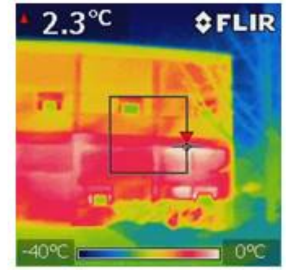
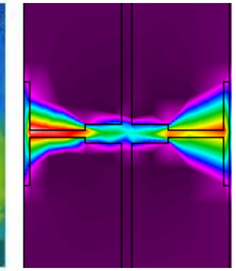
CAE 331/513
Building Science
Fall 2016





Week 4: September 15, 2016
Human thermal comfort

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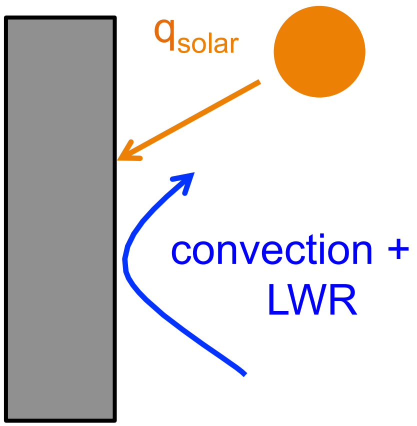
Schedule updates

- Last time:
  - Combined mode heat transfer
  - Building energy balances

- Today:
  - Finishing building energy balances
  - Human thermal comfort

- Next time:
  - Review for exam 1



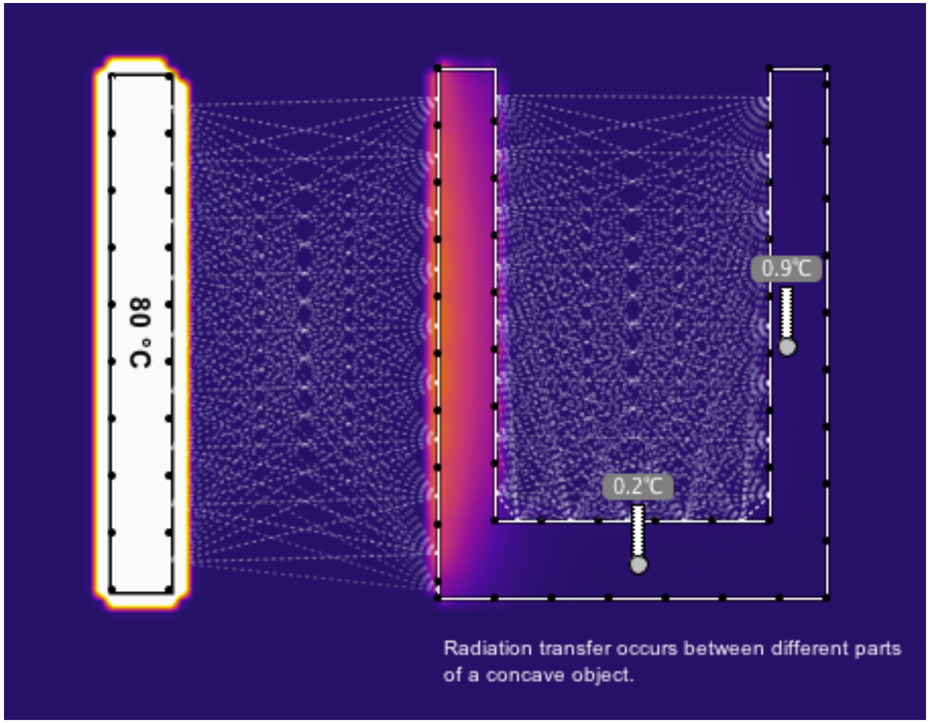
ENERGY BALANCES

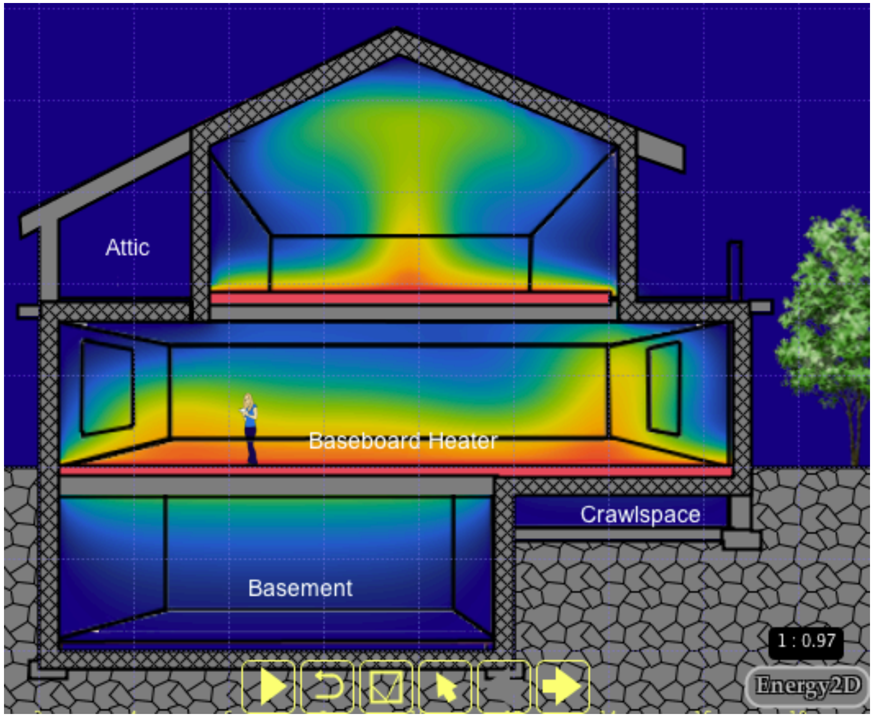
Building energy balances

- Multiple modes of heat transfer are typically acting at the same time at a particular point in/on a building

- We can write expressions to quantify heat flow/flux to/from these points by accounting for all relevant modes of heat transfer
  - "Building energy balances"

Building energy balances

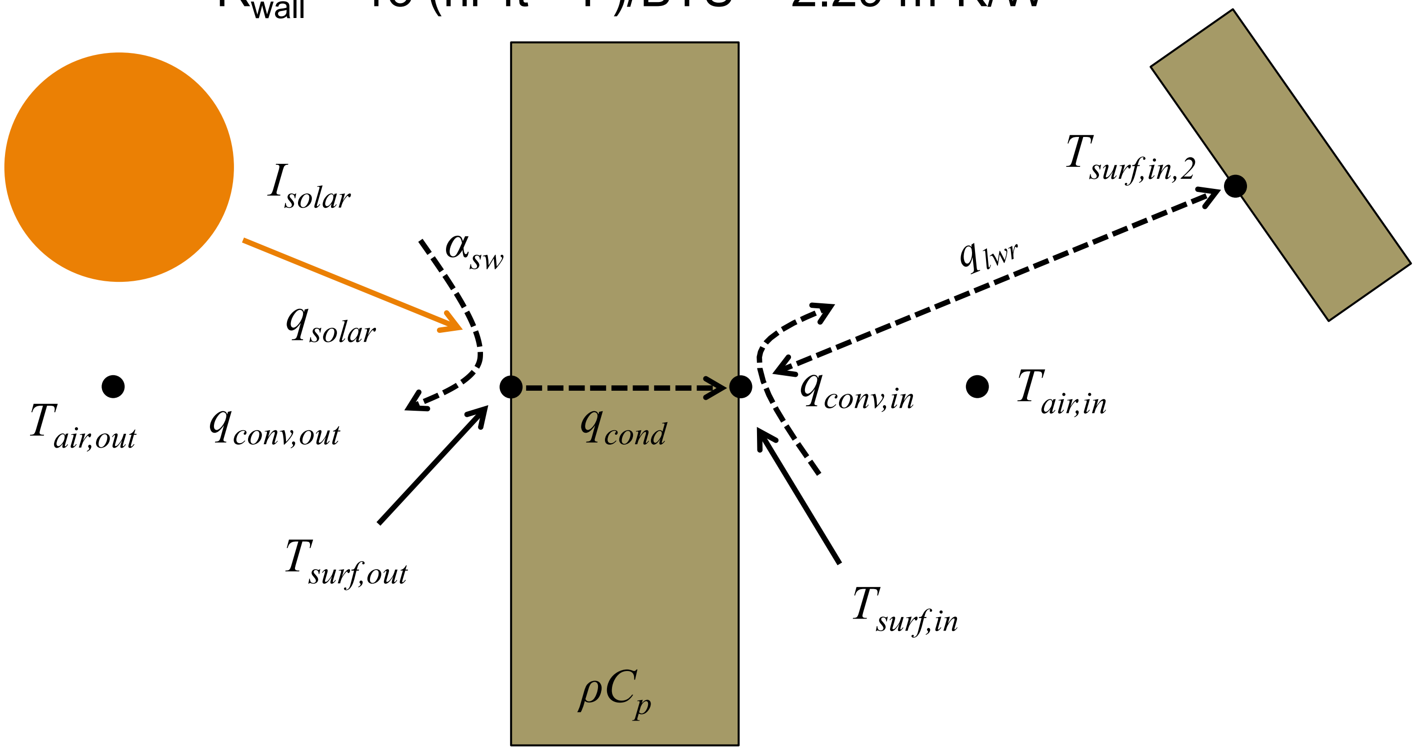




Building energy balances

Imagine an external wall of a building:

R_{wall} = 13 (hr-ft^2-°F)/BTU = 2.29 m^{2}K/W



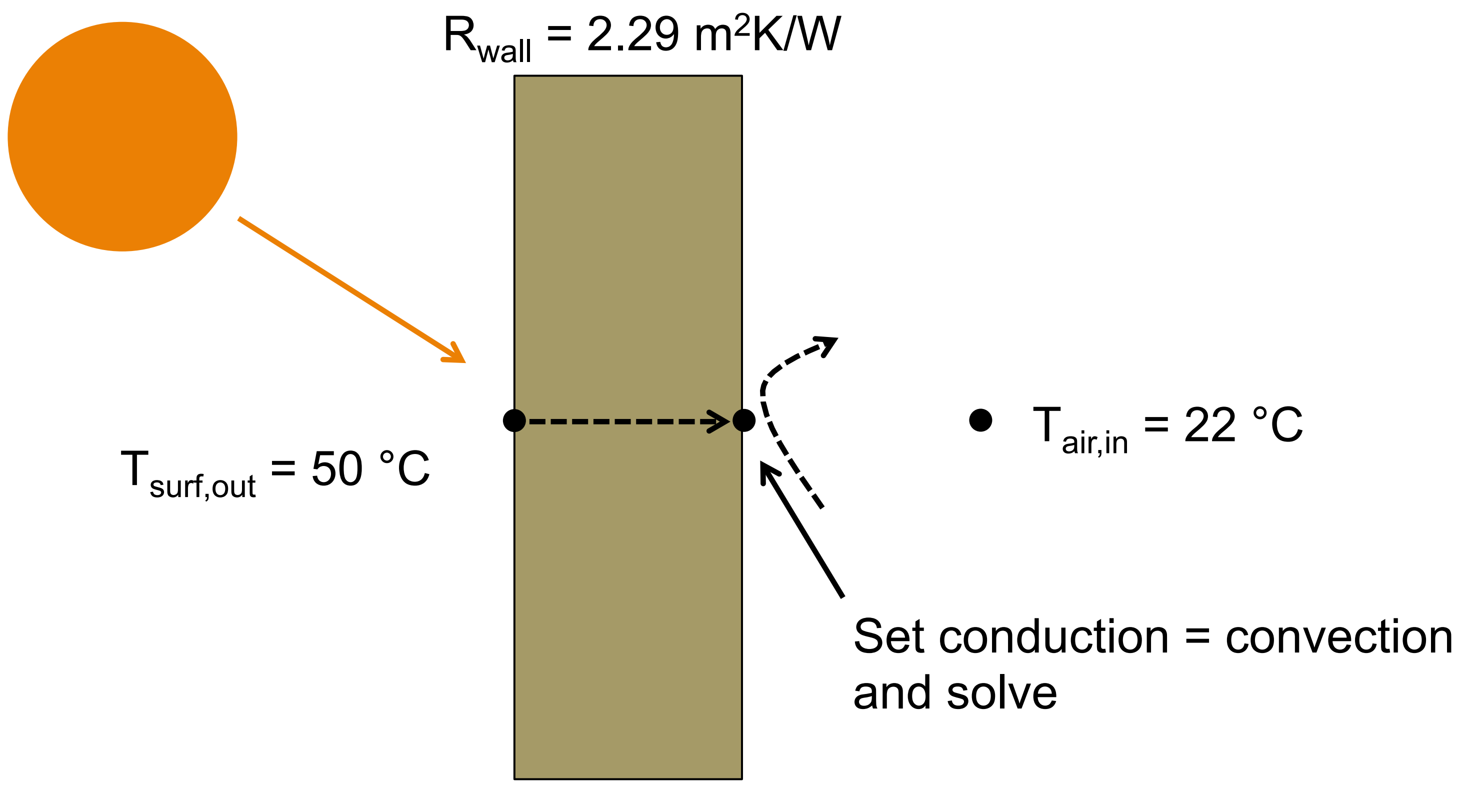
How is this helpful to us?

- Imagine the classroom wall is being heated by the sun on the other side
- The exterior surface temperature is 122°F (50°C)
- The interior air temperature is 72°F (22°C)
- The R-value of the wall is R-13 (IP) (2.29 m^2K/W)
- What is the interior surface temperature of the wall?

- This interior surface temperature impacts the heat flux to indoor air, as well as the surrounding surface temperatures (via radiation), which all impact the building's energy balance

Building energy balance example

- Estimate the surface temperature of an interior wall whose exterior side is being warmed by the sun
  - Assume that indoor LWR can be ignored and assume steady-state

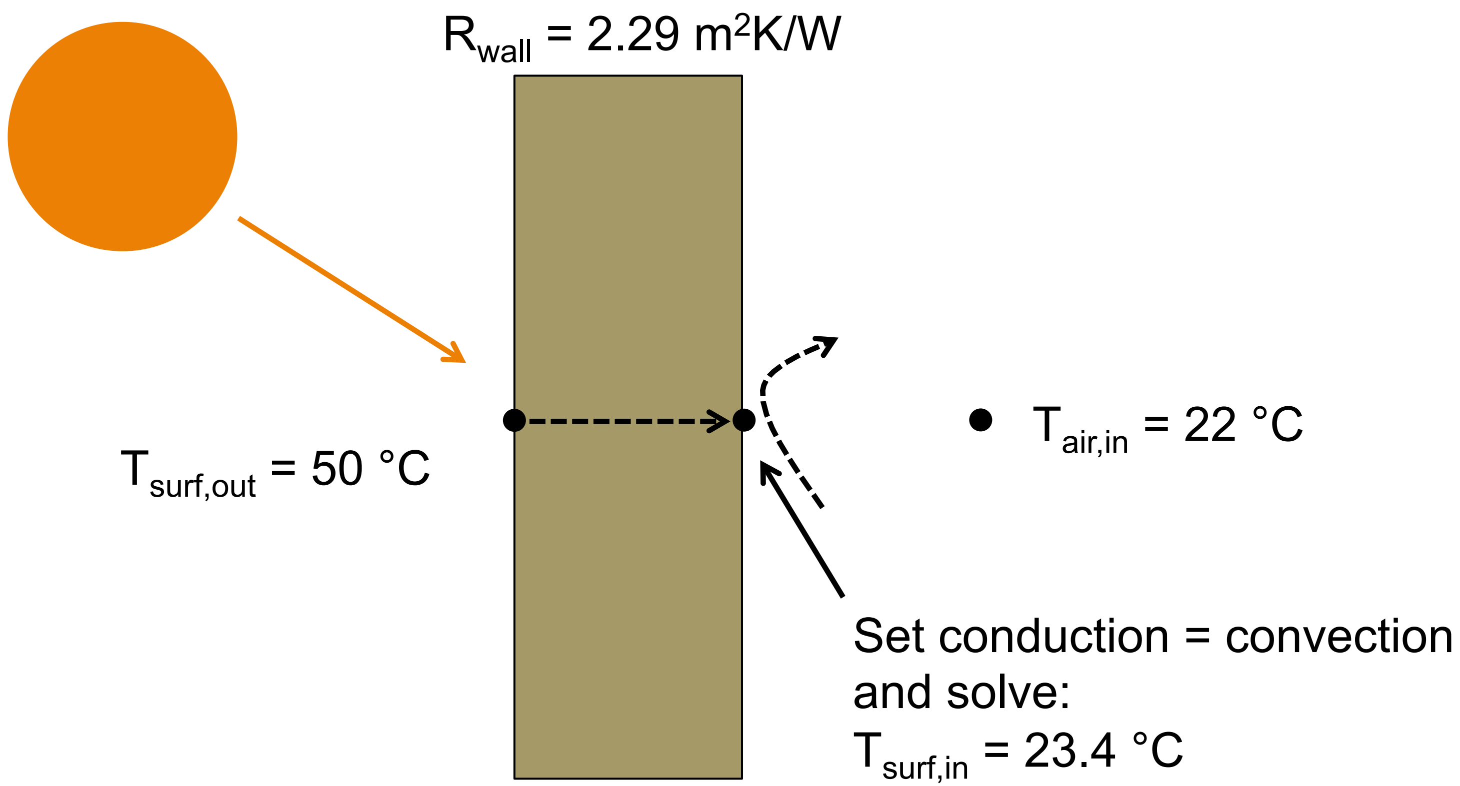


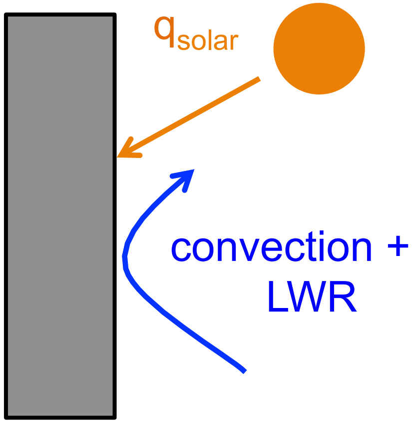
Convective film resistances

Surface Conditions	Horizontal Heat Flow	Upwards Heat Flow	Downwards Heat Flow
Indoors: R_{in}	0.12 m^2K/W (SI) 0.68 $h \cdot ft^2 \cdot °F/Btu$ (IP)	0.11 m^2K/W (SI) 0.62 $h \cdot ft^2 \cdot °F/Btu$ (IP)	0.16 m^2K/W (SI) 0.91 $h \cdot ft^2 \cdot °F/Btu$ (IP)
R_{out}: 6.7 m/s wind (Winter)		0.030 m^2K/W (SI) 0.17 $h \cdot ft^2 \cdot °F/Btu$ (IP)	
R_{out}: 3.4 m/s wind (Summer)		0.044 m^2K/W (SI) 0.25 $h \cdot ft^2 \cdot °F/Btu$ (IP)	

Building energy balance example

- Estimate the surface temperature of an interior wall whose exterior side is being warmed by the sun
  - Assume that LWR can be ignored and assume steady-state

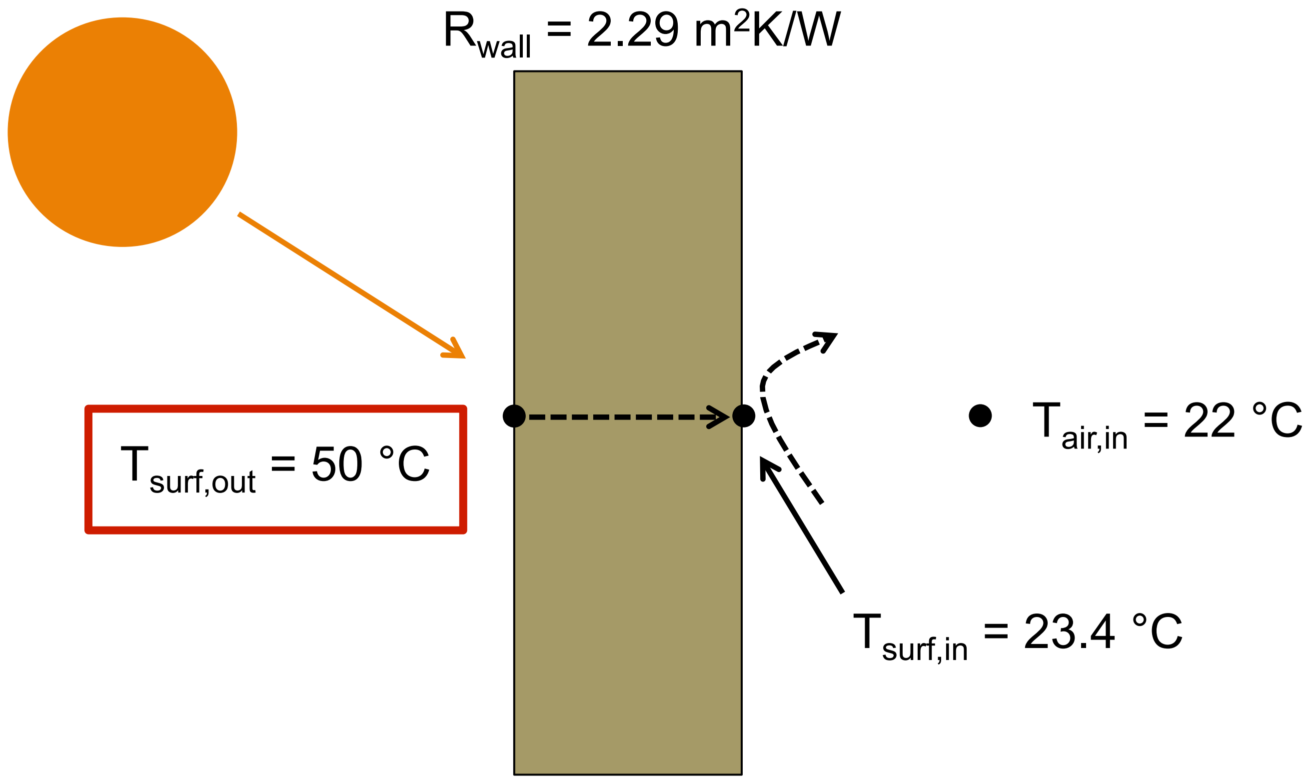




"SOL-AIR" TEMPERATURES

Sol-air temperatures

- In the last example, we were given that the exterior surface temperature was 122°F (50°C)
  - **How did we know that?**



Sol-air temperatures

- If we take an external surface with a combined convective and radiative heat transfer coefficient, $h_{conv+rad}$

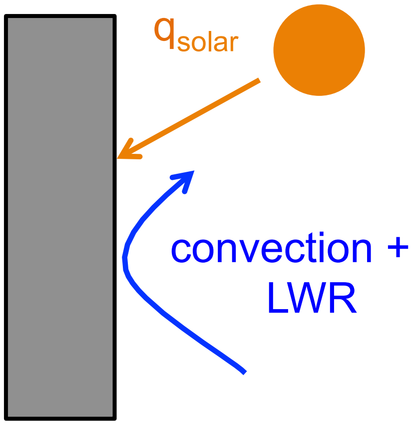
$$q_{conv+rad} = h_{conv+rad}\left(T_{air} - T_{surf}\right)$$

- If that surface now absorbs solar radiation (αI_{solar}), the total heat flow at the exterior surface becomes:

$$q_{conv+rad} = h_{conv+rad}\left(T_{air} - T_{surf}\right) + \alpha I_{solar}$$

- To simplify our calculations, we can define a "**sol-air**" temperature that accounts for all of these impacts:

$$T_{sol-air} = T_{air} + \frac{\alpha I_{solar}}{h_{conv+rad}}$$



- Now we can describe heat transfer at that surface as:

$$q_{total} = h_{conv+rad}\left(T_{sol-air} - T_{surf}\right)$$

Example sol-air temperatures

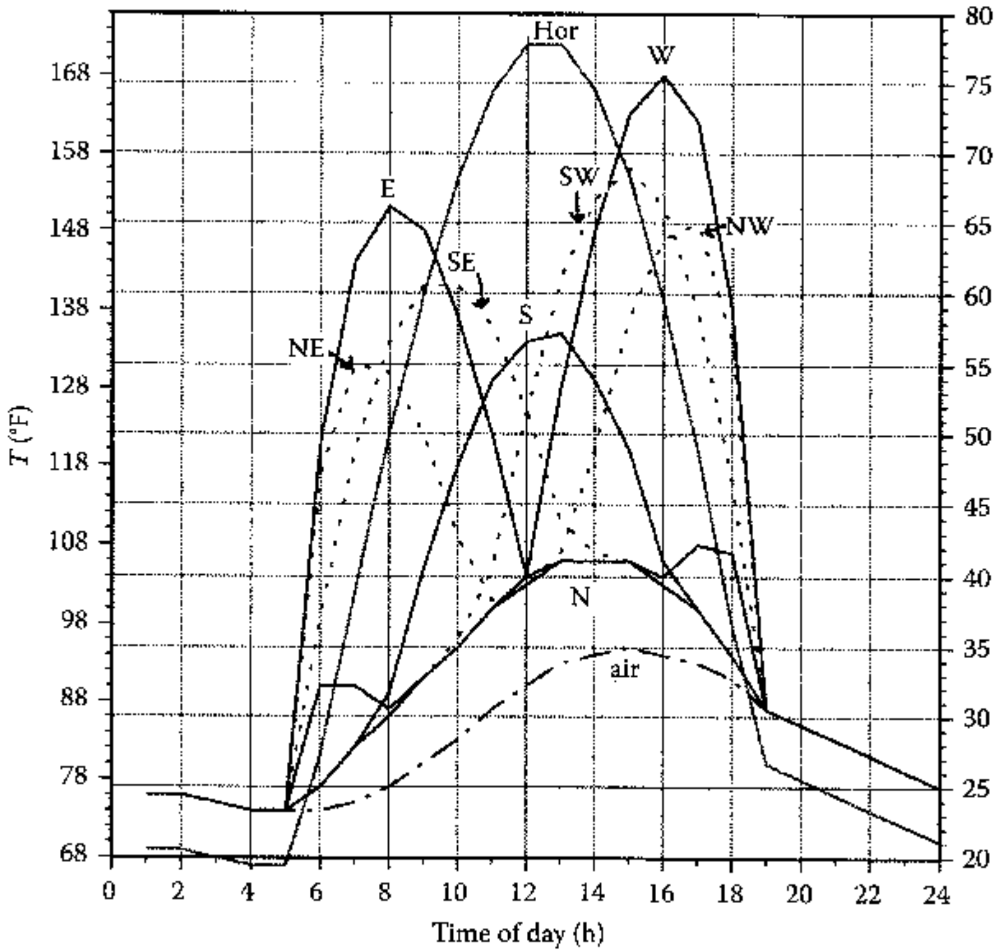


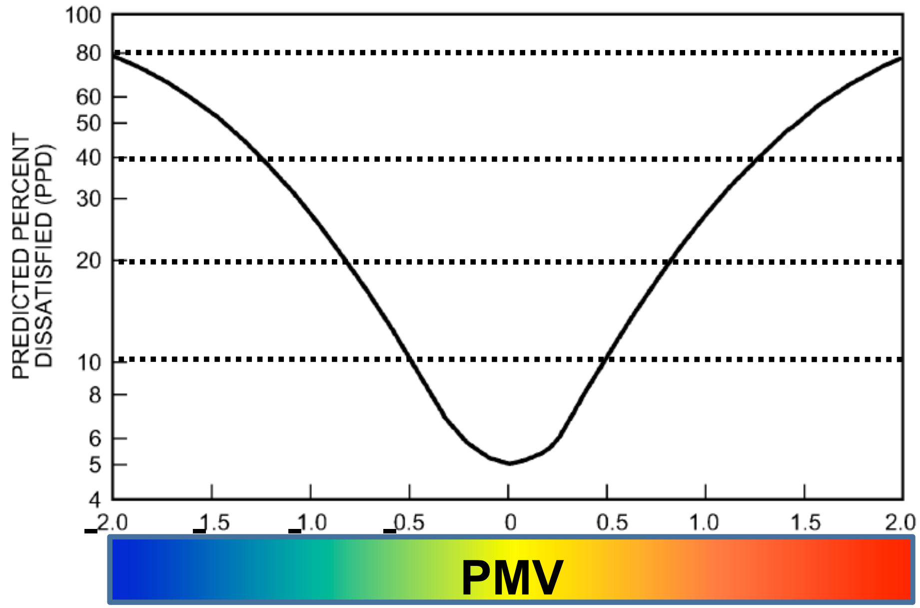
FIGURE 6.17
Sol-air temperature for horizontal and vertical surfaces as a function of time of day for summer design conditions, July 21 at 40° latitude, assuming $\alpha/h_o = 0.30$ (h · ft^2 · °F)/Btu [0.052 (m^2 · K)/W]. The curves overlap when there is no direct radiation on a surface. (Courtesy of ASHRAE, *Handbook of Fundamentals*, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Atlanta, GA, 1989, Table 26.1.)

Solar radiation and external surface temperatures

- We can also use air temperatures and material properties (absorptivity and emissivity) to estimate exterior surface temperatures that are exposed to radiation
  - These are not extremely accurate but provide a reasonable estimate

Situation	Thermally massive	Thermally lightweight
Roofs: direct sun	$t_a + 42\ \alpha$	$t_a + 55\ \alpha$
Roof: sun + reflected /emitted radiation	$t_a + 55\ \alpha$	$t_a + 72\ \alpha$
Roof exposed to night sky	$t_a - 5\ \varepsilon$	$t_a - 10\ \varepsilon$
Walls: winter sun	$t_a + 35\ \alpha$	$t_a + 48\ \alpha$
Walls: summer sun	$t_a + 28\ \alpha$	$t_a + 40\ \alpha$
Walls exposed to night sky	$t_a - 2\ \varepsilon$	$t_a - 4\ \varepsilon$

Source: Straube and Burnett

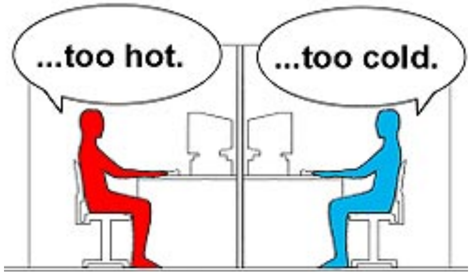


HUMAN THERMAL COMFORT

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

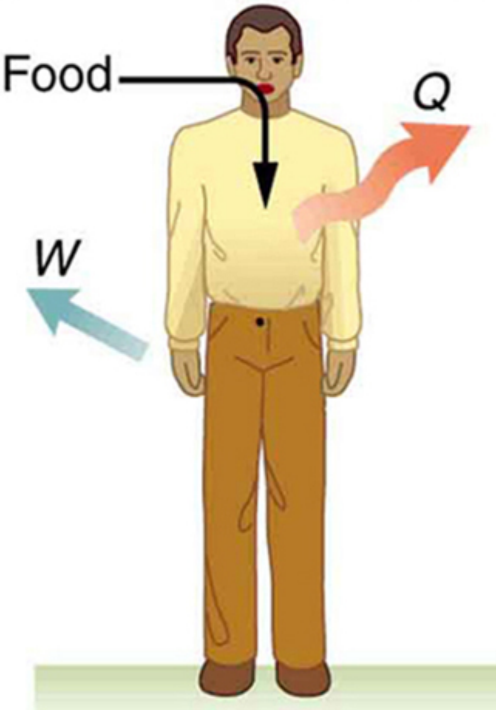
- In general, **thermal comfort** occurs when:
  - Body temperatures are held within narrow ranges
  - Skin moisture is low
  - The physiological effort of regulation is minimized



- 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

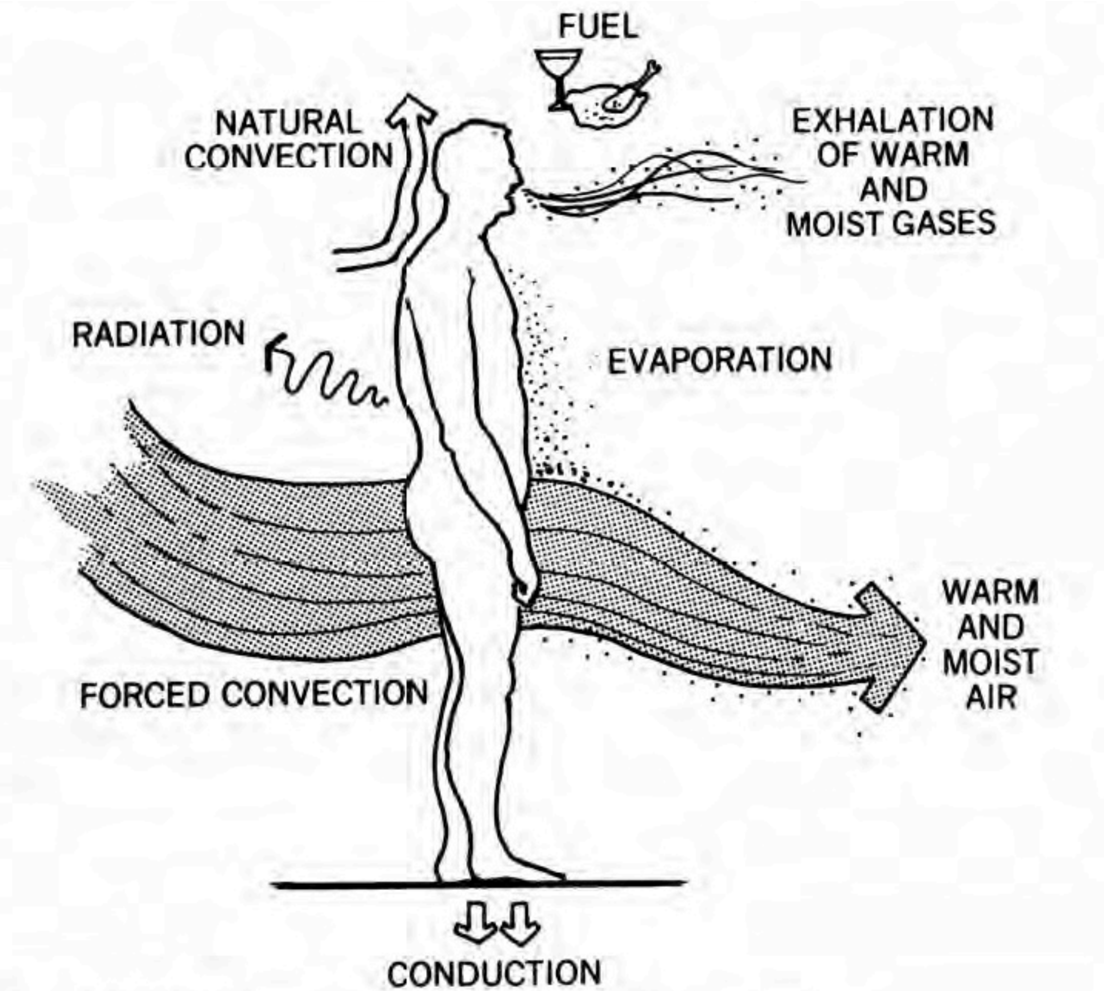
Energy balance of the human body

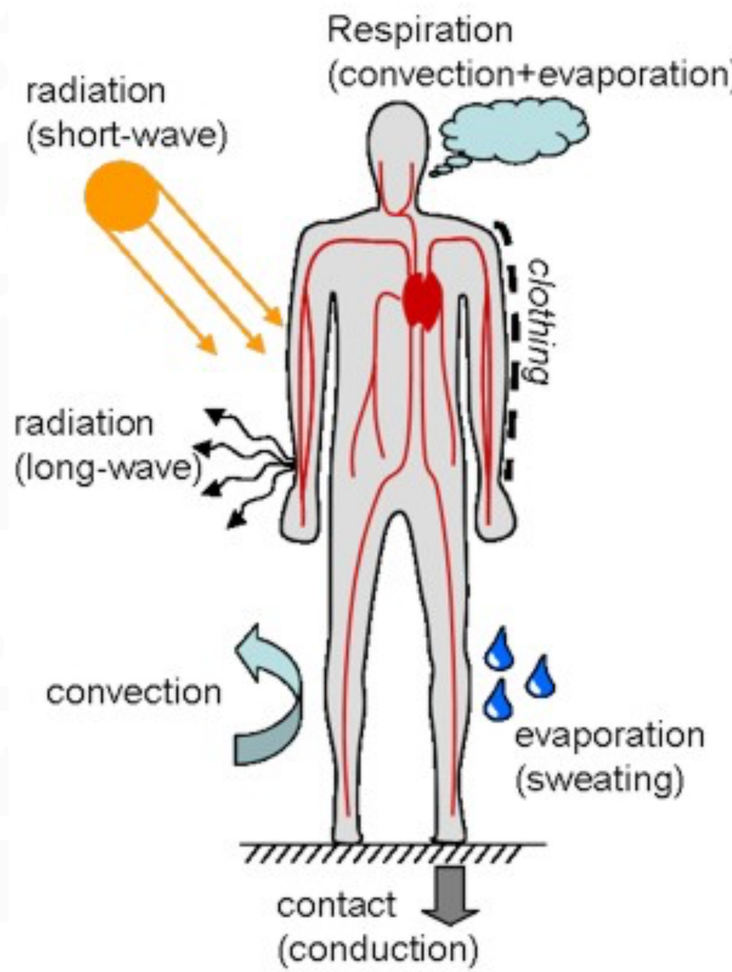
- The heat produced by the body's metabolism dissipates to the environment
  - Otherwise we would overheat
- If the rate of heat transfer away is higher than the rate of heat production, the body cools down and we feel cold
  - If heat transfer to surroundings is lower than our heat production, we feel 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

<u>Your largest organ, your skin, covers ~2 m^2 and makes up ~15% of your body weight</u>





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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):

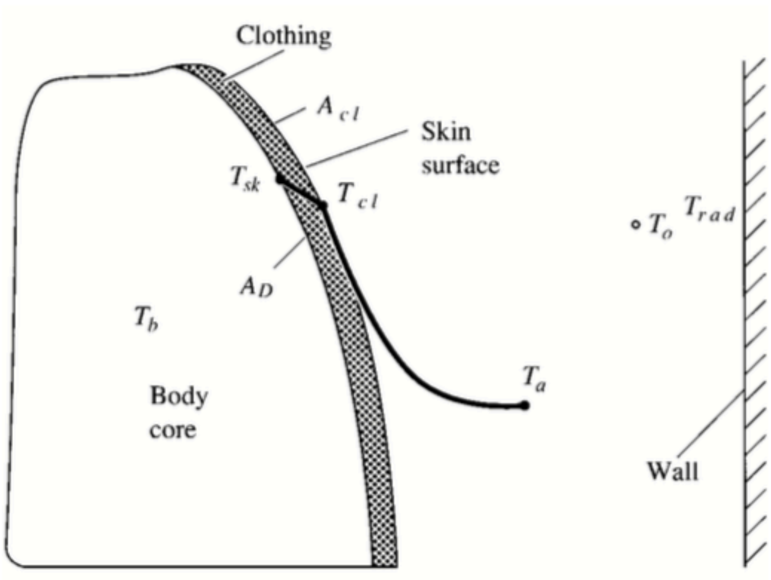
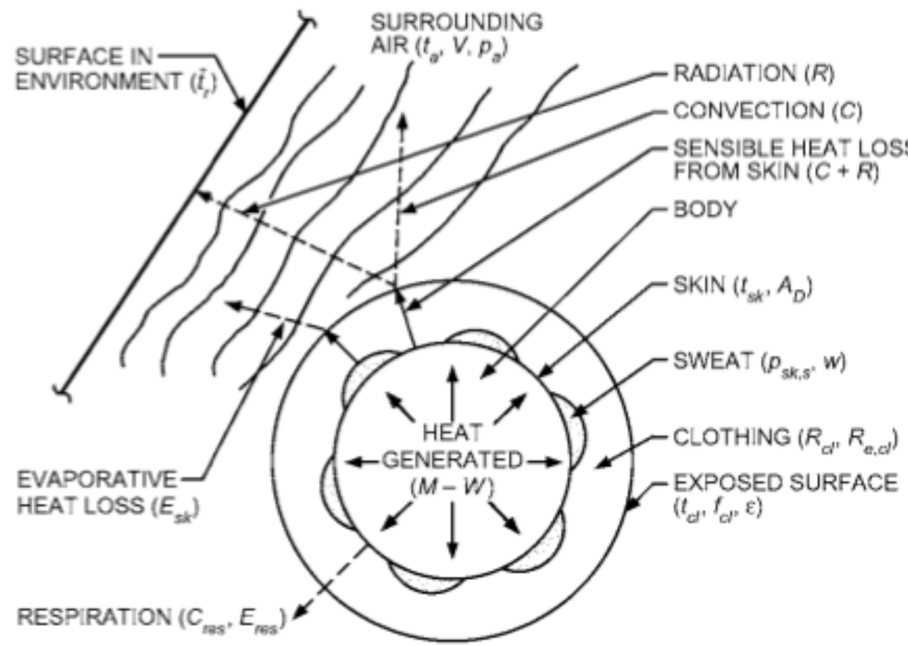


FIGURE 4.1 Sensible heat exchange between the human body and the indoor environment.



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

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

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 <u>predict</u> the results of a questionnaire through equations and generate a **predicted mean vote (PMV)**
- The <u>PMV</u> 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)

The PPD Function:

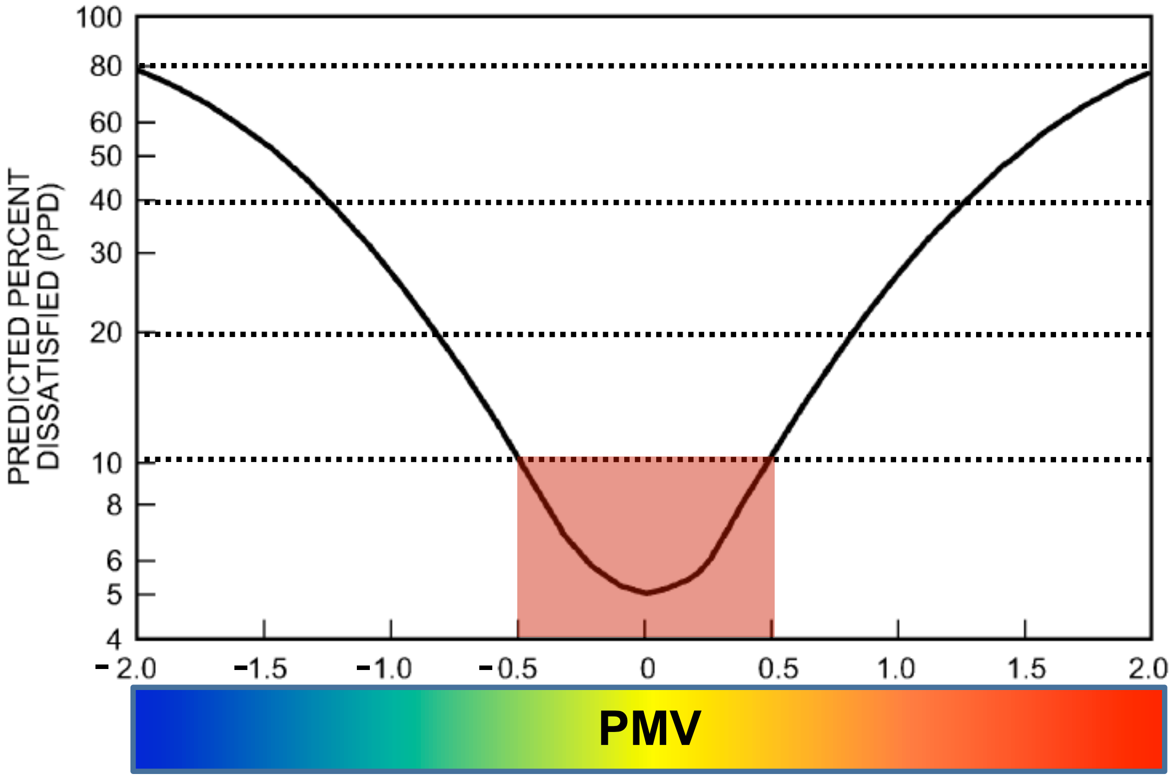
Since we want:

PPD < 10%

we can see that:

-0.5 < PMV < 0.5

is our target



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

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

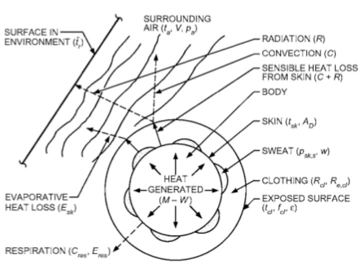
Predicting PMV and PPD

- 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:

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

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



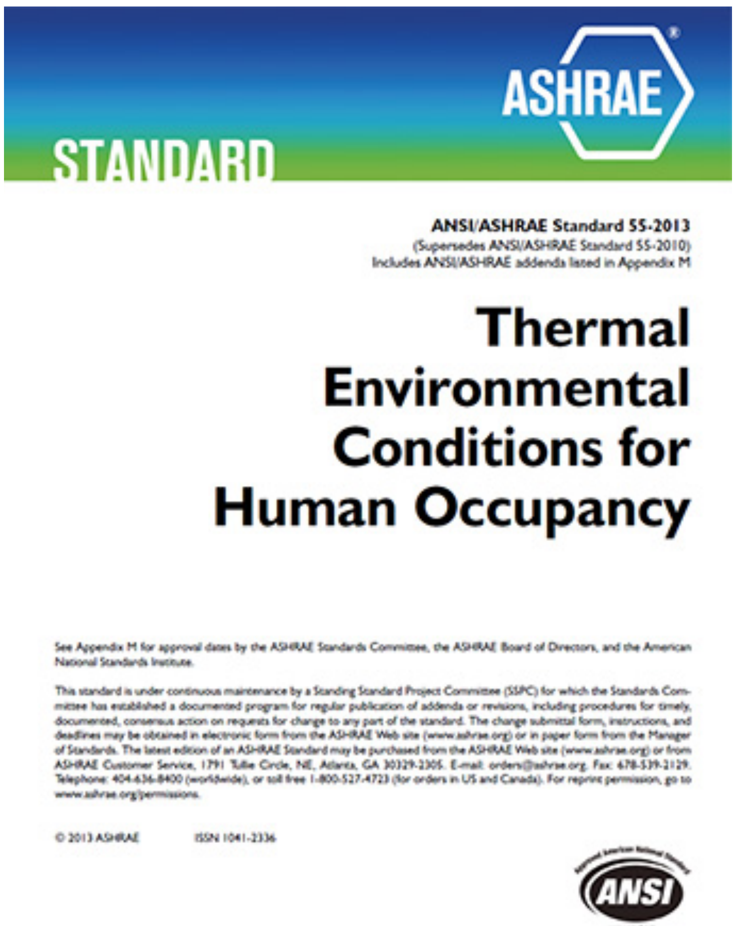
M = metabolic activity

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

Source: ASHRAE HoF 2013 & ASHRAE Standard 55

Thermal comfort standards in building design

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


STANDARD

ASHRAE

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 Tullie Circle, NE, Atlanta, GA 30329-2305. E-mail: orders@ashrae.org. Fax: 678-539-2129. 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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ANSI

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)

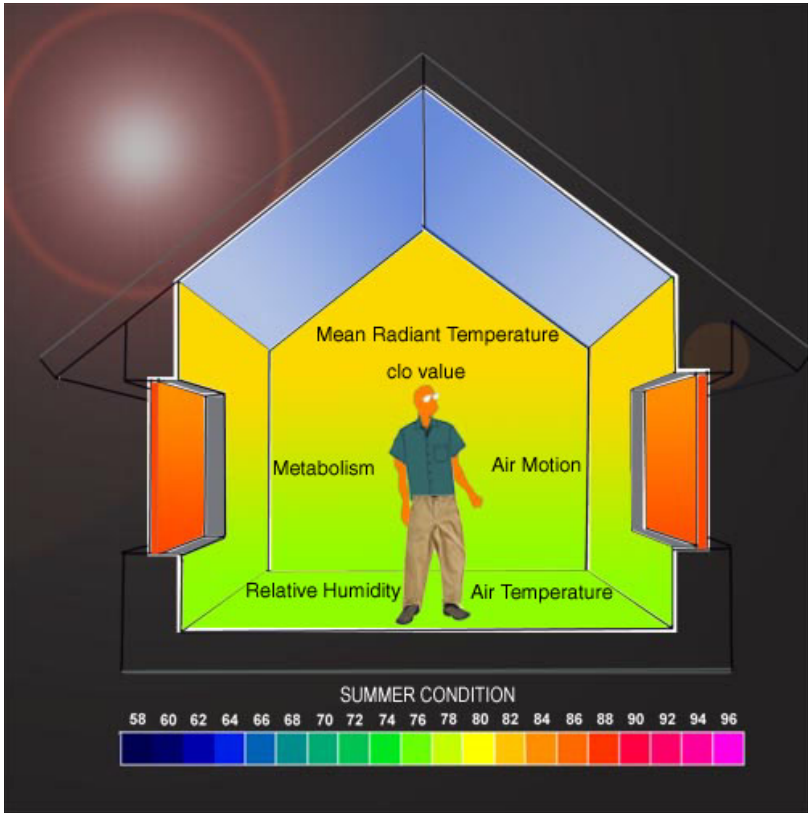
Local air speed (v)

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 ft^2 (1.5 to 2 m^2)
  - Typically we use 1.8 m^2

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

A_D = DuBois surface area, m^2
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

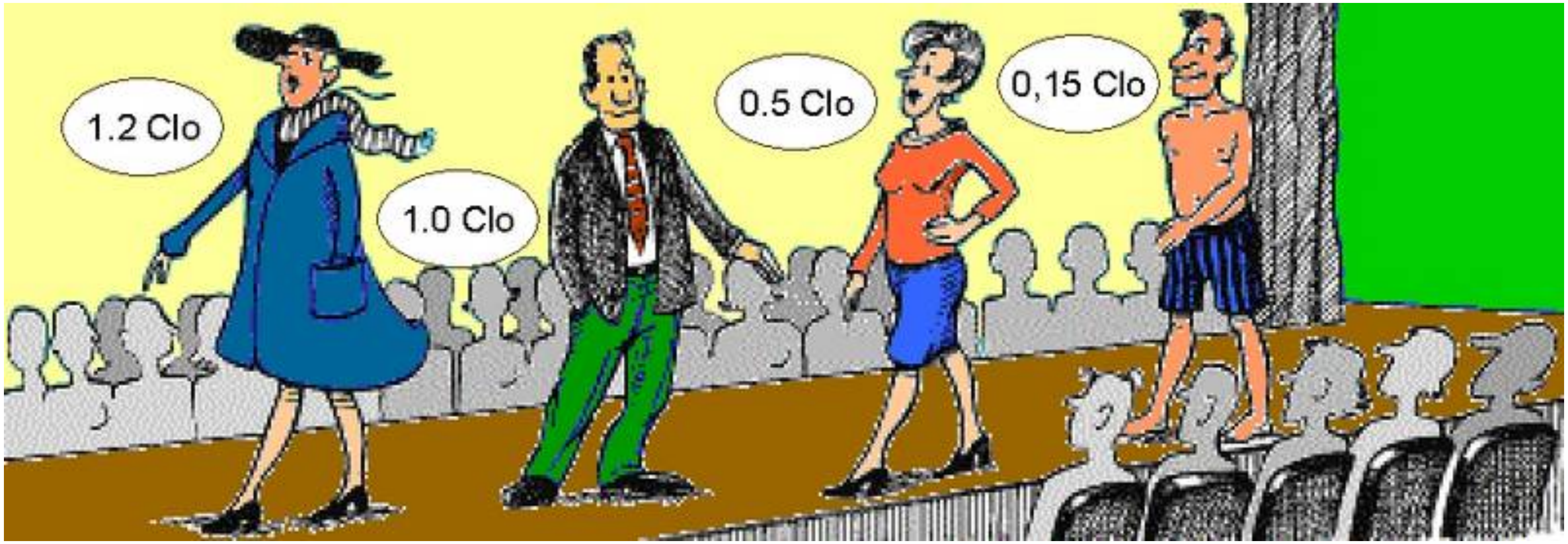
Activity	Met Units	Metabolic Rate W/m²	(Btu/h·ft²)
Resting			
Sleeping	0.7	40	(13)
Reclining	0.8	45	(15)
Seated, quiet	1.0	60	(18)
Standing, relaxed	1.2	70	(22)
Walking (on level surface)			
0.9 m/s, 3.2 km/h, 2.0 mph	2.0	115	(37)
1.2 m/s, 4.3 km/h, 2.7 mph	2.6	150	(48)
1.8 m/s, 6.8 km/h, 4.2 mph	3.8	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 **clos** (1 clo = 0.88 h·ft^2·˚F/Btu)
- Insulating values for various garments are found in ASHRAE Fundamentals and Appendix B of Standard 55



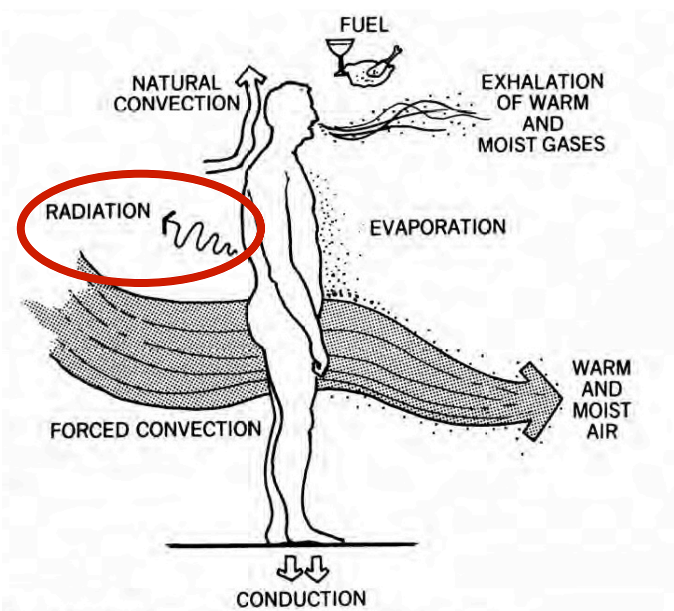
Thermal insulation, I_{cl}

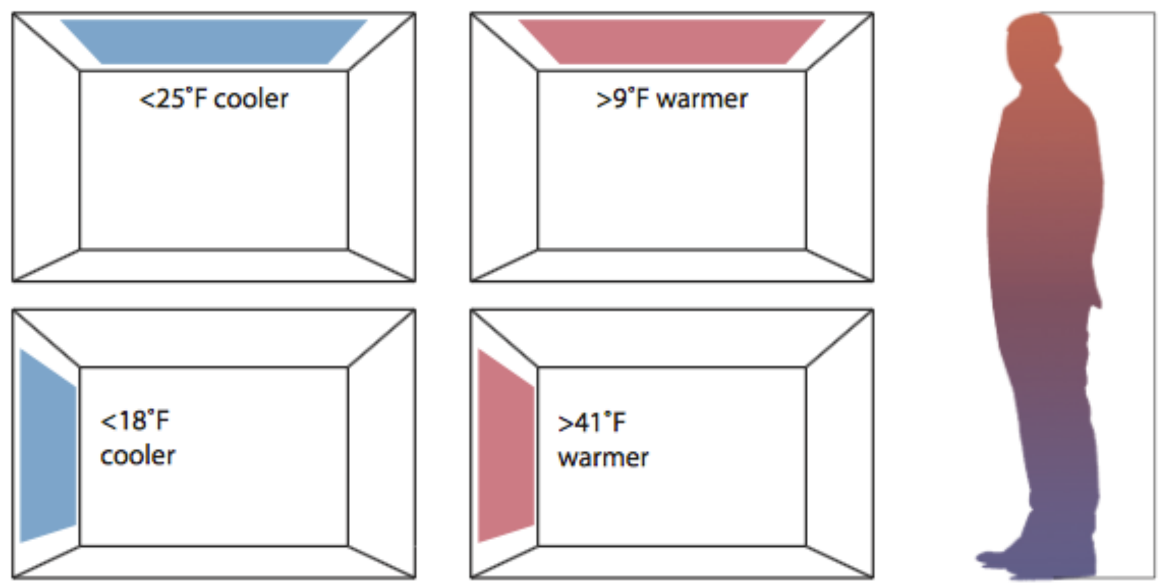
Clothing Insulation Values for Typical Ensembles[a]

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**





https://soa.utexas.edu/sites/default/disk/preliminary/preliminary/1-Boduch_Fincher-Standards_of_Human_Comfort.pdf

Mean radiant temperature, T_r

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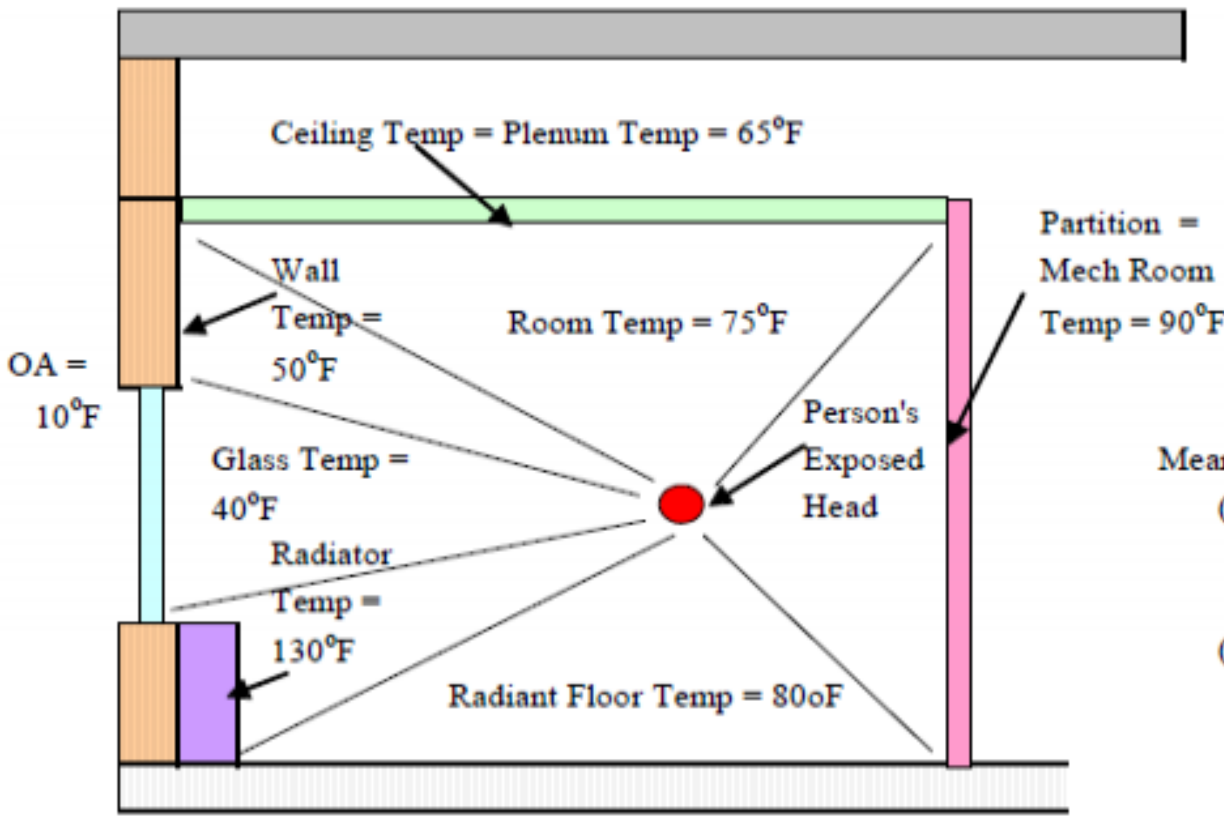


SURFACE		Temp	Angle
Name	No.	°F	degs
Ceiling	1	65	105
Partition	2	90	100
Floor	3	80	110
Radiator	4	130	20
Window	5	40	30
Wall	6	50	20

Mean Radiant Temp (MRT) =
(A1*T1 + A2*T2 + A3*T3 +
A4*T4 + A5*T5 + A5*T5 +
A6*T6) / 360 =
(105*65 + 100*90 + 110*80 +
20*130 + 30*40 + 20*50) / 360 =
29,425 / 360 = 81.74oF

http://energy-models.com/sites/all/files/resize/advanced-pages-30991/comfort-2-735x326.png

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

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

where

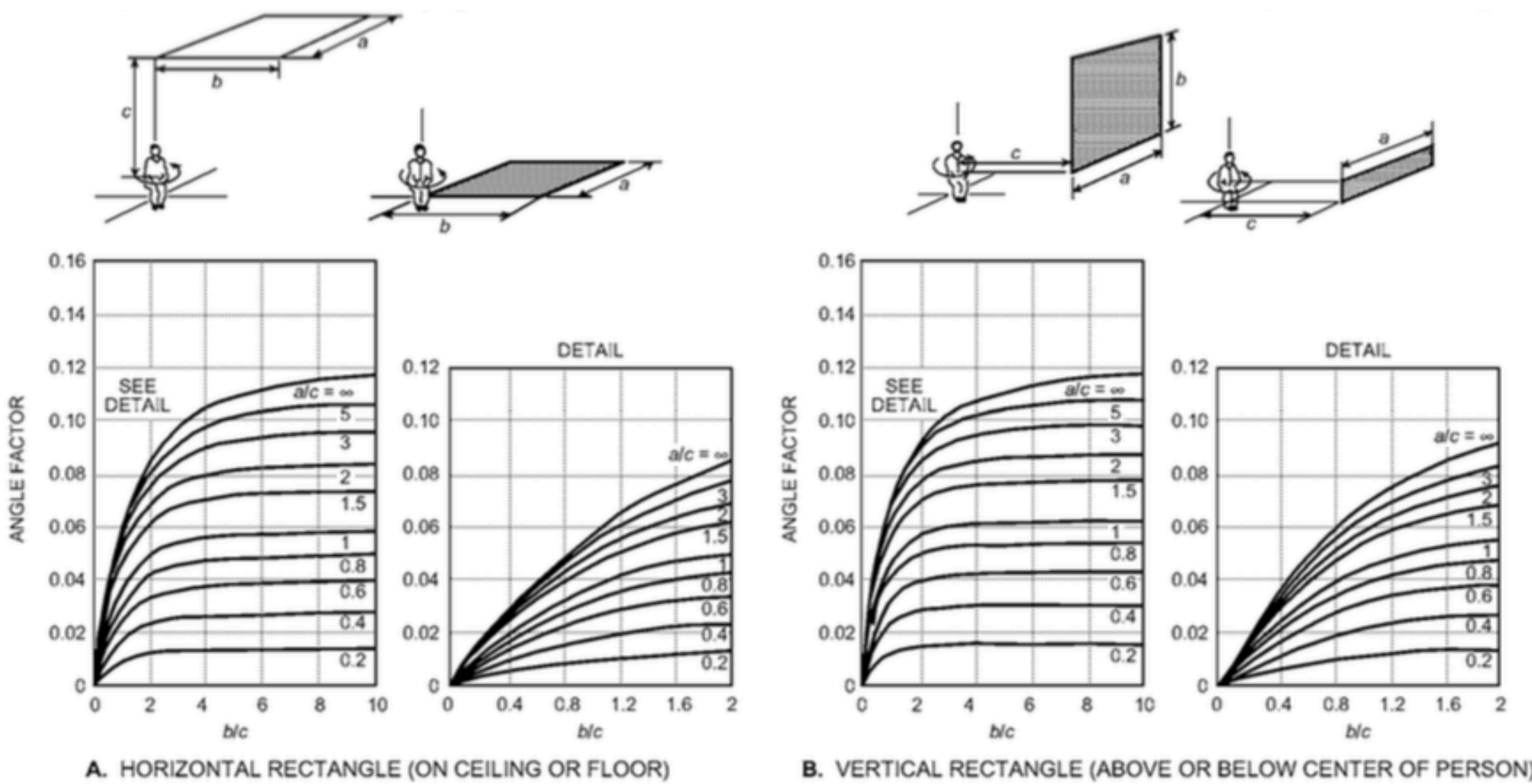
$\bar{T}_r$ = mean radiant temperature, K

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



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

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

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?

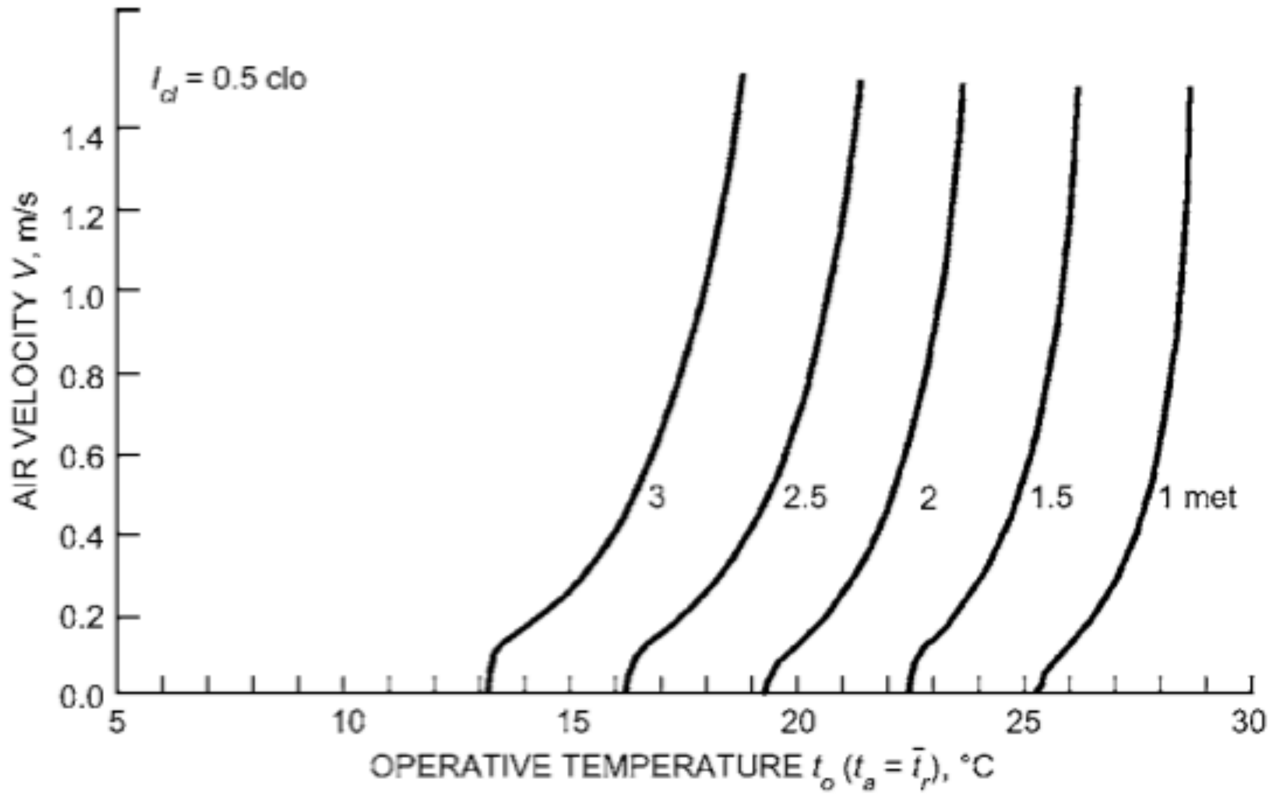


Fig. 14 Air Velocities and Operative Temperatures at 50% rh Necessary for Comfort (PMV = 0) of Persons in Summer Clothing at Various Levels of Activity

Operative temperatures, air velocity, clo, and met levels

How do these all interact to affect comfort?

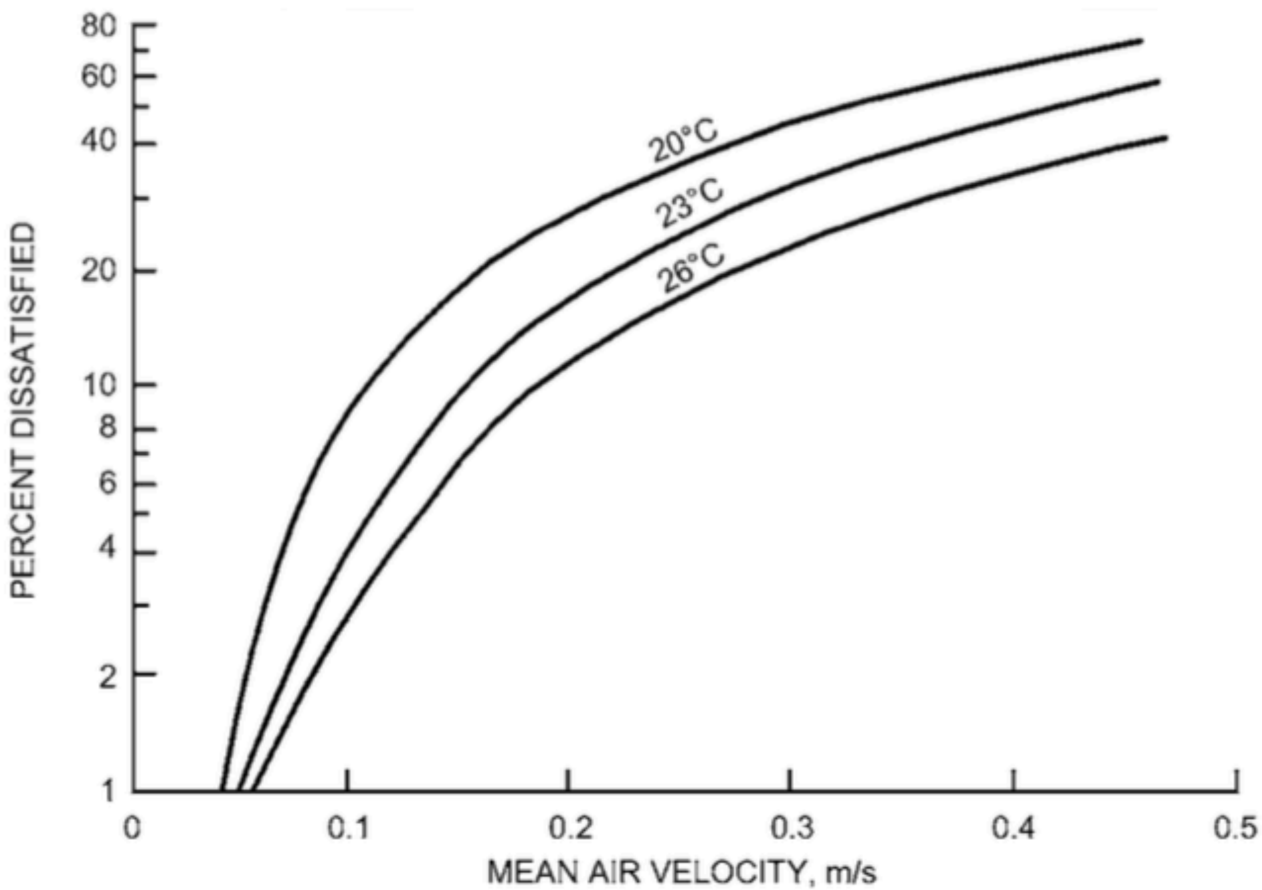


Fig. 10 Percentage of People Dissatisfied as Function of Mean Air Velocity

Operative temperatures, air velocity, clo, and met levels

How do these all interact to affect comfort?

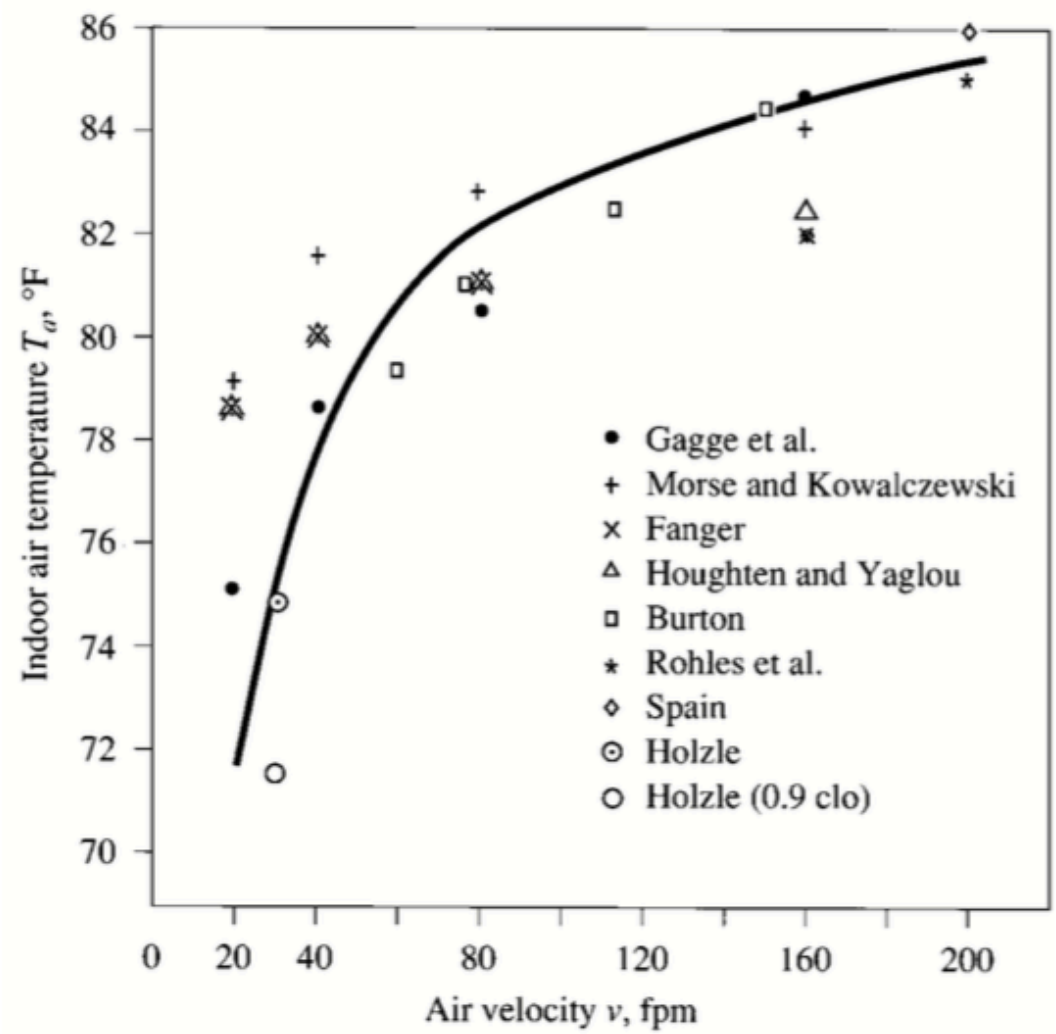
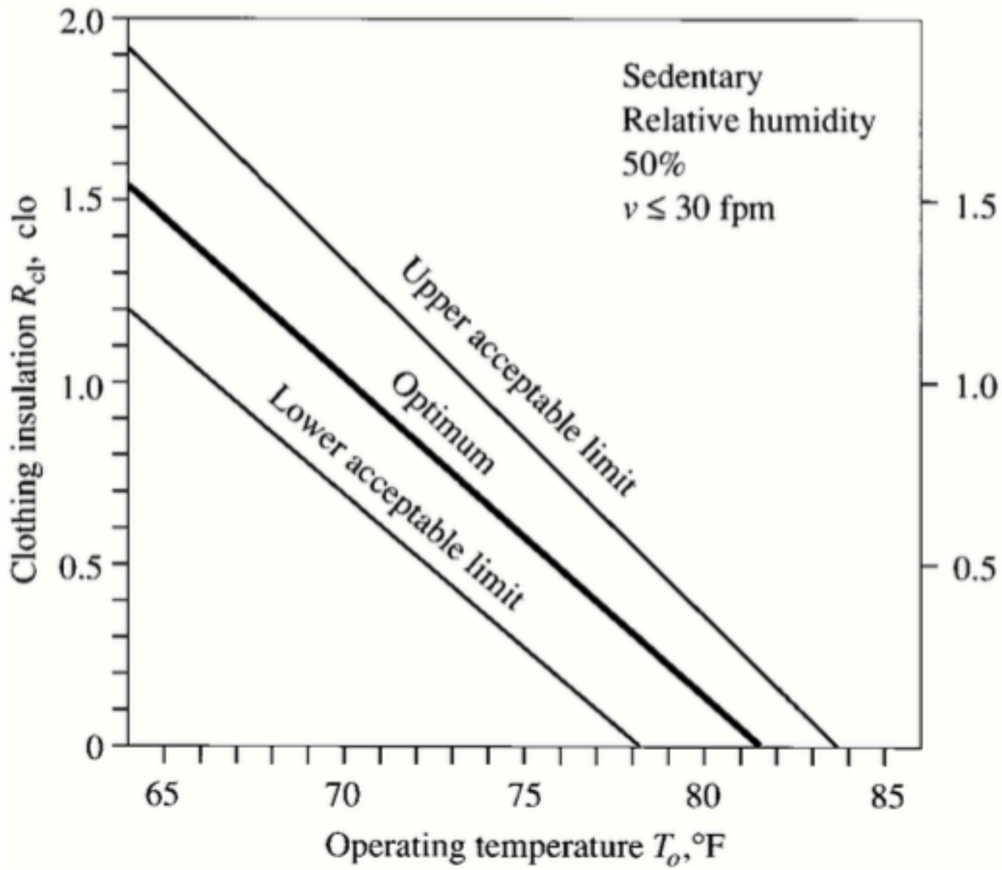


FIGURE 4.8 Preferred indoor air temperatures at various air velocities.

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

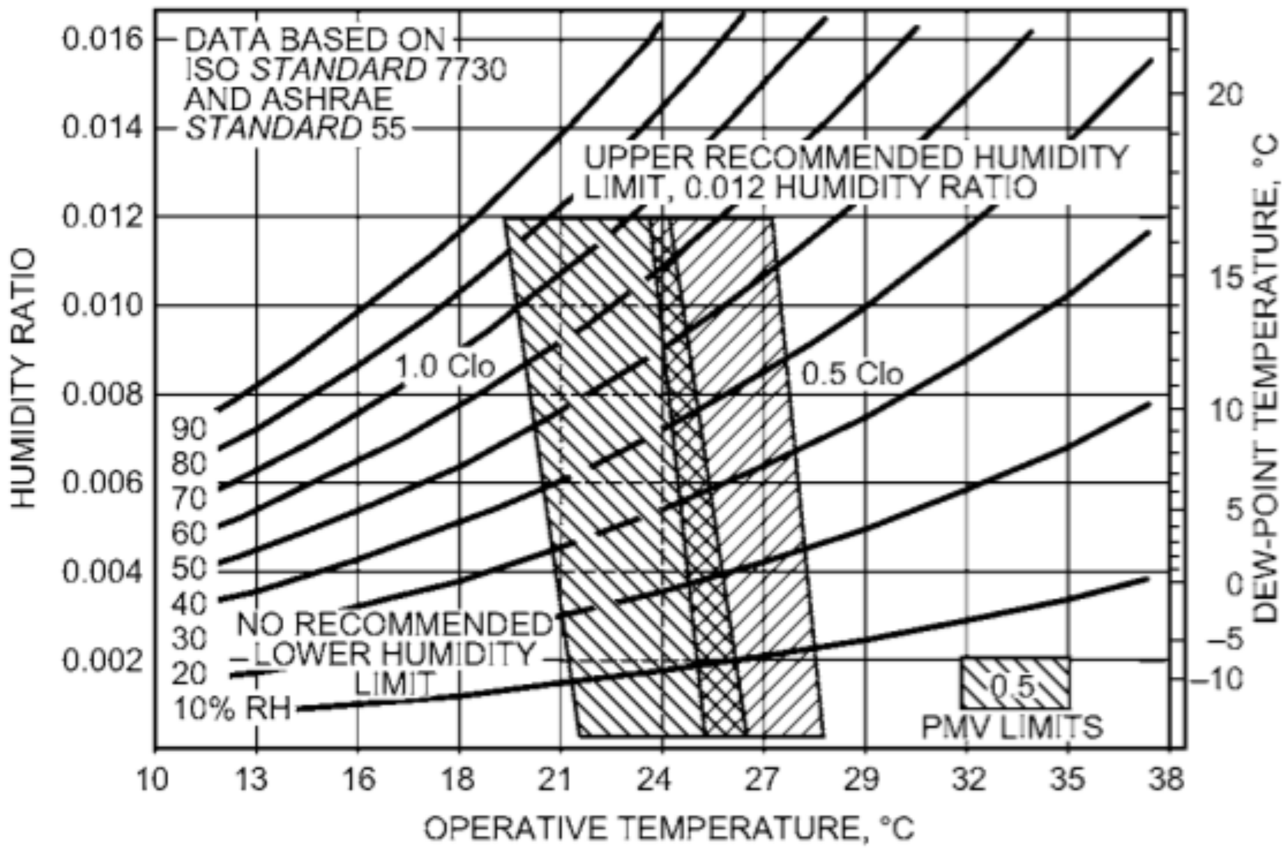
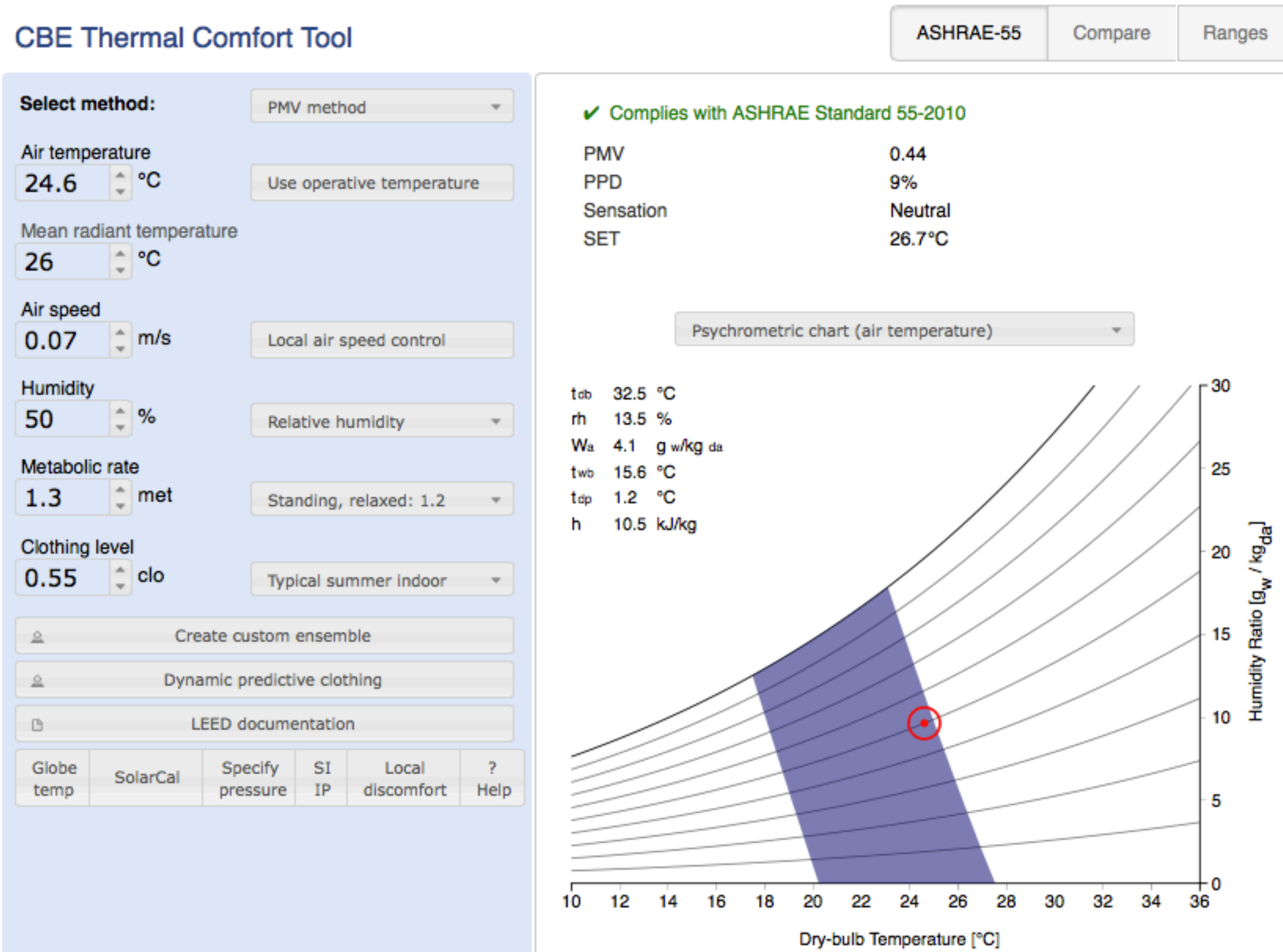


Fig. 5 ASHRAE Summer and Winter Comfort Zones

[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



http://smap.cbe.berkeley.edu/comforttool