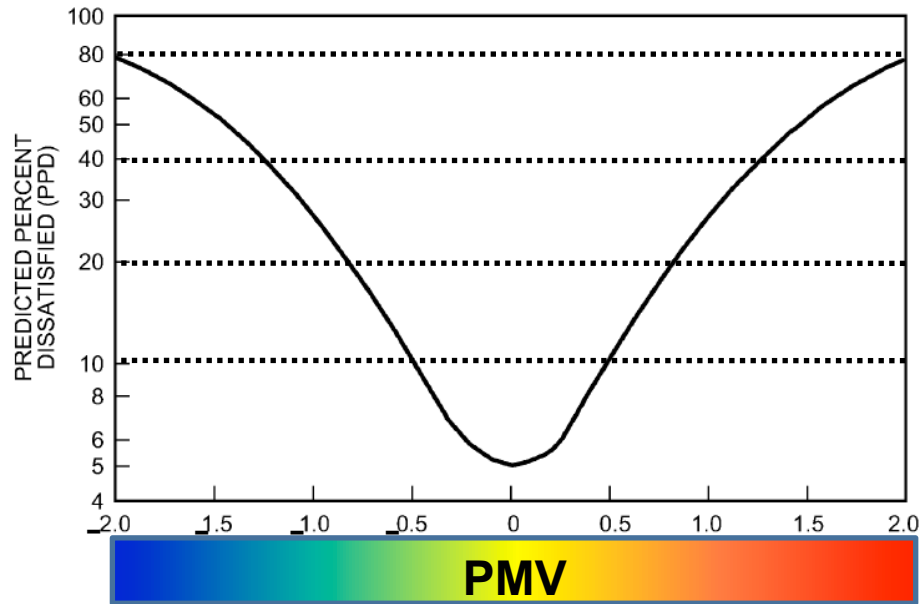
- Last time:
 - Fenestration and heat transfer
- Today:
 - Human thermal comfort
- Next time:
 - Review for exam 1

Fenestration heat transfer



Window (combined modes)

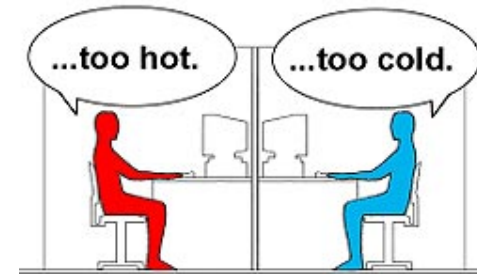
$$Q_{window} = UA_{pf} (T_{out} - T_{in}) + I_{solar} A_{pf} SHGC \cdot IAC$$



HUMAN THERMAL COMFORT

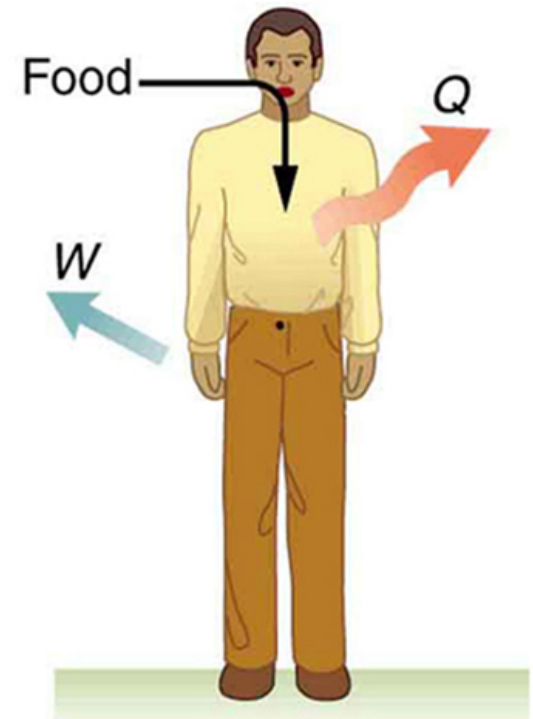
Human thermal comfort

- One of our main goals in designing a building and its HVAC system(s) is to provide a suitably comfortable environment for the occupants
- In general, **thermal comfort** occurs when:
 - Body temperatures are held within narrow ranges
 - Skin moisture is low
 - The physiological effort of regulation is minimized
- Metrics for thermal comfort include quantifying the amount of discomfort that a space might present to people and what fraction of occupants **are dissatisfied** with a space



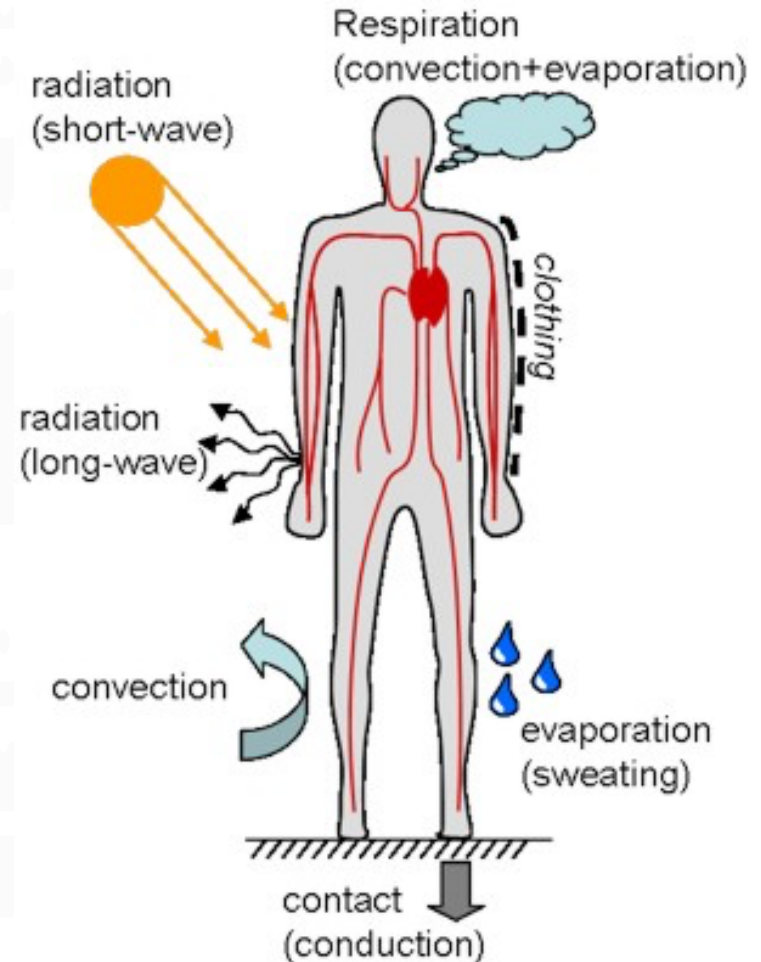
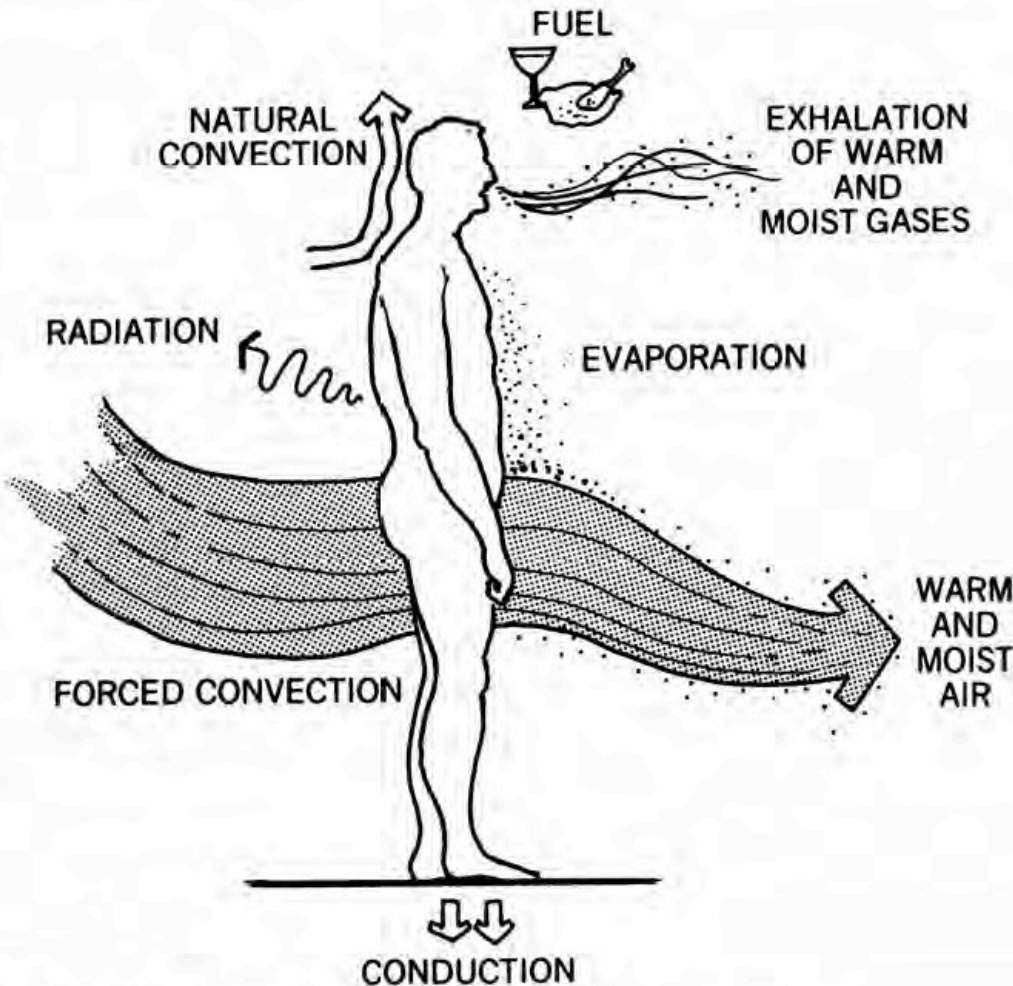
Energy balance of the human body

- The heat produced by the body's metabolism dissipates to the environment
 - Otherwise we would overheat
- If the rate of heat transfer away is higher than the rate of heat production, the body **cools down** and we feel **cold**
 - If heat transfer to surroundings is lower than our heat production, we feel **hot**
- This is a complex problem in transient heat transfer, involving radiation, convection, conduction, and evaporation, and many variables including skin wetness and clothing composition
 - We can simplify a lot of this



Energy balance of the human body

Your largest organ, your skin, covers $\sim 2 \text{ m}^2$ and makes up $\sim 15\%$ of your body weight



Body energy balance in a space

- Our internal body temperatures are consistent around 36-37°C
- We can set our heat production rate equal to the instantaneous heat flow to the environment (assuming no storage):

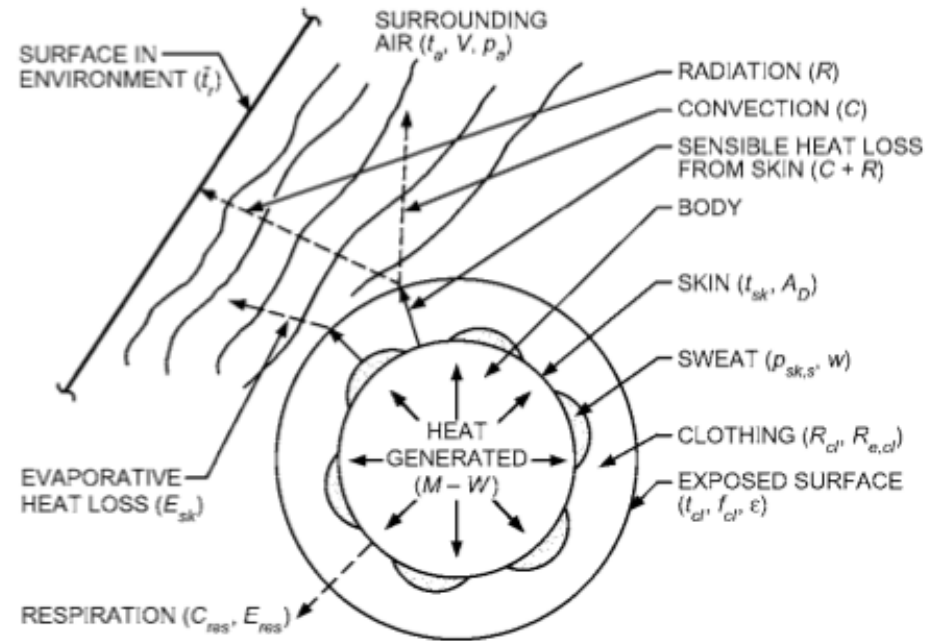
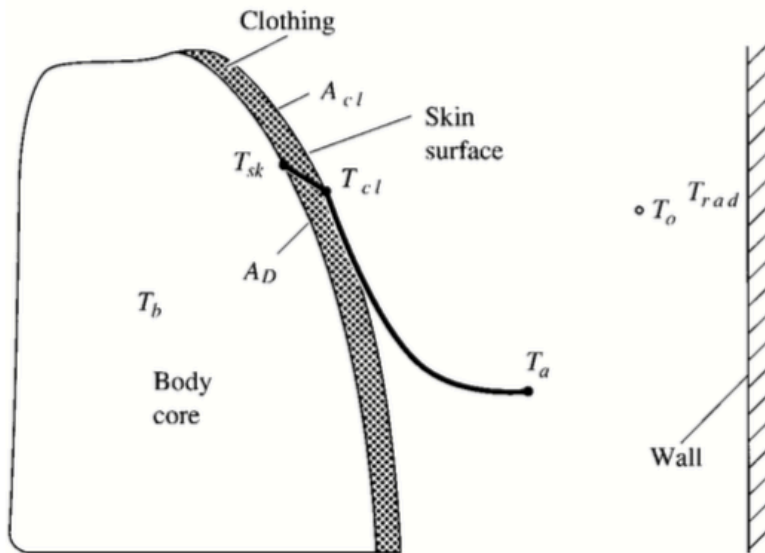


FIGURE 4.1 Sensible heat exchange between the human body and the indoor environment.

$$\dot{Q} = MA_{skin} = \dot{Q}_{conv} + \dot{Q}_{rad} + \dot{Q}_{evap} + \dot{Q}_{resp,sens} + \dot{Q}_{resp,latent}$$

$$q = M = q_{conv} + q_{rad} + q_{evap} + q_{resp,sens} + q_{resp,latent}$$

Body energy balance in a space

- Our internal body temperatures are consistent around 36-37°C
- We can set our heat production rate equal to the instantaneous heat flow to the environment (assuming no storage):

Some obviously important variables for comfort:

- Activity level (heat production)
- Air temperature (convection)
- Air velocity (convection)
- Clothing level (skin temperature)
- Temperature of surrounding surfaces (radiation)
- Air relative and absolute humidity

Modeling gets complicated quickly....

$$\dot{Q} = MA_{skin} = \dot{Q}_{conv} + \dot{Q}_{rad} + \dot{Q}_{evap} + \dot{Q}_{resp,sens} + \dot{Q}_{resp,latent}$$

$$q = M = q_{conv} + q_{rad} + q_{evap} + q_{resp,sens} + q_{resp,latent}$$

Assessing thermal comfort

- To develop guidelines for thermal comfort, we have to have some idea of what we perceive to be comfortable
- Comfort analysis is usually done through surveys of users in real spaces and through controlled human experiments and a questionnaire that rates comfort on a seven point scale
- The result of the questionnaire is the **Mean Vote (MV)**:

-3	-2	-1	0	+1	+2	+3
cold	cool	slightly cool	neutral	slightly warm	warm	hot

Predicted Mean Vote (PMV)

- We can attempt to predict the results of a questionnaire through equations and generate a **predicted mean vote (PMV)**
- The PMV is an estimate of the mean value that would be obtained if a large number of people were asked to vote on thermal comfort using a 7 point scale:

-3	-2	-1	0	+1	+2	+3
cold	cool	slightly cool	neutral	slightly warm	warm	hot

Survey the class...

Percent People Dissatisfied (PPD)

- Once we have the PMV (which are average results), we need to estimate how many people are satisfied with the thermal conditions for that PMV
 - We quantify that as the **percent of people dissatisfied (PPD)**
- Our design goal usually is to achieve a **PPD < 10%**
- After a lot of surveys and experiments, researchers have found that PPD is a nonlinear function of PMV that can be predicted reasonably well in most environments

Percent People Dissatisfied (PPD)

Since we want:

$$\text{PPD} < 10\%$$

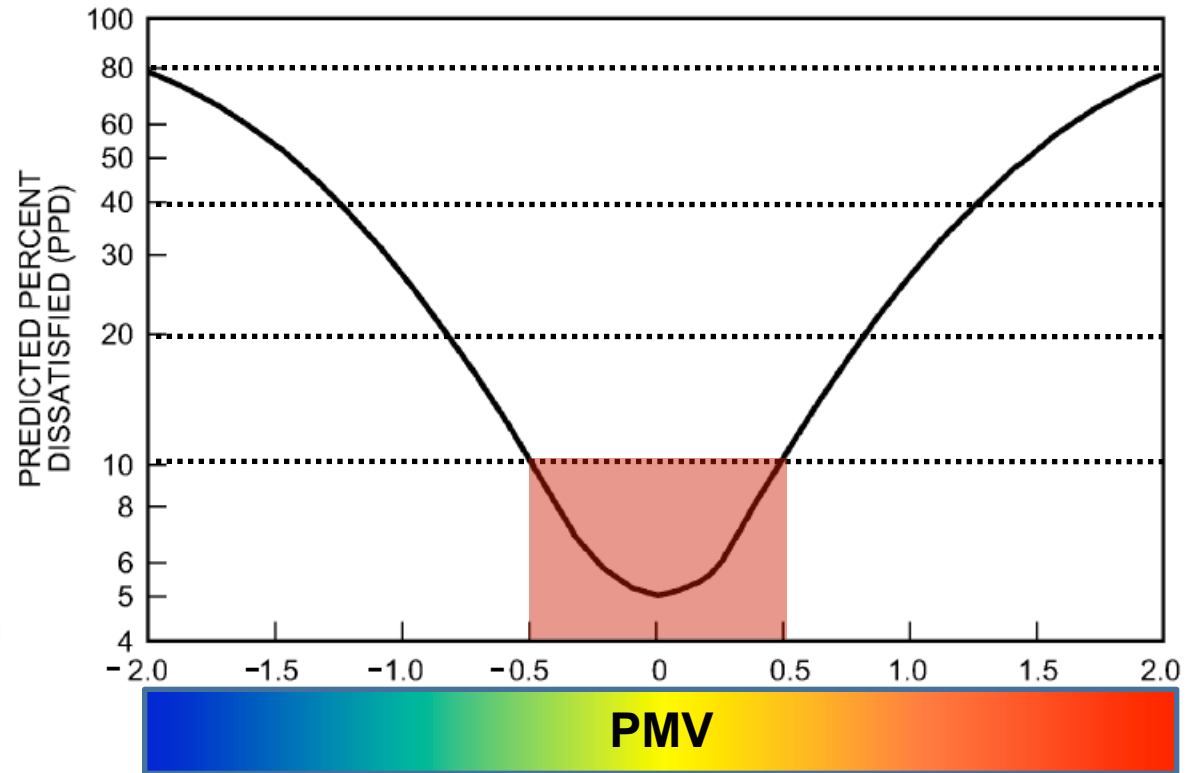
we can see that:

$$-0.5 < \text{PMV} < 0.5$$

is our target

*Notice that the absolute minimum PPD is 5% showing that you cannot satisfy everyone at the same time!

The PPD Function:



How many of you are “dissatisfied” with thermal comfort right now?

Predicting PMV and PPD

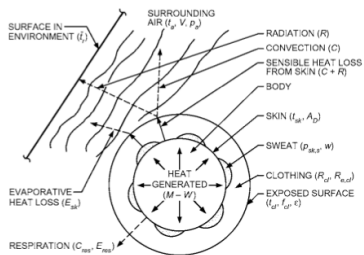
- How can we predict PMV and PPD?
- Fanger comfort analysis:
 - Physically: a relationship between the imbalance between heat flow from the body and the heat flow required for optimum thermal comfort
 - Empirically: Correlations derived between sensations of thermal comfort (PMV/PPD) and environmental variables:

$$PPD = 100 - 95 \exp[-(0.03353PMV^4 + 0.2179PMV^2)]$$

$$PMV = [0.303 \exp(-0.036M) + 0.028]L$$

M = metabolic activity

L = thermal load (difference between actual skin temperature and the skin temperature required for comfort) at a given activity level



Thermal comfort standards in building design

- **ASHRAE Standard 55** is the primary resource for engineers and architects to design for thermal comfort



ANSI/ASHRAE Standard 55-2013
(Supersedes ANSI/ASHRAE Standard 55-2010)
Includes ANSI/ASHRAE addenda listed in Appendix M

Thermal Environmental Conditions for Human Occupancy

See Appendix M for approval dates by the ASHRAE Standards Committee, the ASHRAE Board of Directors, and the American National Standards Institute.

This standard is under continuous maintenance by a Standing Standard Project Committee (SSPC) for which the Standards Committee has established a documented program for regular publication of addenda or revisions, including procedures for timely, documented, consensus action on requests for change to any part of the standard. The change submittal form, instructions, and deadlines may be obtained in electronic form from the ASHRAE Web site (www.ashrae.org) or in paper form from the Manager of Standards. The latest edition of an ASHRAE Standard may be purchased from the ASHRAE Web site (www.ashrae.org) or from ASHRAE Customer Service, 1791 16th Circle, NE, Atlanta, GA 30329-2305. E-mail: orders@ashrae.org. Fax: 478-539-2129. Telephone: 404-636-8400 (worldwide), or toll free 1-800-527-4723 (for orders in US and Canada). For reprint permission, go to www.ashrae.org/permissions.

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1. PURPOSE

The purpose of this standard is to specify the combinations of indoor thermal environmental factors and personal factors that will produce thermal environmental conditions acceptable to a majority of the occupants within the space.

Variables affecting thermal comfort

- **ASHRAE Standard 55** considers 6 main parameters to govern thermal comfort

Some are familiar:

Ambient air temperature (T)

Humidity (W or RH)

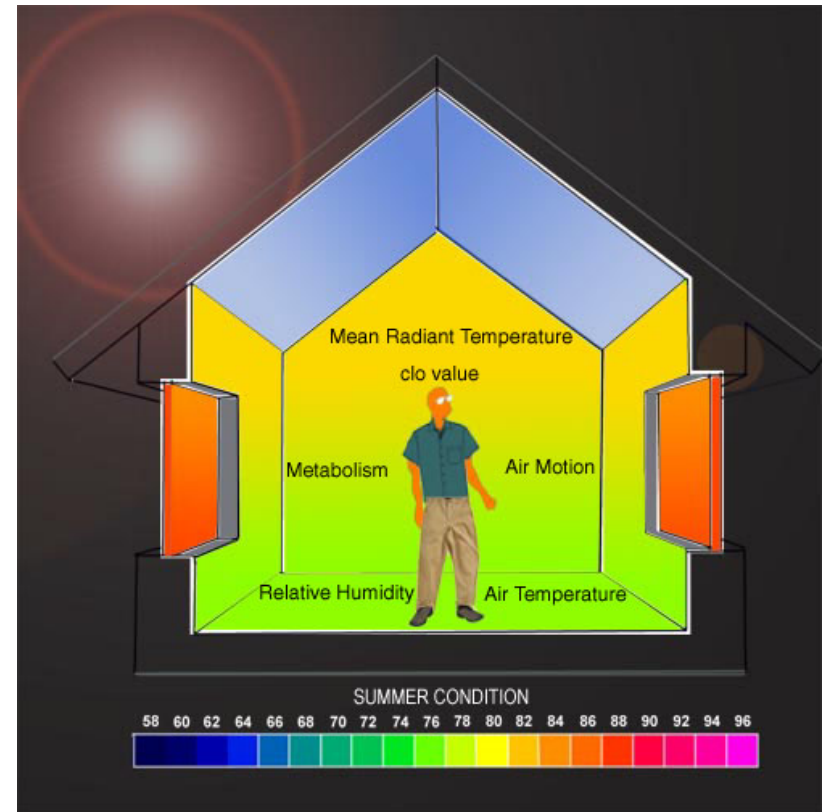
Local air speed (v)

Some are probably not:

Metabolic rate (M)

Clothing insulation (I_{cl})

Mean radiant temperature (T_r)



Metabolic energy production

- The total energy production rate of the human body is the sum of the production rates of heat (Q) and work (W):

$$\dot{Q} + \dot{W} = MA_{skin}$$

where

M = rate of metabolic energy production per surface area of skin (W/m^2)

A_{skin} = total surface area of skin (m^2)

(work, W , is typically neglected), so: $\dot{Q} = MA_{skin}$

$$1 \text{ met} = 18.4 \frac{\text{Btu}}{\text{h} \cdot \text{ft}^2} = 58 \frac{\text{W}}{\text{m}^2}$$

What about A_{skin} ?

- For an adult, the area of our skin is typically on the order of 16-22 ft² (1.5 to 2 m²)

– Typically we use 1.8 m²

$$A_D = 0.202m^{0.425}l^{0.725}$$

A_D = DuBois surface area, m²

m = mass, kg

l = height, m

- So for a typical adult doing typical indoor activities, their heat production rate will be:

$$\dot{Q} + \dot{W} = MA_{skin} \approx (1 \text{ met})(1.8 \text{ m}^2)$$

$$\approx (58.2 \frac{\text{W}}{\text{m}^2})(1.8 \text{ m}^2) \approx 100 \text{ W } (\pm 20 \text{ W})$$

Metabolic Rates for Typical Tasks

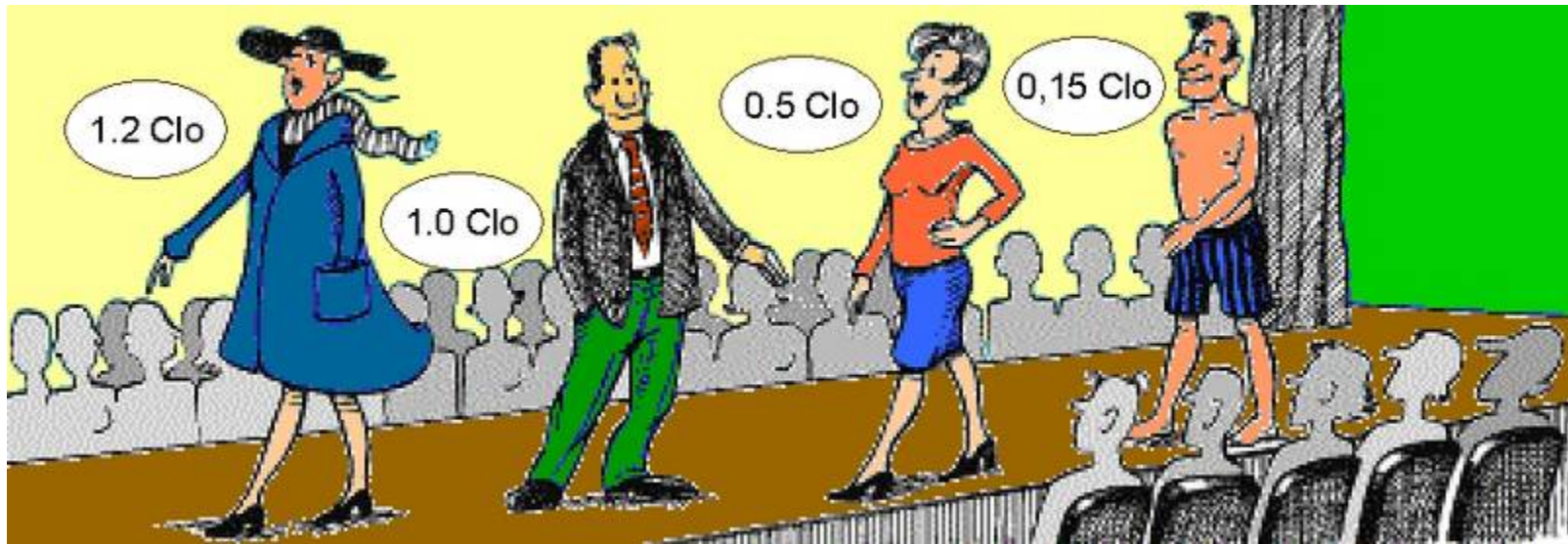
Activity	Met Units	Metabolic Rate	
		W/m ²	(Btu/h ft ²)
Resting			
Sleeping	0.7	40	(13)
Reclining	0.8	45	(15)
Seated, quiet	1.0	60	(18)
Standing, relaxed	1.2	70	(22)
Walking (on level surface)			
0.9 m/s, 3.2 km/h, 2.0 mph	2.0	115	(37)
1.2 m/s, 4.3 km/h, 2.7 mph	2.6	150	(48)
1.8 m/s, 6.8 km/h, 4.2 mph	3.8	220	(70)
Office Activities			
Seated, reading, or writing	1.0	60	(18)
Typing	1.1	65	(20)
Filing, seated	1.2	70	(22)
Filing, standing	1.4	80	(26)
Walking about	1.7	100	(31)
Lifting/packing	2.1	120	(39)
Driving/Flying			
Automobile	1.0-2.0	60-115	(18-37)
Aircraft, routine	1.2	70	(22)
Aircraft, instrument landing	1.8	105	(33)
Aircraft, combat	2.4	140	(44)
Heavy vehicle	3.2	185	(59)

Metabolic rates (continued)

Activity	Met Units	Metabolic Rate	
		W/m ²	(Btu/h-ft ²)
Miscellaneous Occupational Activities			
Cooking	1.6-2.0	95-115	(29-37)
House cleaning	2.0-3.4	115-200	(37-63)
Seated, heavy limb movement	2.2	130	(41)
Machine work			
sawing (table saw)	1.8	105	(33)
light (electrical industry)	2.0-2.4	115-140	(37-44)
heavy	4.0	235	(74)
Handling 50 kg (100 lb) bags	4.0	235	(74)
Pick and shovel work	4.0-4.8	235-280	(74-88)
Miscellaneous Leisure Activities			
Dancing, social	2.4-4.4	140-255	(44-81)
Calisthenics/exercise	3.0-4.0	175-235	(55-74)
Tennis, single	3.6-4.0	210-270	(66-74)
Basketball	5.0-7.6	290-440	(92-140)
Wrestling, competitive	7.0-8.7	410-505	(129-160)

Thermal insulation, I_{cl}

- The thermal insulating effects of clothes are measured in **clo** (1 clo = 0.88 h·ft²·°F/Btu)
- Insulating values for various garments are found in ASHRAE Fundamentals and Appendix B of Standard 55



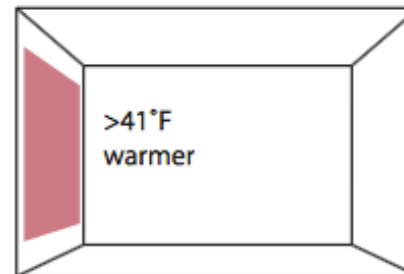
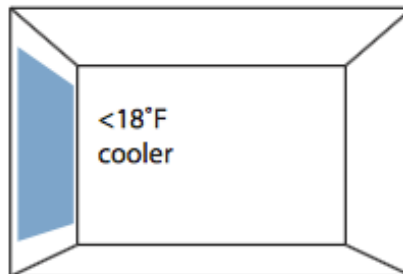
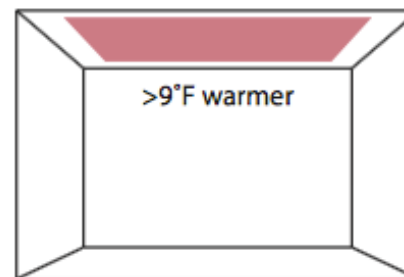
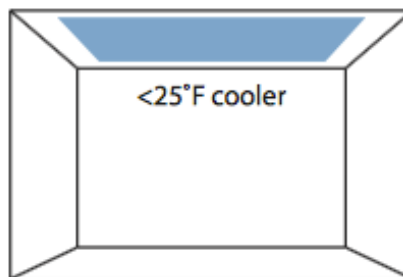
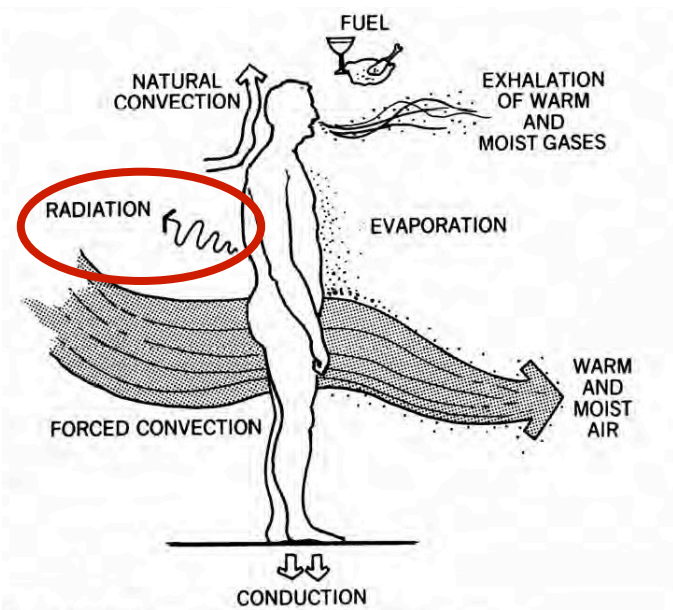
Thermal insulation, I_{cl}

Clothing Insulation Values for Typical Ensembles^a

Clothing Description	Garments Included ^b	I_{cl} (clo)
Trousers	1) Trousers, short-sleeve shirt	0.57
	2) Trousers, long-sleeve shirt	0.61
	3) #2 plus suit jacket	0.96
	4) #2 plus suit jacket, vest, T-shirt	1.14
	5) #2 plus long-sleeve sweater, T-shirt	1.01
	6) #5 plus suit jacket, long underwear bottoms	1.30
Skirts/Dresses	7) Knee-length skirt, short-sleeve shirt (sandals)	0.54
	8) Knee-length skirt, long-sleeve shirt, full slip	0.67
	9) Knee-length skirt, long-sleeve shirt, half slip, long-sleeve sweater	1.10
	10) Knee-length skirt, long-sleeve shirt, half slip, suit jacket	1.04
	11) Ankle-length skirt, long-sleeve shirt, suit jacket	1.10
Shorts	12) Walking shorts, short-sleeve shirt	0.36
Overalls/Coveralls	13) Long-sleeve coveralls, T-shirt	0.72
	14) Overalls, long-sleeve shirt, T-shirt	0.89
	15) Insulated coveralls, long-sleeve thermal underwear tops and bottoms	1.37
Athletic	16) Sweat pants, long-sleeve sweatshirt	0.74
Sleepwear	17) Long-sleeve pajama tops, long pajama trousers, short 3/4 length robe (slippers, no socks)	0.96

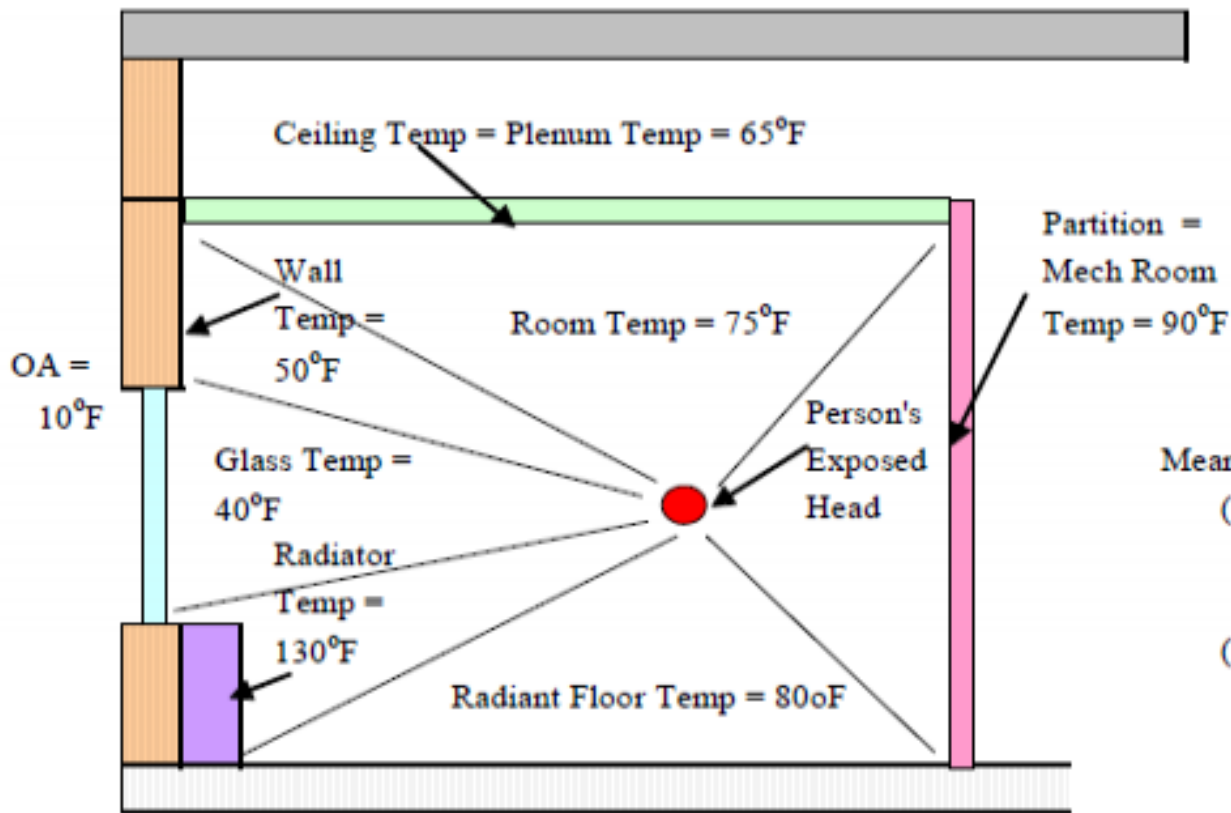
Mean radiant temperature, T_r

- Radiation to/from occupants is an important form of energy exchange
 - We can estimate its effects using the mean radiant temperature



Mean radiant temperature, T_r

- Radiation to/from occupants is an important form of energy exchange
 - We can estimate its effects using the mean radiant temperature



SURFACE		Temp	Angle
Name	No.	°F	degs
Ceiling	1	65	105
Partition	2	90	100
Floor	3	80	110
Radiator	4	130	20
Window	5	40	30
Wall	6	50	20

$$\begin{aligned}
 \text{Mean Radiant Temp (MRT)} &= \\
 &= (A_1 \cdot T_1 + A_2 \cdot T_2 + A_3 \cdot T_3 + \\
 &\quad A_4 \cdot T_4 + A_5 \cdot T_5 + A_5 \cdot T_5 + \\
 &\quad A_6 \cdot T_6) / 360 = \\
 &= (105 \cdot 65 + 100 \cdot 90 + 110 \cdot 80 + \\
 &\quad 20 \cdot 130 + 30 \cdot 40 + 20 \cdot 50) / 360 = \\
 &= 29,425 / 360 = 81.74 \text{°F}
 \end{aligned}$$

Mean radiant temperature, T_r

- The **mean radiant temperature** is the temperature of an imaginary uniform black box that results in the same radiation heat loss to the occupant as the current room
- This is particularly important for environments with drastically different surface temperatures
 - e.g. a poorly insulated window on a winter day has a surface temperature much lower than most other surfaces around it
 - e.g. a concrete slab warmed by the sun may have a higher temperature than its surroundings

$$\bar{T}_r^4 = T_1^4 F_{p-1} + T_2^4 F_{p-2} + \dots + T_N^4 F_{p-N}$$

where

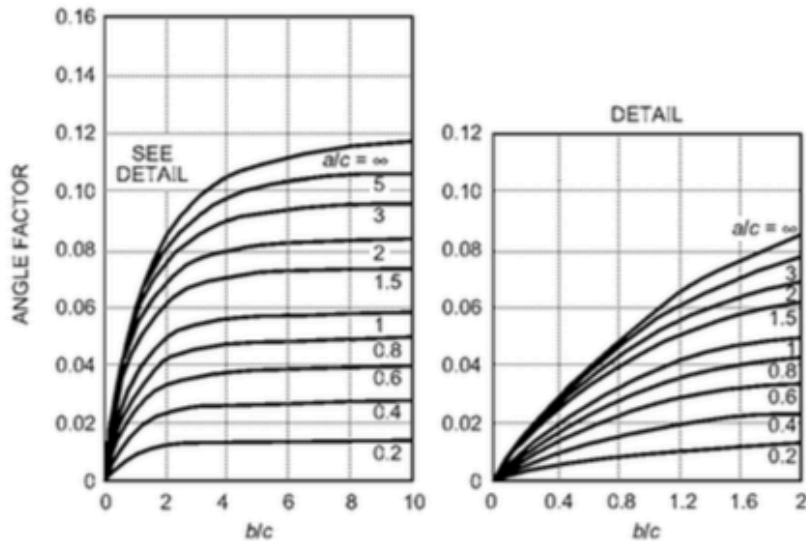
\bar{T}_r = mean radiant temperature, K

T_N = surface temperature of surface N , K

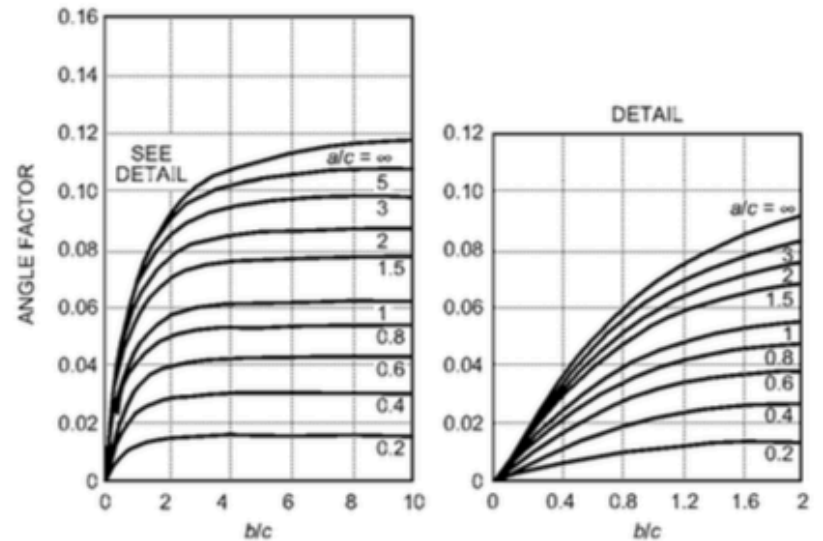
F_{p-N} = angle factor between a person and surface N

Mean radiant temperature, T_r

- View factors between people and horizontal or vertical rectangular surfaces



A. HORIZONTAL RECTANGLE (ON CEILING OR FLOOR)



B. VERTICAL RECTANGLE (ABOVE OR BELOW CENTER OF PERSON)

Predicting view factors and MRT gets complicated quickly as well...

Finding T_r from “globe temperature”

- We can measure the temperature of the interior of a black globe as well as the ambient air temperature to estimate MRT (T_r)
 - The black globe acts as a perfectly round black body radiator



$$T_r = \left[(T_{globe} + 273)^4 + \frac{1.1 \times 10^8 v_{air}^{0.6}}{\epsilon D^{0.4}} (T_{globe} - T_{air}) \right]^{1/4} - 273$$

T_{globe} = temperature inside globe (°C)

T_{air} = air temperature (°C)

v_{air} = air velocity (m/s)

D = globe diameter (m)

ϵ = emissivity of globe (-)

Operative temperature, T_o

- The **operative temperature** is essentially the average value between the air temperature and the mean radiant temperature, adjusted for air velocity effects:

Most accurate:

$$t_o = \frac{(h_r t_{mr} + h_c t_a)}{h_r + h_c}$$

Less accurate:

$$t_o = \frac{(t_{mr} + (t_a \times \sqrt{10v}))}{1 + \sqrt{10v}}$$

Least accurate:

$$t_o = \frac{(t_a + t_{mr})}{2}$$

h_c = convective heat transfer coefficient

h_r = linear radiative heat transfer coefficient

t_a = air temperature

t_{mr} = mean radiant temperature

*These are all reasonable to use depending on your application

Operative temperatures, air velocity, clo, and met levels

How do these all interact to affect comfort?

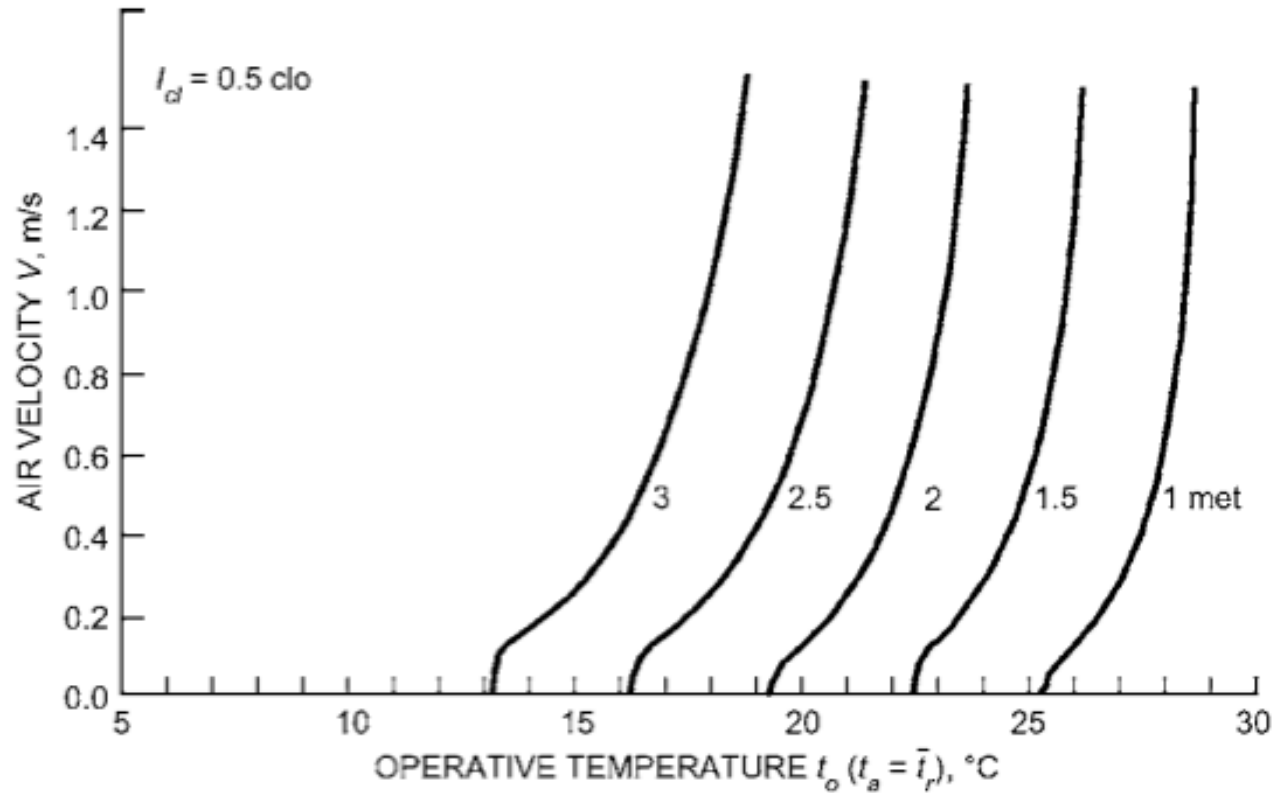


Fig. 14 Air Velocities and Operative Temperatures at 50% rh Necessary for Comfort (PMV = 0) of Persons in Summer Clothing at Various Levels of Activity

Operative temperatures, air velocity, clo, and met levels

How do these all interact to affect comfort?

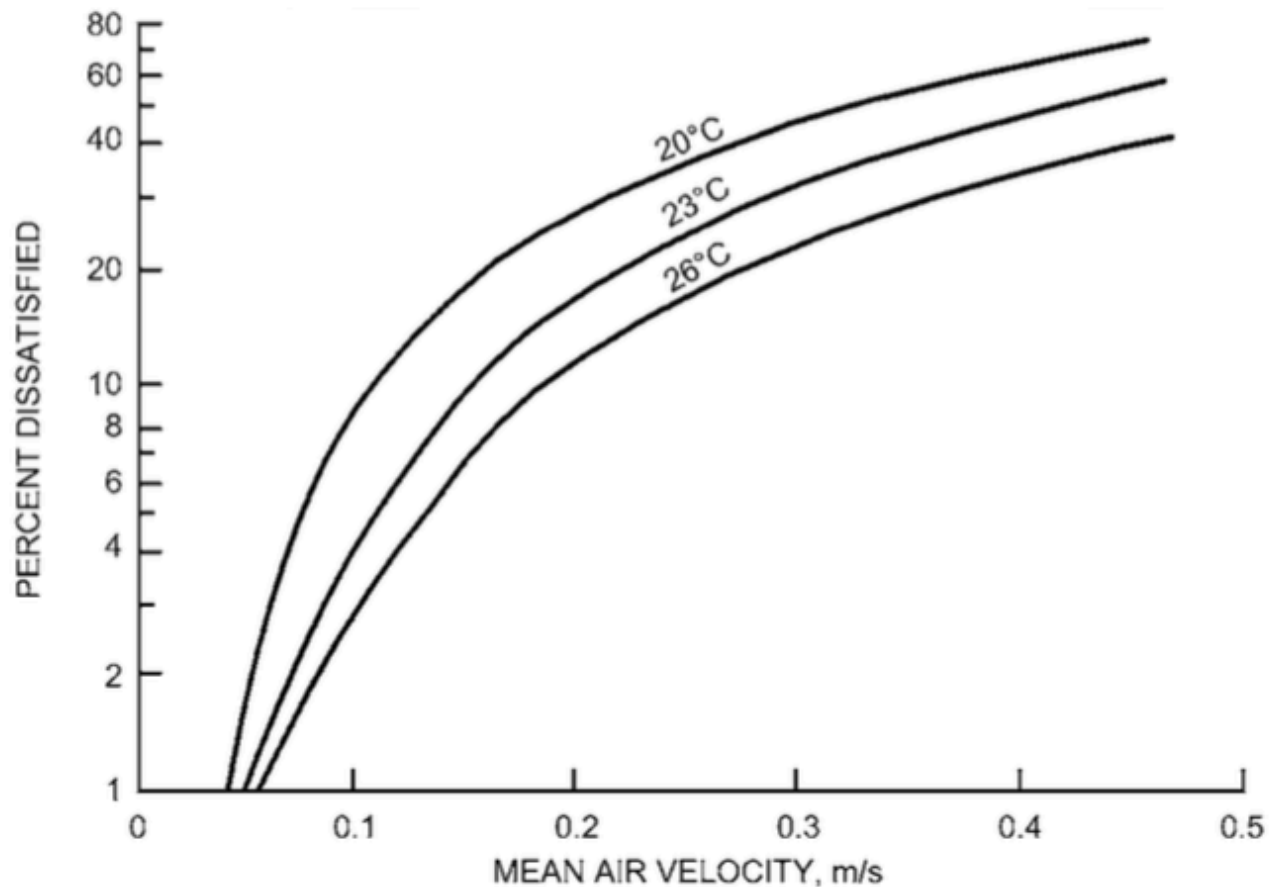


Fig. 10 Percentage of People Dissatisfied as Function of Mean Air Velocity

Operative temperatures, air velocity, clo, and met levels

How do these all interact to affect comfort?

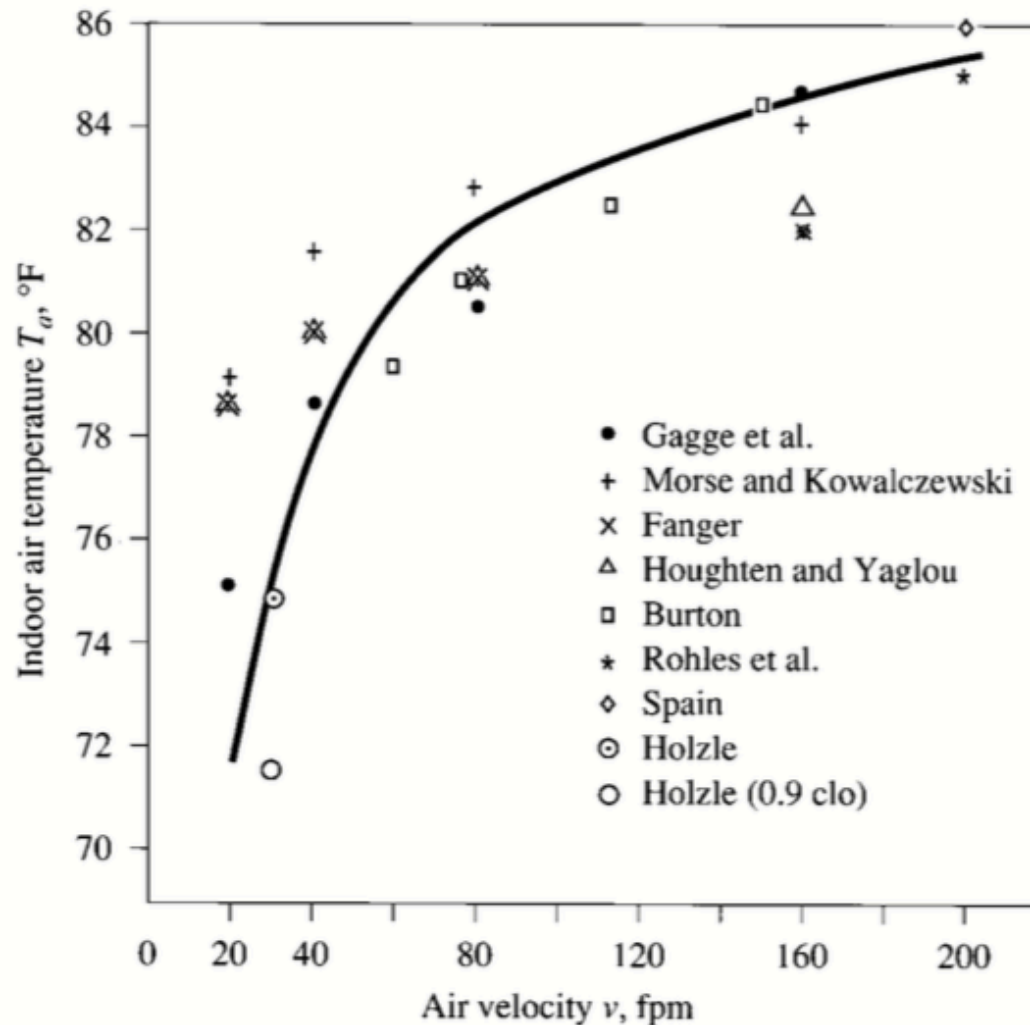
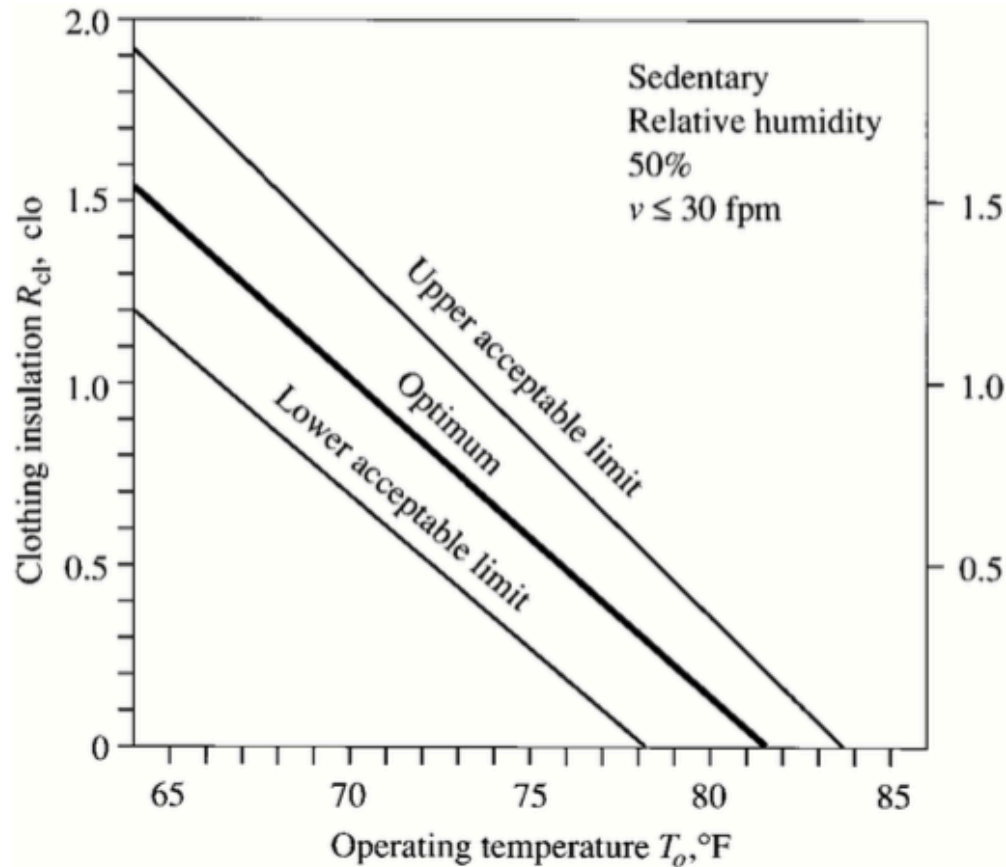


FIGURE 4.8 Preferred indoor air temperatures at various air velocities.

Defining the ASHRAE comfort zone



	Typical clothing insulation, clo	Optimum operative temperature	Indoor design temperature range
Winter	0.9	71°F (22°C)	69–74°F (20.5–23.5°C)
Summer	0.5	76°F (24.5°C)	74–79°F (23.5–26°C)

Defining the ASHRAE comfort zone

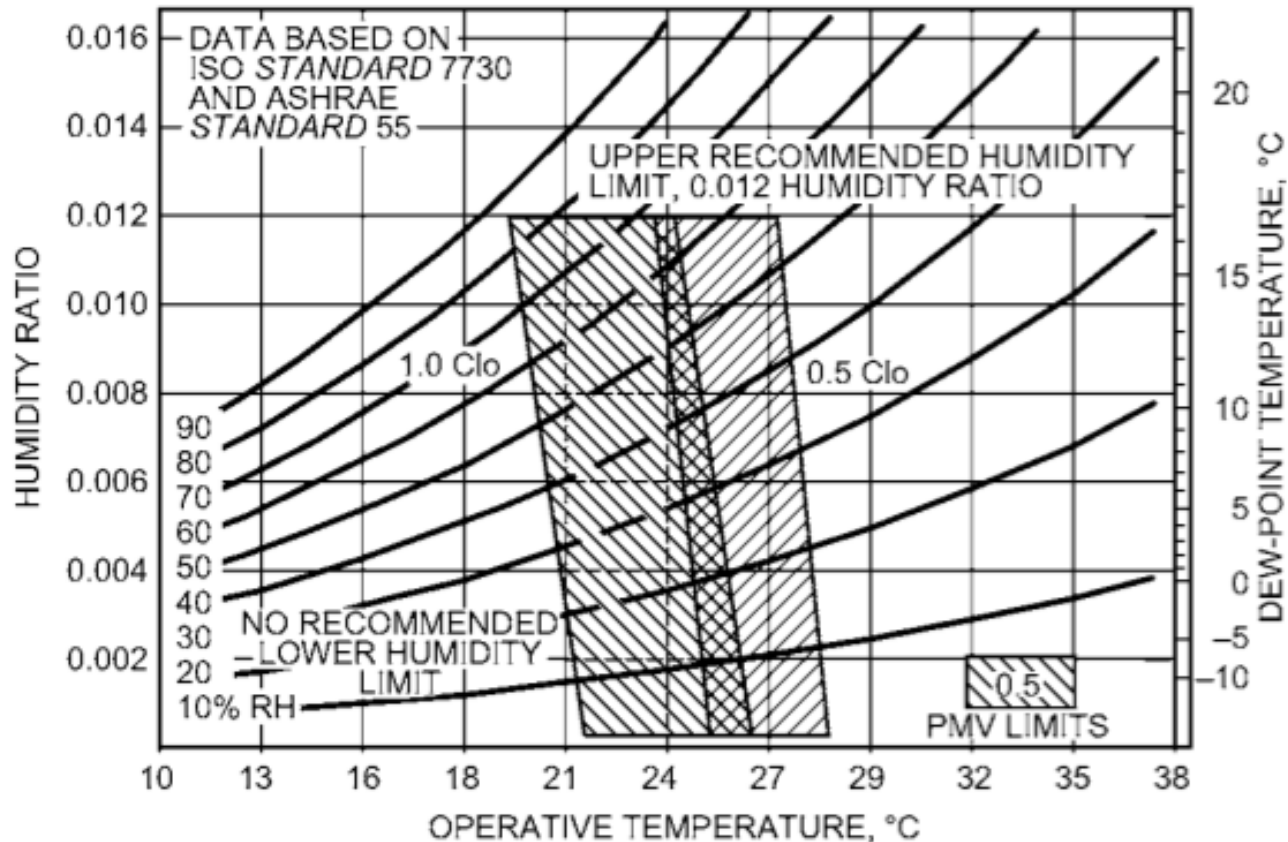


Fig. 5 ASHRAE Summer and Winter Comfort Zones
[Acceptable ranges of operative temperature and humidity with air speed ≤ 0.2 m/s for people wearing 1.0 and 0.5 clo clothing during primarily sedentary activity (≤ 1.1 met)].

ASHRAE comfort zone: CBE Thermal Comfort Tool

CBE Thermal Comfort Tool

ASHRAE-55

Compare

Ranges

Select method:

PMV method

Air temperature

24.6 °C

Use operative temperature

Mean radiant temperature

26 °C

Air speed

0.07 m/s

Local air speed control

Humidity

50 %

Relative humidity

Metabolic rate

1.3 met

Standing, relaxed: 1.2

Clothing level

0.55 clo

Typical summer indoor

Create custom ensemble

Dynamic predictive clothing

LEED documentation

Globe temp SolarCal Specify pressure SI IP Local discomfort ? Help

✓ Complies with ASHRAE Standard 55-2010

PMV 0.44
PPD 9%
Sensation Neutral
SET 26.7°C

Psychrometric chart (air temperature)

t_{db} 32.5 °C
 rh 13.5 %
 W_a 4.1 g w/kg da
 t_{wb} 15.6 °C
 t_{dp} 1.2 °C
 h 10.5 kJ/kg

