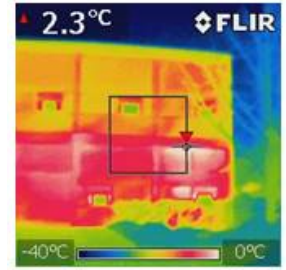
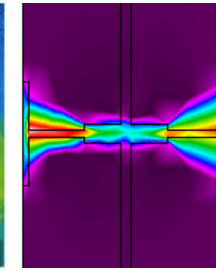
CAE 331/513
Building Science
Fall 2014





Week 4: September 18, 2014
Finish solar radiation (and windows)
Thermal comfort

Built
Environment
Research
@ IIT

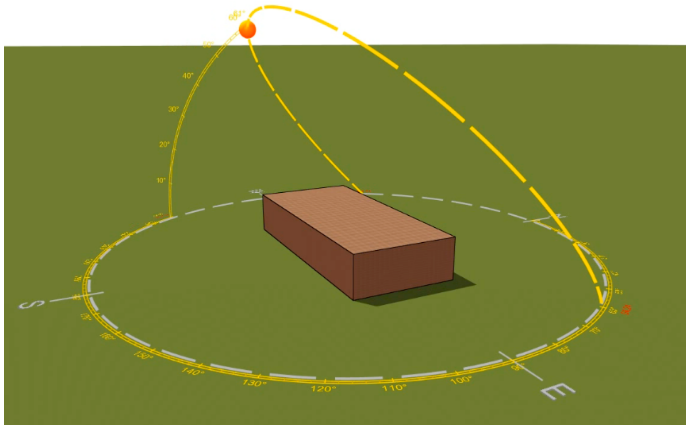
Advancing energy, environmental, and sustainability research within the built environment

www.built-envi.com

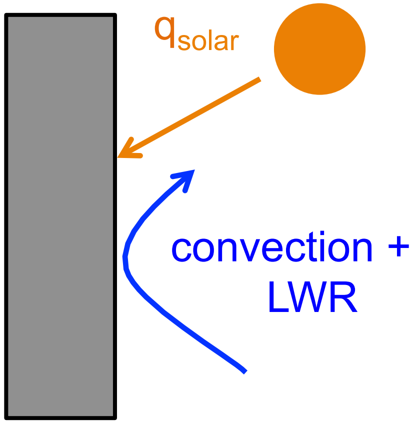
Twitter: @built_envi

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

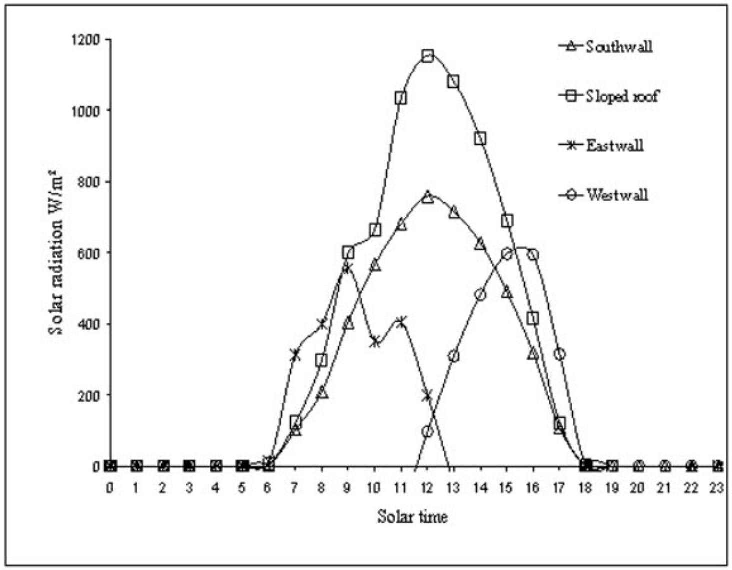
Last time: Solar radiation

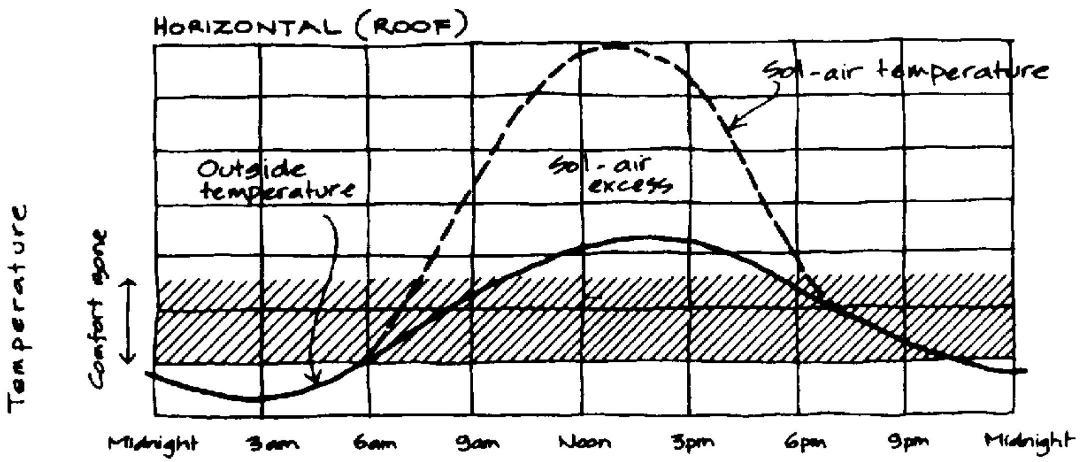


$$q_{solar} = \alpha I_{solar}$$



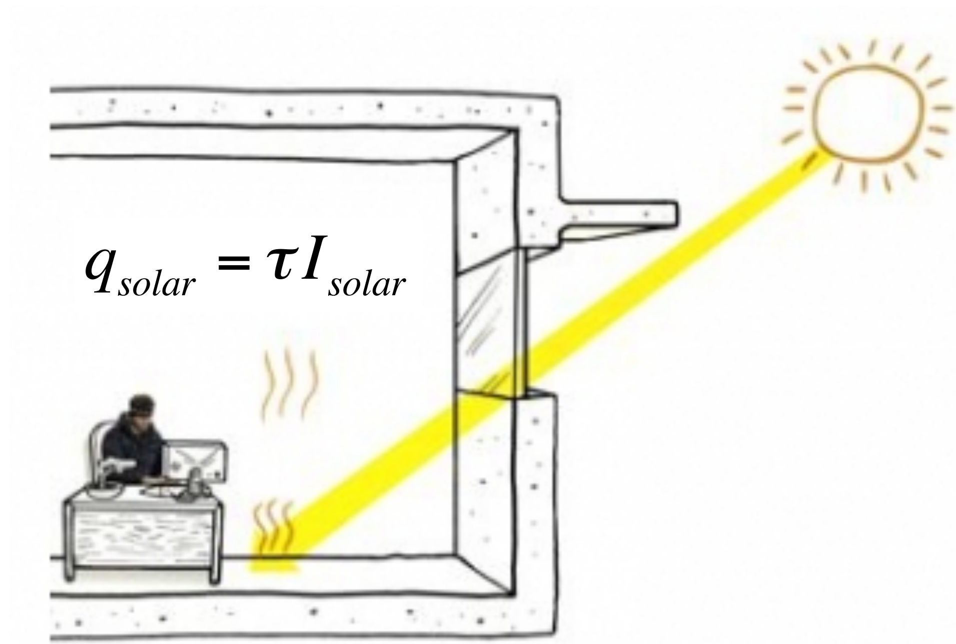
$$T_{sol-air} = T_{air} + \frac{\alpha I_{solar}}{h_{conv+rad}}$$





Today’s topics

Solar radiation
and windows



$$q_{solar} = \tau I_{solar}$$

And:
Human thermal comfort

Solar radiation and windows (i.e., fenestration)

- Solar radiation through a single glaze

100% incident

8% reflected

80% transmitted

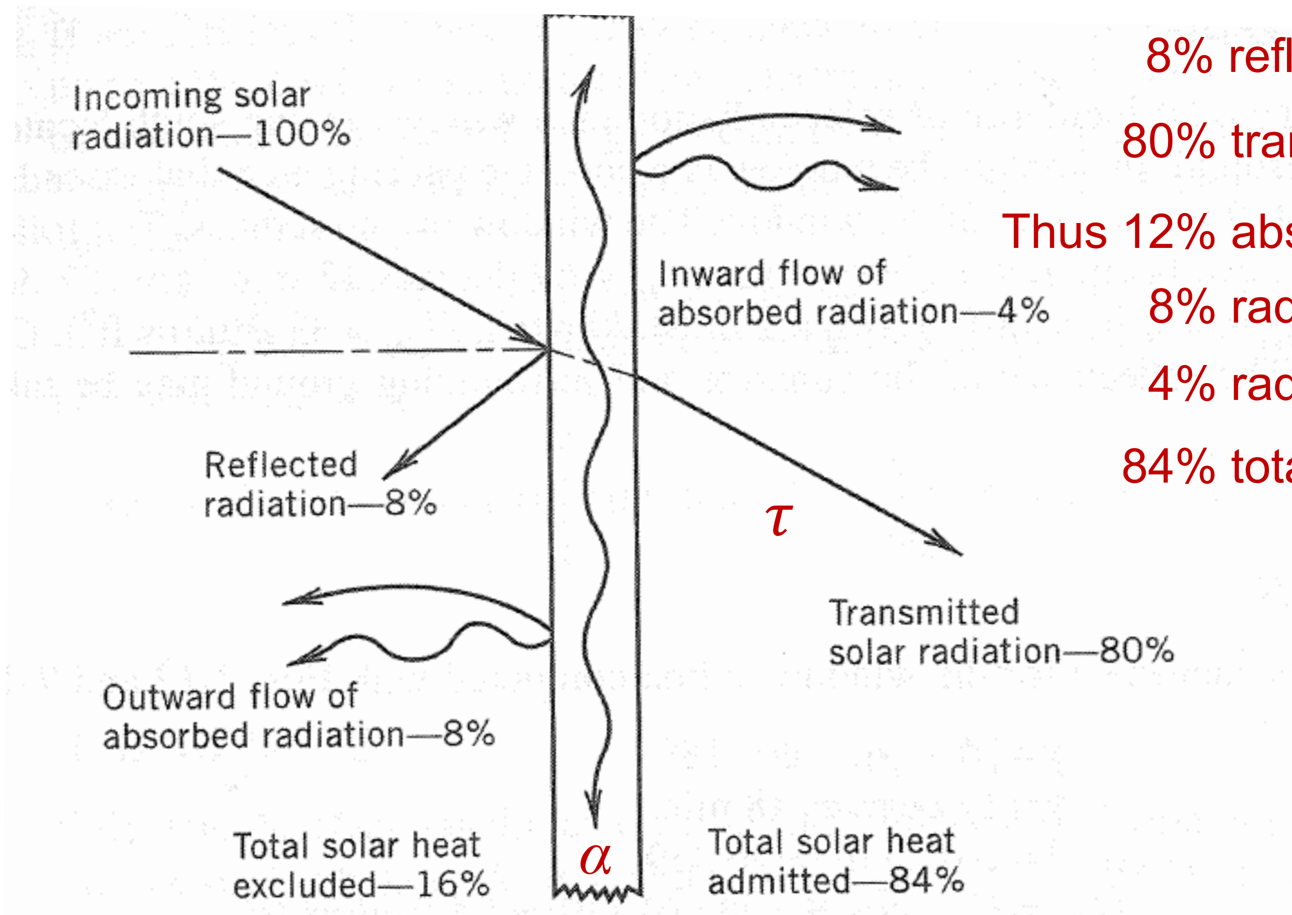
Thus 12% absorbed

8% rad/conv outward

4% rad/conv inward

84% total transmitted

outside



inside

Windows and total heat gain

- The total heat gain of a window is the sum of two terms:
  - The solar radiation heat gain from solar radiation (transmittance)
  - Combined conductive/convective/LWR thermal heat gain from the temperature difference between the interior and exterior
- In the summer, both terms are positive towards the interior and add to heat gains
- In the winter, solar is positive inwards (gain) but conduction/ convection/LWR is negative towards the exterior (loss)
  - Net heat gain may be in either direction

Heat gain through windows

- Calculating the **conductive** heat gain/loss through a window is easy:

$$Q = UA(T_{in} - T_{out}) = UA\Delta T$$

- Accounting for **solar** heat gain is more complicated
  - Need to include absorption of solar energy and re-radiation of thermal energy
  - Need to include spectral and angular characteristics of radiation and glazing
- We can do this with a simplified metric
  - The solar heat gain coefficient (SHGC):

$$Q_{solar,window} = \left(I_{solar} A\right) SHGC$$

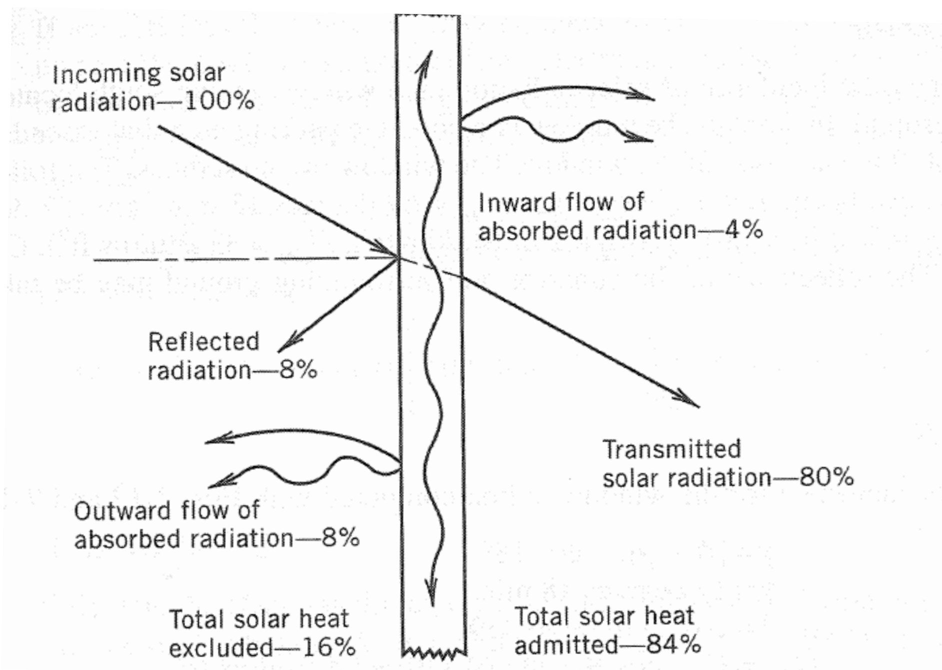
Solar heat gain coefficient, SHGC

- For a single pane of glass:

$$SHGC = \tau + \alpha \frac{U}{h_{ext}}$$

$$R = \frac{1}{U} = \frac{1}{h_{int}} + \frac{L_{glass}}{k_{glass}} + \frac{1}{h_{ext}}$$

k_{glass} = ~1 W/mK
L_{glass} = ~5 mm (0.2")
$^{*}R_{glass}$ is negligible (~0.005 m^{2}K/W)



$$Q_{solar,window} = \left(I_{solar} A\right) SHGC$$

$$q_{solar,window} = \left(I_{solar}\right) SHGC$$

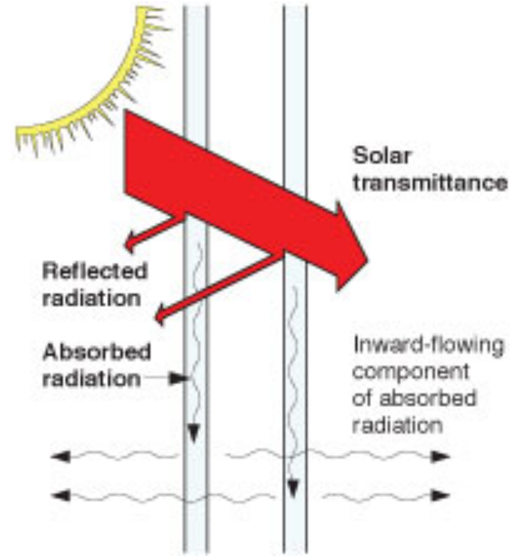
Solar heat gain coefficient, SHGC

- For double glazing with a small air space:

$$SHGC = \tau + \alpha_{outer\ pane} \frac{U}{h_{ext}} + \alpha_{inner\ pane} U \left(\frac{1}{h_{ext}} + \frac{1}{h_{airspace}} \right)$$

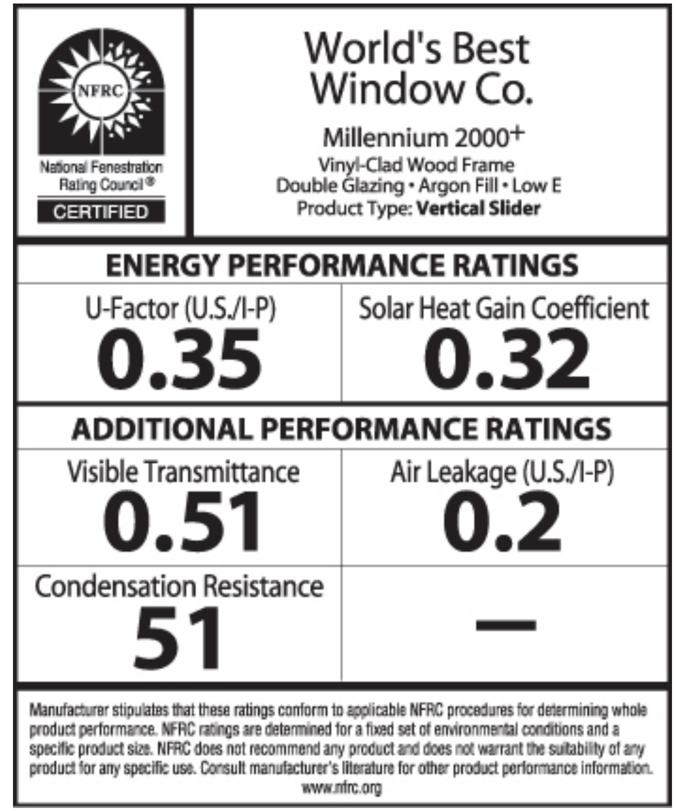
$$R = \frac{1}{U} = \frac{1}{h_{int}} + \frac{L_{outer\ pane}}{k_{outer\ pane}} + \frac{1}{h_{airspace}} + \frac{L_{inner\ pane}}{k_{inner\ pane}} + \frac{1}{h_{ext}}$$

$^{*}R_{outer\ pane}$ and $R_{inner\ pane}$ are negligible



Manufacturer supplied SHGC

- Glazing manufacturers will measure and present SHGC for normal incidence according to the methods of NFRC 200
  - National Fenestration Rating Council has developed methods for rating and labeling SHGC, U factors, air leakage, visible transmittance and condensation resistance of fenestration products
- In reality, SHGC is a function of incidence angle (θ)



More accurately: $$Q_{solar,window} = I_{direct} SHGC(\theta) A + (I_{diffuse+reflected}) SHGC_{diffuse+reflected} A$$

Complex SHGC

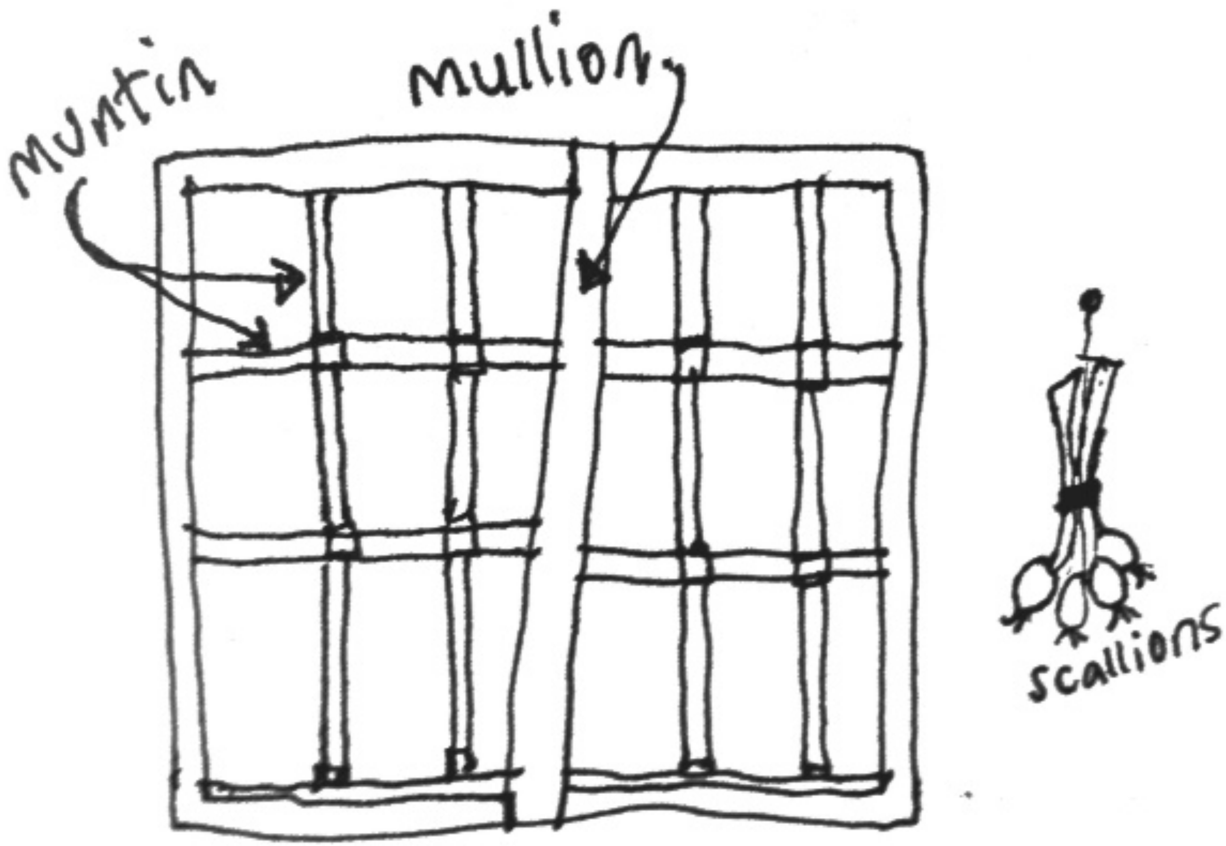
- SHGC, solar transmittance, reflectance, and absorptance properties for glazing all vary with incidence angles of solar radiation
- The ASHRAE Handbook of Fundamentals 2013 Chapter 15 provides data for a large variety of glazing types

Table 10 Visible Transmittance (T_v), Solar Heat Gain Coefficient (SHGC), Solar Transmittance (T), Front Reflectance (R^f), Back Reflectance (R^b), and Layer Absorptance ($\mathcal{A}_n^f$) for Glazing and Window Systems

	Glazing System				Center-of-Glazing Properties							Total Window SHGC at Normal Incidence				Total Window T_v at Normal Incidence			
					Incidence Angles							Aluminum		Other Frames		Aluminum		Other Frames	
ID	Glass Thick., mm		Center Glazing T_v		Normal 0.00	40.00	50.00	60.00	70.00	80.00	Hemis., Diffuse	Operable	Fixed	Operable	Fixed	Operable	Fixed	Operable	Fixed
Uncoated Single Glazing																			
1a	3	CLR	0.90	SHGC	0.86	0.84	0.82	0.78	0.67	0.42	0.78	0.78	0.79	0.70	0.76	0.80	0.81	0.72	0.79
				T	0.83	0.82	0.80	0.75	0.64	0.39	0.75								
				R^f	0.08	0.08	0.10	0.14	0.25	0.51	0.14								
				R^b	0.08	0.08	0.10	0.14	0.25	0.51	0.14								
				$\mathcal{A}_1^f$	0.09	0.10	0.10	0.11	0.11	0.11	0.10								
1b	6	CLR	0.88	SHGC	0.81	0.80	0.78	0.73	0.62	0.39	0.73	0.74	0.74	0.66	0.72	0.78	0.79	0.70	0.77
				T	0.77	0.75	0.73	0.68	0.58	0.35	0.69								
				R^f	0.07	0.08	0.09	0.13	0.24	0.48	0.13								
				R^b	0.07	0.08	0.09	0.13	0.24	0.48	0.13								
				$\mathcal{A}_1^f$	0.16	0.17	0.18	0.19	0.19	0.17	0.17								

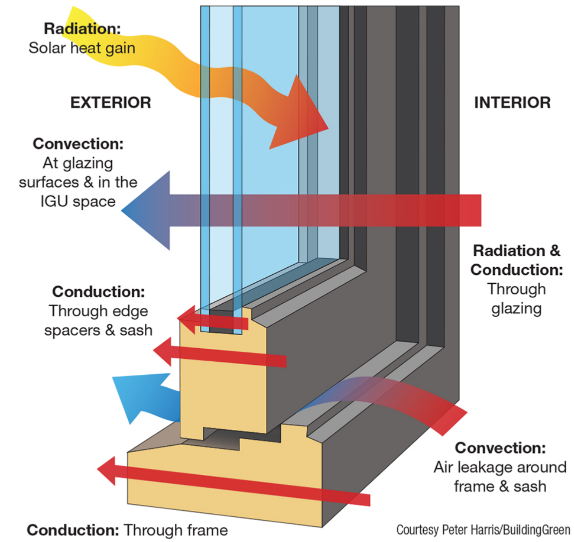
What about window assemblies?

- In addition to glazing material, windows also include framing, mullions, muntin bars, dividers, and shading devices
  - These all combine to make **fenestration systems**



What about window assemblies?

- In addition to glazing material, windows also include framing, mullions, muntin bars, dividers, and shading devices
  - These all combine to make **fenestration systems**
- Total heat transfer through an assembly:



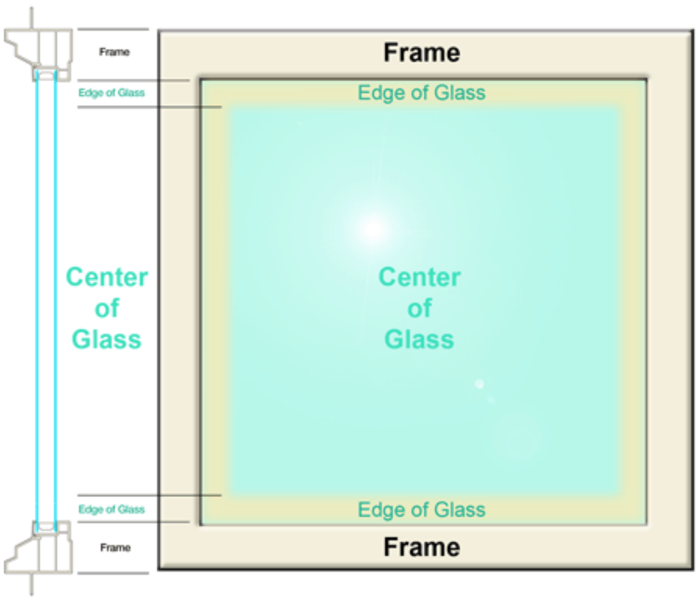
$$Q_{window} = UA_{pf}\left(T_{out} - T_{in}\right) + I_{solar}A_{pf}SHGC$$

Where:
U = overall coefficient of heat transfer (U-factor), W/m^2K
A_{pf} = total *projected* area of fenestration, m^2
T_{in} = indoor air temperature, K
T_{out} = outdoor air temperature, K
SHGC = solar heat gain coefficient, -
I_{solar} = incident total irradiance, W/m^2

Window U-factors

- U-values (or U-factors) for windows include all of the elements of the fenestration system
  - Center of glass properties (cg)
  - Edge of glass properties (eg)
  - Frame properties (f)
- The overall U-factor is estimated using area-weighted U-factors for each:

$$U = \frac{U_{cg}A_{cg} + U_{eg}A_{eg} + U_f A_f}{A_{pf}}$$



U-values and multiple layers of glazing

- We can separate glass panes with **air-tight layers** of air or other gases

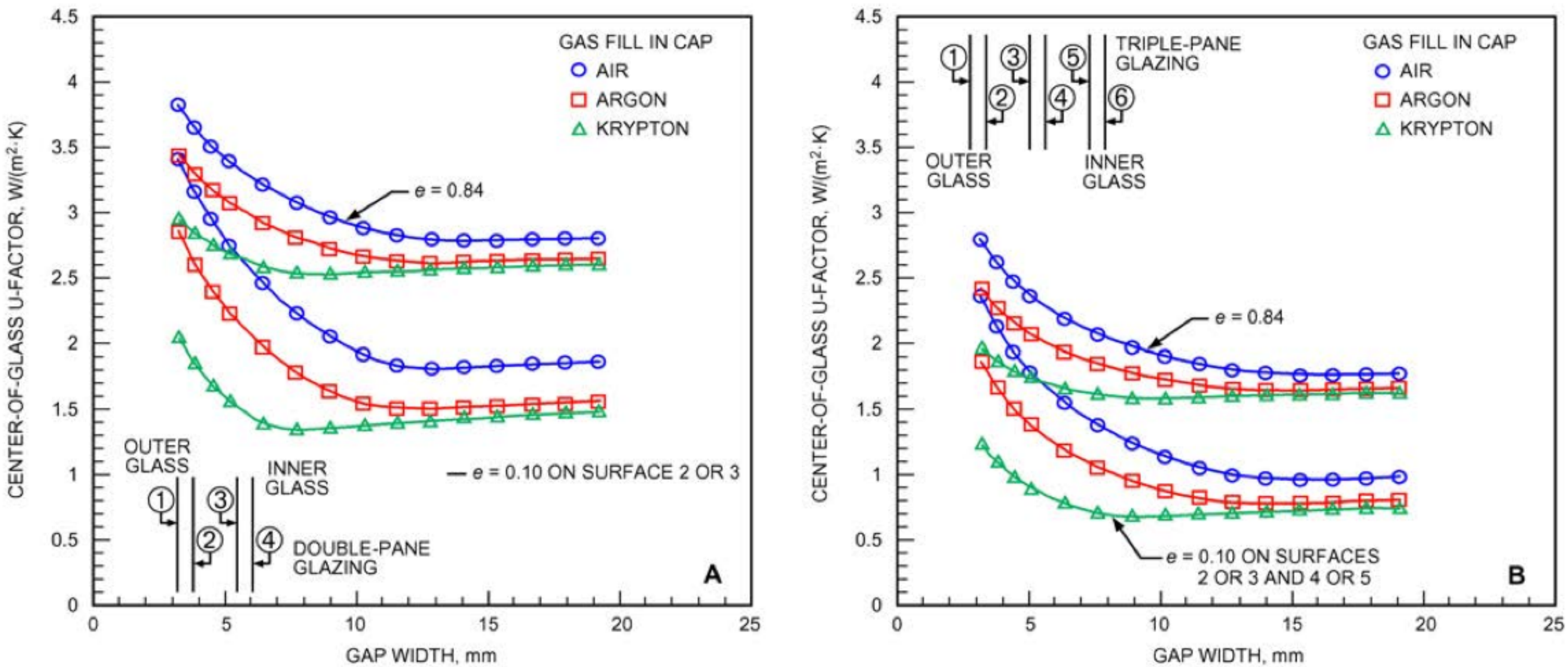


Fig. 3 Center-of-Glass U-Factor for Vertical Double- and Triple-Pane Glazing Units

Q: Why does argon have lower U value than air?

k_{air} = 0.025 W/mK

k_{argon} = 0.016 W/mK

$k_{krypton}$ = 0.0088 W/mK

2013 ASHRAE Handbook of Fundamentals: Chapter 15

Combined U-factor data: ASHRAE 2013 HOF

Table 4 U-Factors for Various Fenestration Products in W/(m²·K)

Product Type		Glass Only		Vertical Installation: Operable (including sliding and swinging glass doors)					Vertical Installation: Fixed				
Frame Type													
ID	**Glazing Type**	**Center of Glass**	**Edge of Glass**	**Aluminum Without Thermal Break**	**Aluminum With Thermal Break**	**Reinforced Vinyl/ Aluminum Clad Wood**	**Wood/ Vinyl**	**Insulated Fiberglass/ Vinyl**	**Aluminum Without Thermal Break**	**Aluminum With Thermal Break**	**Reinforced Vinyl/ Aluminum Clad Wood**	**Wood/ Vinyl**	**Insulated Fiberglass/ Vinyl**
	Single Glazing												
1	3 mm glass	*5.91*	*5.91*	7.01	6.08	5.27	5.20	4.83	6.38	6.06	5.58	5.58	5.40
2	6 mm acrylic/polycarb	*5.00*	*5.00*	6.23	5.35	4.59	4.52	4.18	5.55	5.23	4.77	4.77	4.61
3	3.2 mm acrylic/polycarb	*5.45*	*5.45*	6.62	5.72	4.93	4.86	4.51	5.96	5.64	5.18	5.18	5.01
	Double Glazing												
4	6 mm airspace	*3.12*	*3.63*	4.62	3.61	3.24	3.14	2.84	3.88	3.52	3.18	3.16	3.04
5	13 mm airspace	*2.73*	*3.36*	4.30	3.31	2.96	2.86	2.58	3.54	3.18	2.85	2.83	2.72
6	6 mm argon space	*2.90*	*3.48*	4.43	3.44	3.08	2.98	2.69	3.68	3.33	3.00	2.98	2.86
7	13 mm argon space	*2.56*	*3.24*	4.16	3.18	2.84	2.74	2.46	3.39	3.04	2.71	2.69	2.58
	Double Glazing, e = 0.60 on surface 2 or 3												
8	6 mm airspace	*2.95*	*3.52*	4.48	3.48	3.12	3.02	2.73	3.73	3.38	3.04	3.02	2.90
9	13 mm airspace	*2.50*	*3.20*	4.11	3.14	2.80	2.70	2.42	3.34	2.99	2.67	2.65	2.53
10	6 mm argon space	*2.67*	*3.32*	4.25	3.27	2.92	2.82	2.54	3.49	3.13	2.81	2.79	2.67
11	13 mm argon space	*2.33*	*3.08*	3.98	3.01	2.68	2.58	2.31	3.20	2.84	2.52	2.50	2.39
	Double Glazing, e = 0.40 on surface 2 or 3												
12	6 mm airspace	*2.78*	*3.40*	4.34	3.35	3.00	2.90	2.61	3.59	3.23	2.90	2.88	2.77
13	13 mm airspace	*2.27*	*3.04*	3.93	2.96	2.64	2.54	2.27	3.15	2.79	2.48	2.46	2.35
14	6 mm argon space	*2.44*	*3.16*	4.07	3.09	2.76	2.66	2.38	3.30	2.94	2.62	2.60	2.49
15	13 mm argon space	*2.04*	*2.88*	3.75	2.79	2.48	2.38	2.11	2.95	2.60	2.29	2.27	2.16
	Double Glazing, e = 0.20 on surface 2 or 3												
16	6 mm airspace	*2.56*	*3.24*	4.16	3.18	2.84	2.74	2.46	3.39	3.04	2.71	2.69	2.58
17	13 mm airspace	*1.99*	*2.83*	3.70	2.75	2.44	2.34	2.07	2.91	2.55	2.24	2.22	2.12
18	6 mm argon space	*2.16*	*2.96*	3.84	2.88	2.56	2.46	2.19	3.05	2.70	2.38	2.36	2.26
19	13 mm argon space	*1.70*	*2.62*	3.47	2.53	2.24	2.14	1.88	2.66	2.30	2.00	1.98	1.88
	Double Glazing, e = 0.10 on surface 2 or 3												
20	6 mm airspace	*2.39*	*3.12*	4.02	3.05	2.72	2.62	2.34	3.25	2.89	2.57	2.55	2.44
21	13 mm airspace	*1.82*	*2.71*	3.56	2.62	2.32	2.22	1.96	2.76	2.40	2.10	2.08	1.98
22	6 mm argon space	*1.99*	*2.83*	3.70	2.75	2.44	2.34	2.07	2.91	2.55	2.24	2.22	2.12
23	13 mm argon space	*1.53*	*2.49*	3.33	2.40	2.12	2.02	1.76	2.51	2.16	1.86	1.84	1.74

Thermal resistances of still air cavities

Combining convection + radiation:

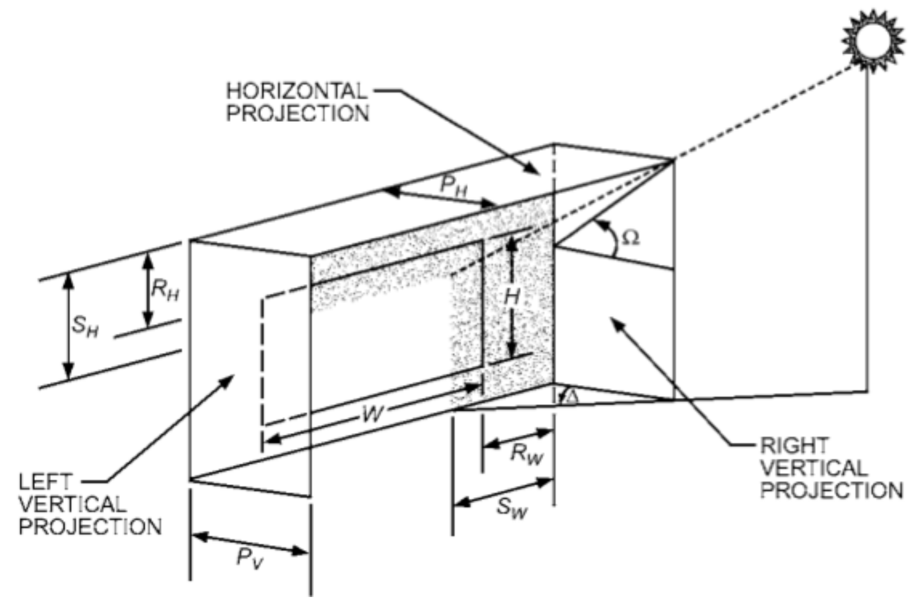
Table 3 Thermal Resistances of Plane Air Spaces,[a,b,c] $(m^2 \cdot K)/W$

Position of Air Space	Direction of Heat Flow	Air Space: Mean Temp.[d], °C	Air Space: Temp. Diff.,[d] K	Effective Emittance ε_{eff}[d,e]: 13 mm Air Space[c]					20 mm Air Space[c]				
				0.03	0.05	0.2	0.5	0.82	0.03	0.05	0.2	0.5	0.82
Horiz.	Up	32.2	5.6	0.37	0.36	0.27	0.17	0.13	0.41	0.39	0.28	0.18	0.13
		10.0	16.7	0.29	0.28	0.23	0.17	0.13	0.30	0.29	0.24	0.17	0.14
		10.0	5.6	0.37	0.36	0.28	0.20	0.15	0.40	0.39	0.30	0.20	0.15
		−17.8	11.1	0.30	0.30	0.26	0.20	0.16	0.32	0.32	0.27	0.20	0.16
		−17.8	5.6	0.37	0.36	0.30	0.22	0.18	0.39	0.38	0.31	0.23	0.18
		−45.6	11.1	0.30	0.29	0.26	0.22	0.18	0.31	0.31	0.27	0.22	0.19
		−45.6	5.6	0.36	0.35	0.31	0.25	0.20	0.38	0.37	0.32	0.26	0.21
45° Slope	Up	32.2	5.6	0.43	0.41	0.29	0.19	0.13	0.52	0.49	0.33	0.20	0.14
		10.0	16.7	0.36	0.35	0.27	0.19	0.15	0.35	0.34	0.27	0.19	0.14
		10.0	5.6	0.45	0.43	0.32	0.21	0.16	0.51	0.48	0.35	0.23	0.17
		−17.8	11.1	0.39	0.38	0.31	0.23	0.18	0.37	0.36	0.30	0.23	0.18
		−17.8	5.6	0.46	0.45	0.36	0.25	0.19	0.48	0.46	0.37	0.26	0.20
		−45.6	11.1	0.37	0.36	0.31	0.25	0.21	0.36	0.35	0.31	0.25	0.20
		−45.6	5.6	0.46	0.45	0.38	0.29	0.23	0.45	0.43	0.37	0.29	0.23
Vertical	Horiz.	32.2	5.6	0.43	0.41	0.29	0.19	0.14	0.62	0.57	0.37	0.21	0.15
		10.0	16.7	0.45	0.43	0.32	0.22	0.16	0.51	0.49	0.35	0.23	0.17
		10.0	5.6	0.47	0.45	0.33	0.22	0.16	0.65	0.61	0.41	0.25	0.18
		−17.8	11.1	0.50	0.48	0.38	0.26	0.20	0.55	0.53	0.41	0.28	0.21
		−17.8	5.6	0.52	0.50	0.39	0.27	0.20	0.66	0.63	0.46	0.30	0.22
		−45.6	11.1	0.51	0.50	0.41	0.31	0.24	0.51	0.50	0.42	0.31	0.24
		−45.6	5.6	0.56	0.55	0.45	0.33	0.26	0.65	0.63	0.51	0.36	0.27

2005 ASHRAE Handbook of Fundamentals: Chapter 25; 2013 ASHRAE Handbook of Fundamentals: Chapter 26

What about shading?

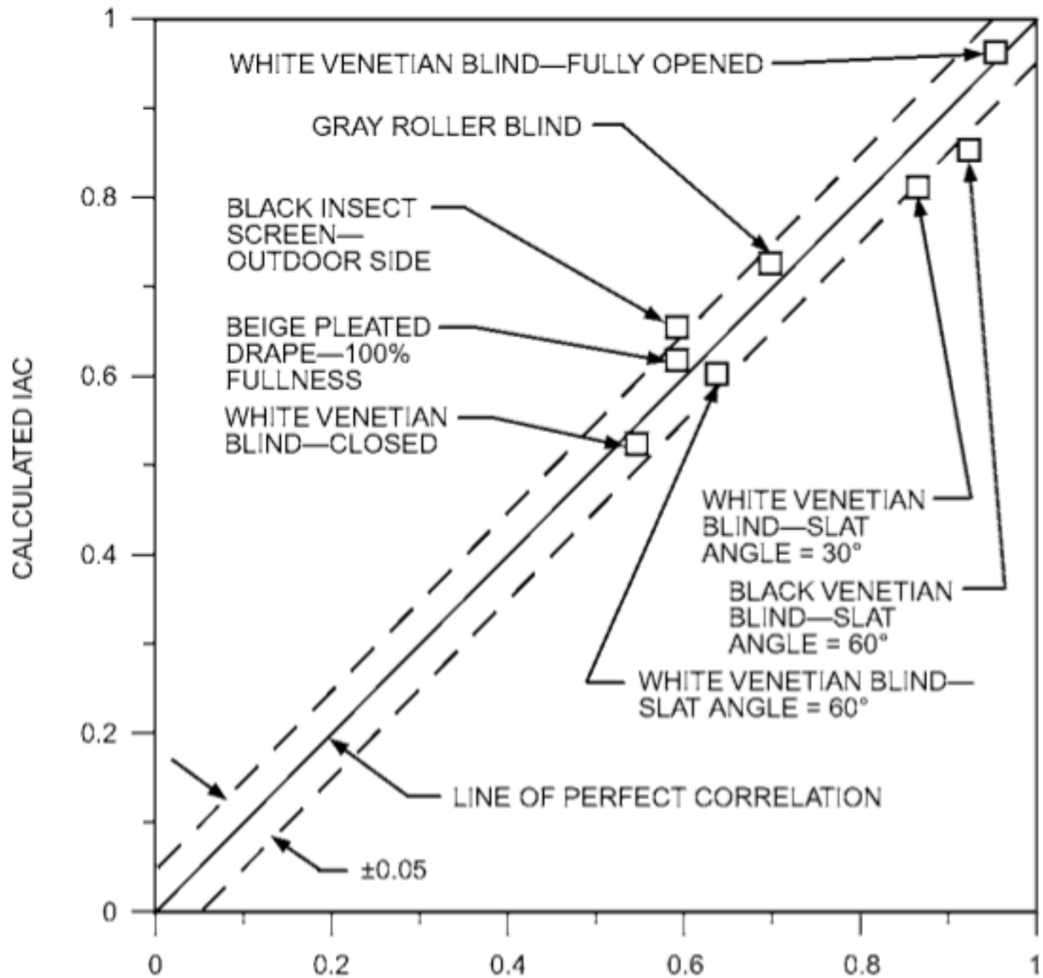
- Shading devices, including drapes and blinds, can mitigate some solar heat gain
- We can attempt to describe this with an **indoor solar attenuation coefficient (IAC)**
- Heat gain through a window can be modified as follows:



$$Q_{window} = UA_{pf}\left(T_{out} - T_{in}\right) + I_{direct} A_{pf} SHGC(\theta) IAC(\theta,\Omega) + (I_{diffuse+reflected}) A_{pf} SHGC_{diffuse+reflected} IAC_{diffuse+reflected}$$

IAC is a function of incidence angle, θ, and the angle created by a shading device

IAC for blinds and drapes: ASHRAE HOF 2013



Combined thermal transmittance for walls + fenestration

- Single assemblies of walls, windows, doors, etc. can be combined into an overall U-value for a building's enclosure
  - **Combined thermal transmittance**: U_o or U_{total}
    - Area-weighted average U-value
    - Just like center of glass, edge of glass, frame analysis for windows

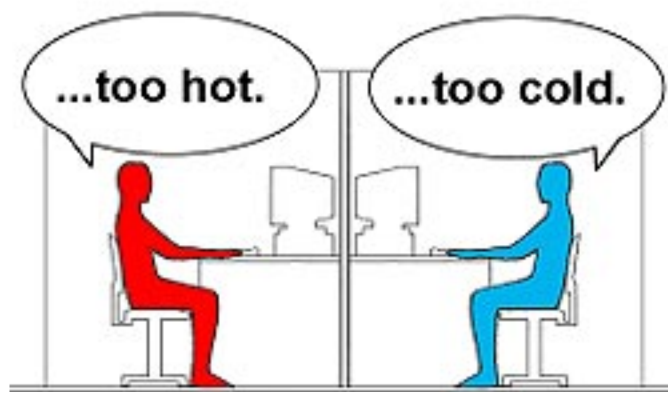
$$U_{total} = \frac{U_{wall}A_{wall} + U_{windows}A_{windows} + U_{doors}A_{doors}}{A_{total}}$$

We will use this later for calculating heating and cooling loads

THERMAL COMFORT

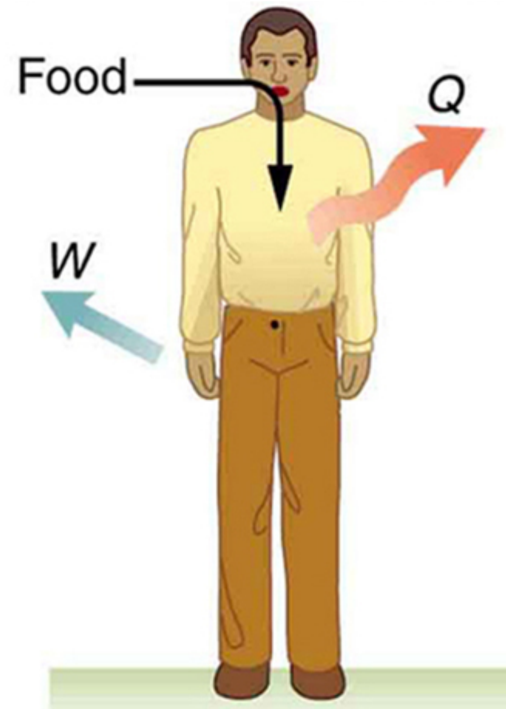
Human thermal comfort

- Our ultimate goal in designing a building and its HVAC system 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, and 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



Thermal balance of body and effective temperature

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



Assessing thermal comfort

- To develop guidelines for thermal comfort, we have to have some idea of what **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)
  - ***Survey the class…***

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

Predicted Mean Vote (PMV)

- If we predict the results of a questionnaire through equations we 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

The environment is considered acceptable when: -0.5 < PMV < 0.5

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 testing, researchers have found that PPD is a nonlinear function of PMV that can be predicted reasonably well

Percent People Dissatisfied (PPD)

Since we want:

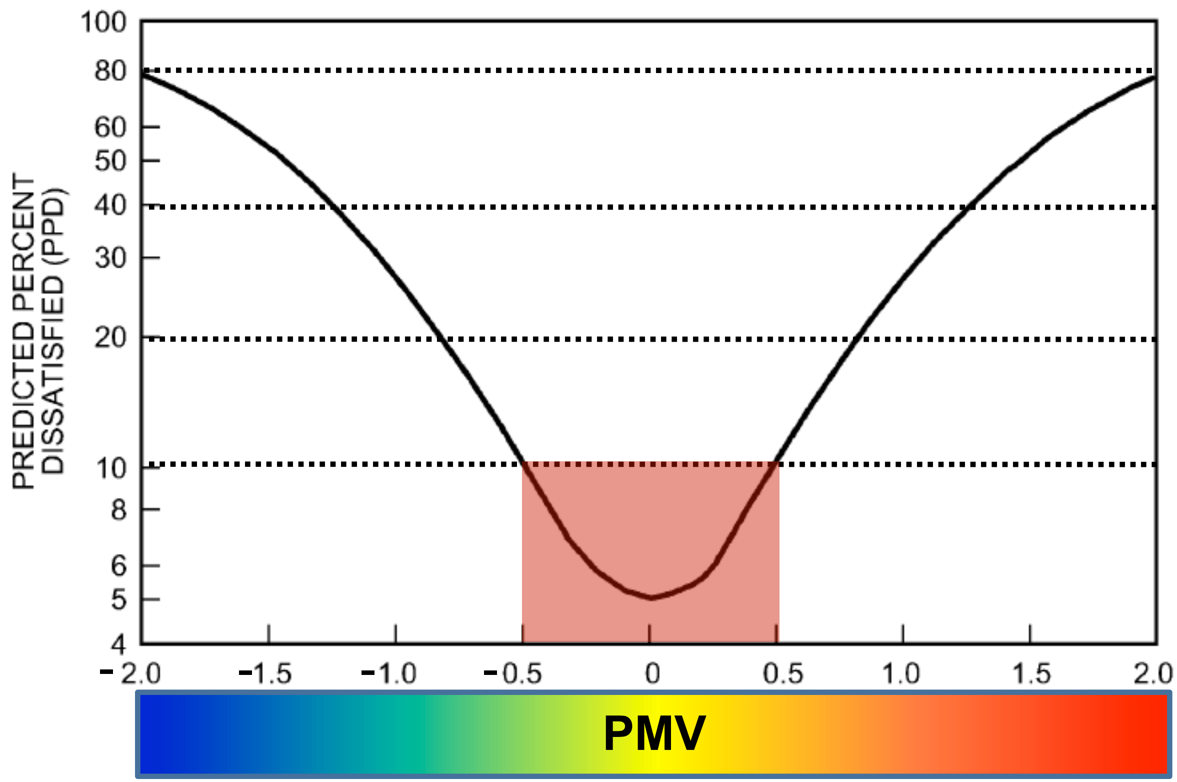
PPD<10%

we can see that:

-0.5<PMV<0.5

Notice that the 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 using building physics

- How can we predict PMV and PPD?

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

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

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

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

Variables affecting thermal comfort

- ASHRAE Standard 55 considers 6 parameters important for thermal comfort

Some are familiar:

Ambient Air Temp (T)

Humidity (W or RH)

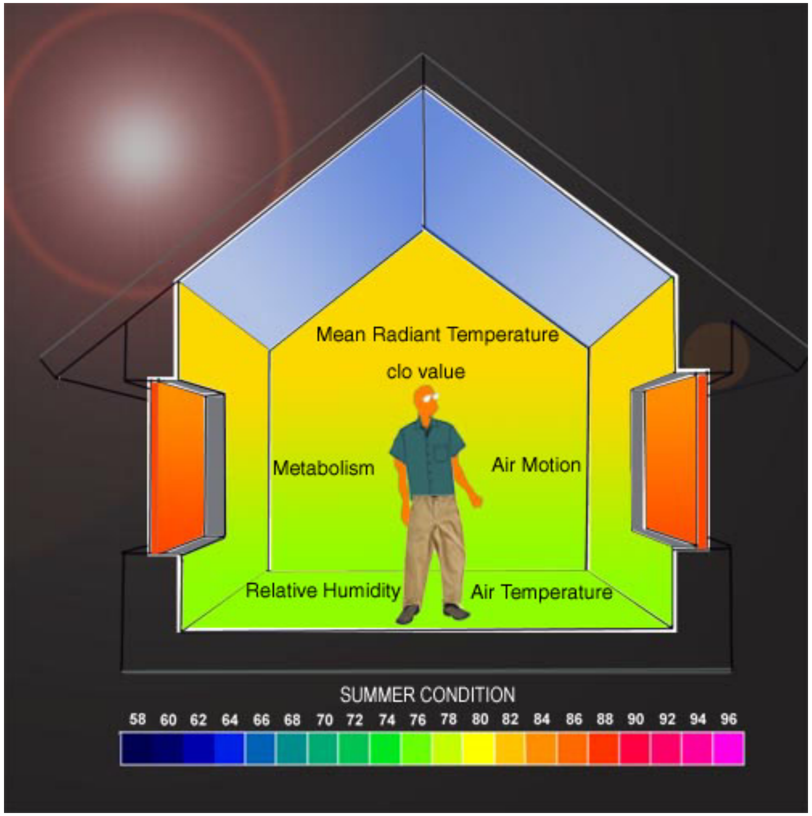
Local Air Speed (v)

Some are probably not:

Metabolic Rate (M)

Clothing Insulation (I_{cl})

Mean Radiant Temp. (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/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)

Body energy balance in a space

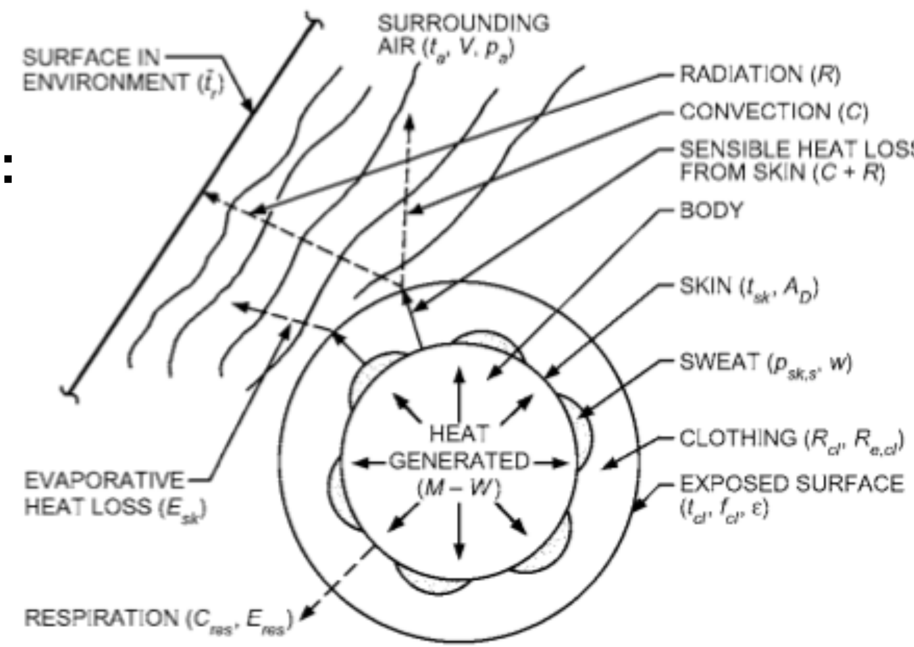
- Our internal body temperatures are consistent around 36-37°C
- We can set our heat production rate equal to the instantaneous heat flow to the environment (no storage):

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

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

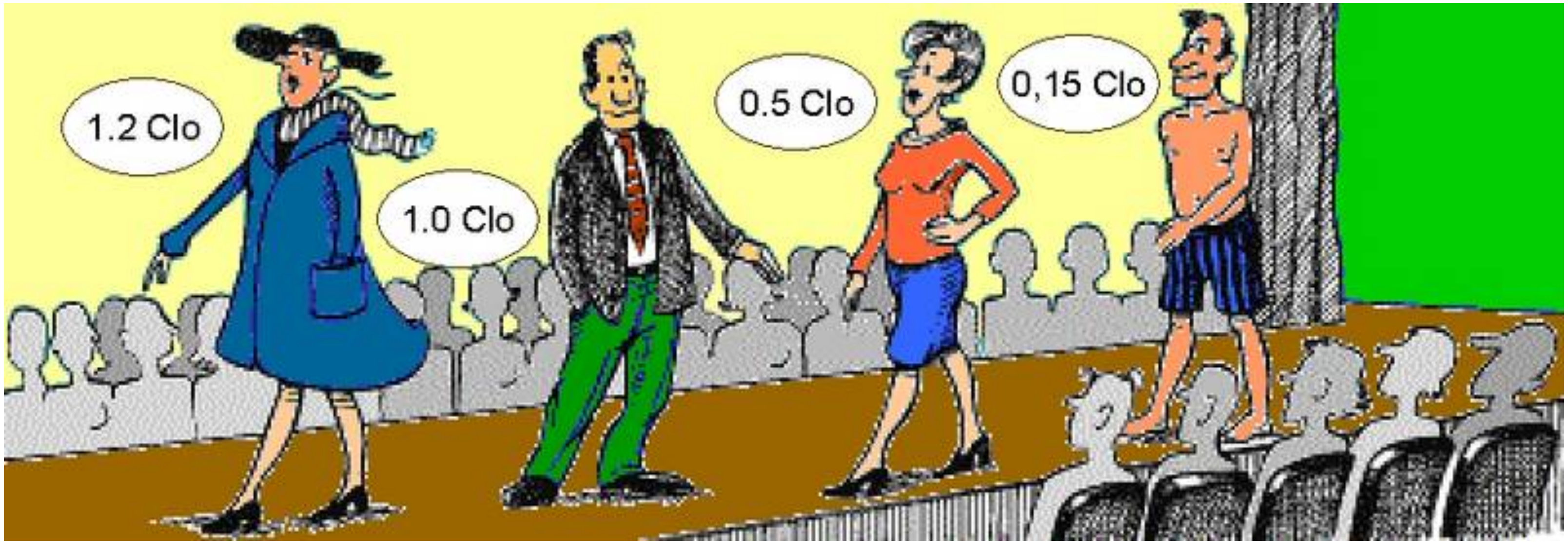
Obviously important variables:

- Air temperature (conv)
- Air velocity (conv)
- Clothing level (skin temp)
- Temperature of surrounding surfaces (conv)



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 Std 55



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**
- 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

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 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 basically 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

Operative temperatures, air velocity, clo, and met levels

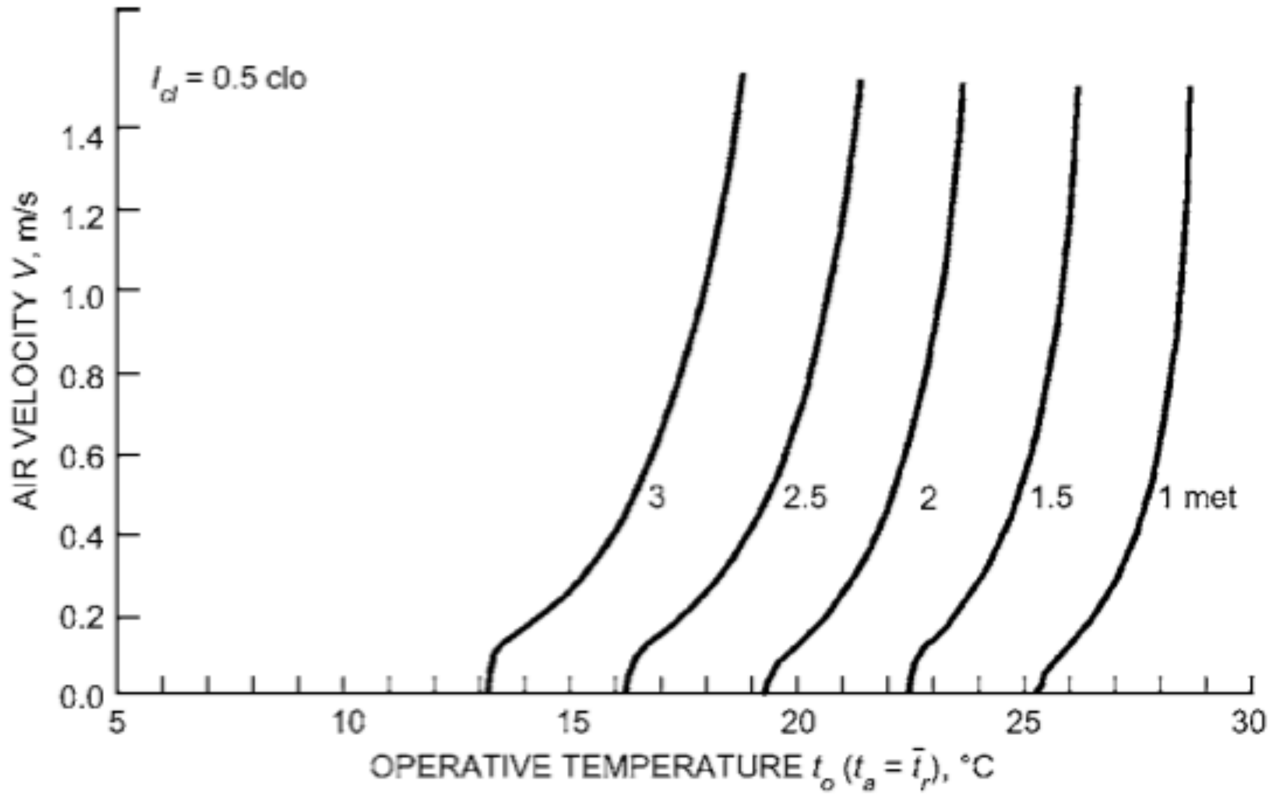


Fig. 14 Air Velocities and Operative Temperatures at 50% rh Necessary for Comfort (PMV = 0) of Persons in Summer Clothing at Various Levels of Activity

ASHRAE comfort zone

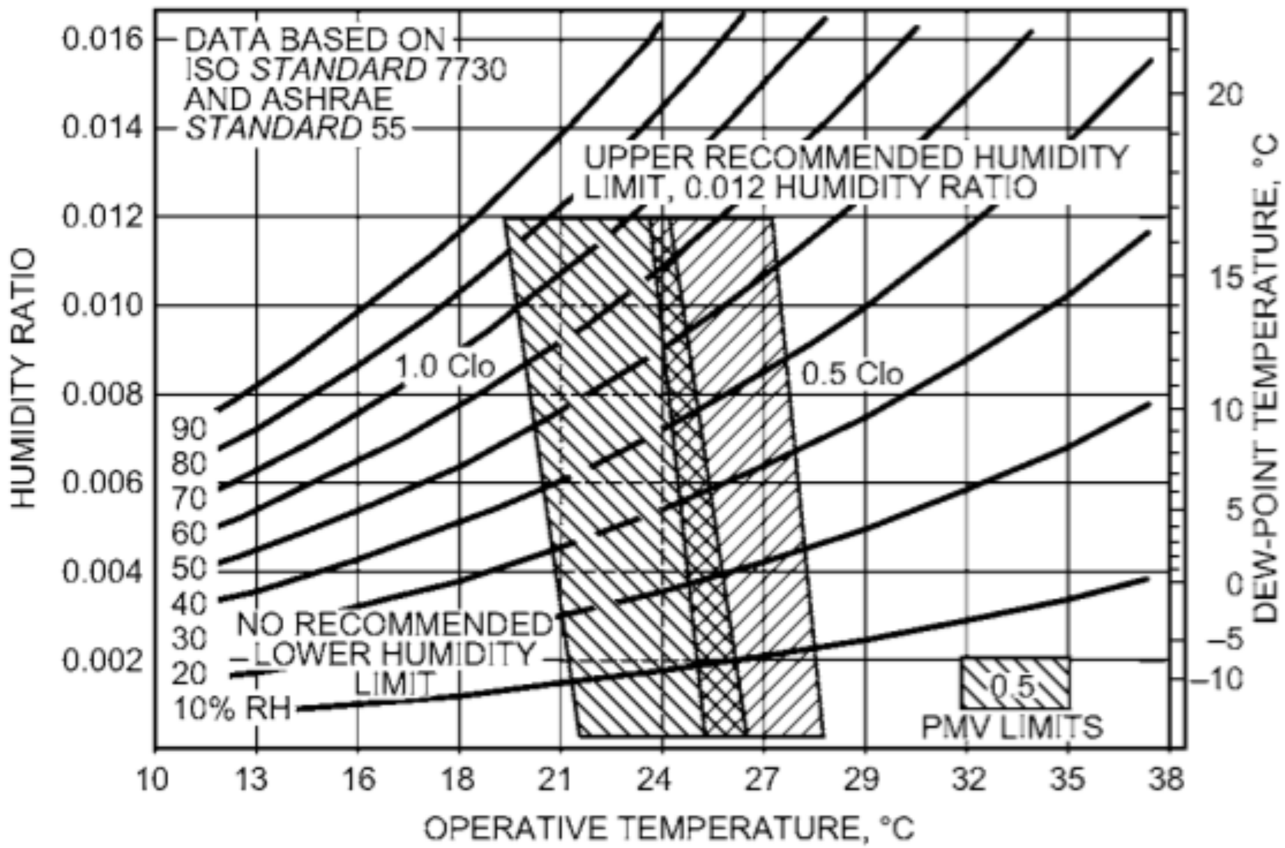
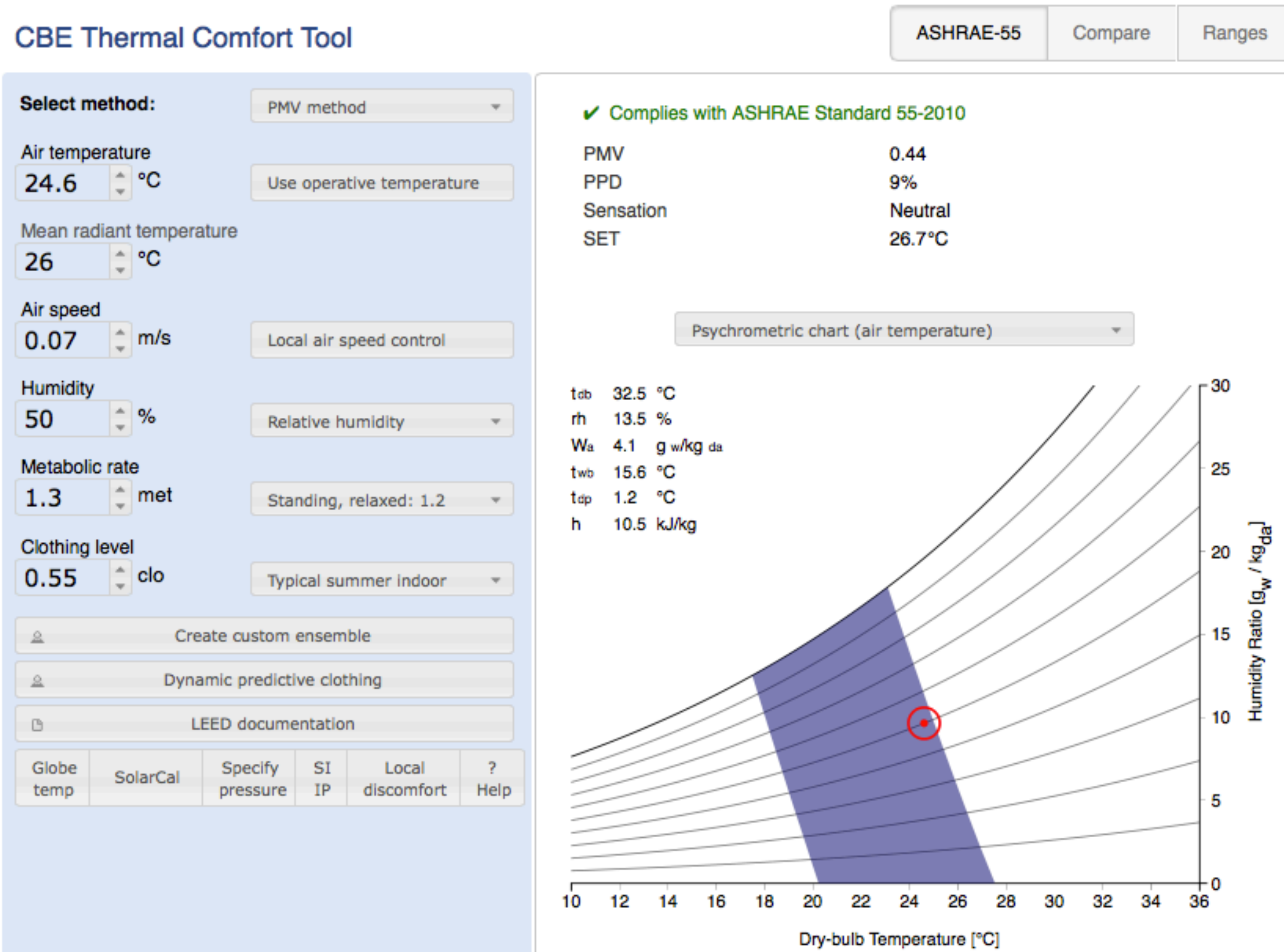


Fig. 5 ASHRAE Summer and Winter Comfort Zones
[Acceptable ranges of operative temperature and humidity with air speed ≤ 0.2 m/s for people wearing 1.0 and 0.5 clo clothing during primarily sedentary activity (≤1.1 met)].

ASHRAE comfort zone: CBE Thermal Comfort Tool



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