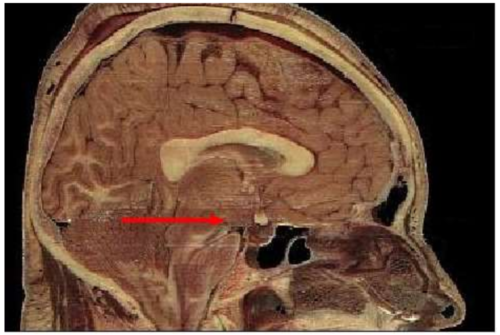
Ch. 4 Thermal Comfort

Thermostat in our brains



- Hypothalamus (시상하부: 視床下部)
  - In response to signals from our skin surface and to changes in our core temperature, the hypothalamus calls for changes in our blood distribution system.
  - When cold → vasoconstriction (혈관수축): decreased blood flow, less water to the skin surface by our sweat glands, reducing evaporation
    - "Goose flesh", "goose bumps": creating insulation by fluffing up our body hair
  - When hot → vasodilation (혈관확장)

Heat loss in four ways

- Four ways to pass body heat to the indoor environment: convection, conduction, radiation, evaporation
- At 18’C: Table 4.2

TABLE 4.2 Approximate Heat Loss Distribution under Comfort Conditions

Radiation, convection, and conduction	72%
Evaporation	
From skin surface	15%
From lungs (exhaled air)	7%
Warming of air inhaled to lungs	3%
Heat expelled in feces and urine	3%

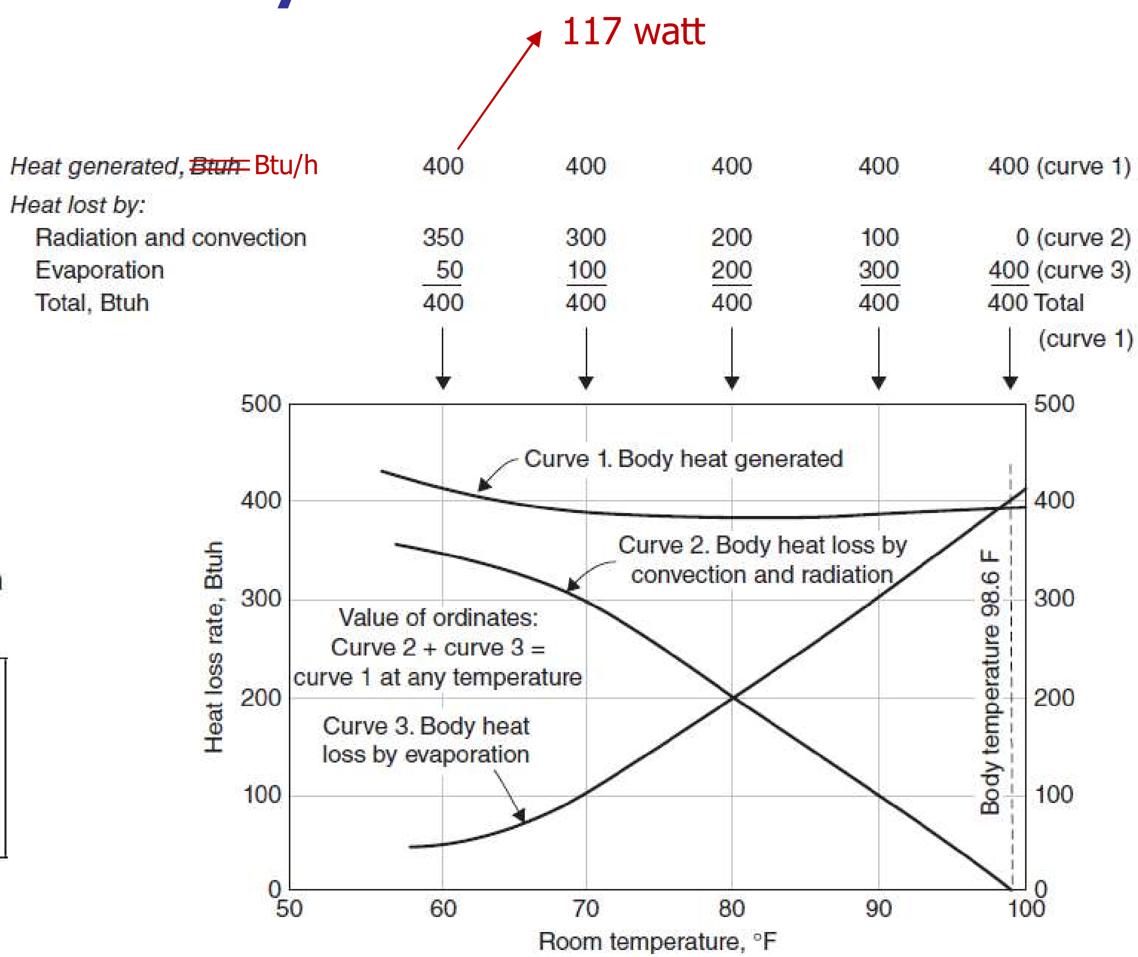


Fig. 4.2 Heat generated and lost (approximate) by a person at rest (with 45% relative humidity).

Psychrometry

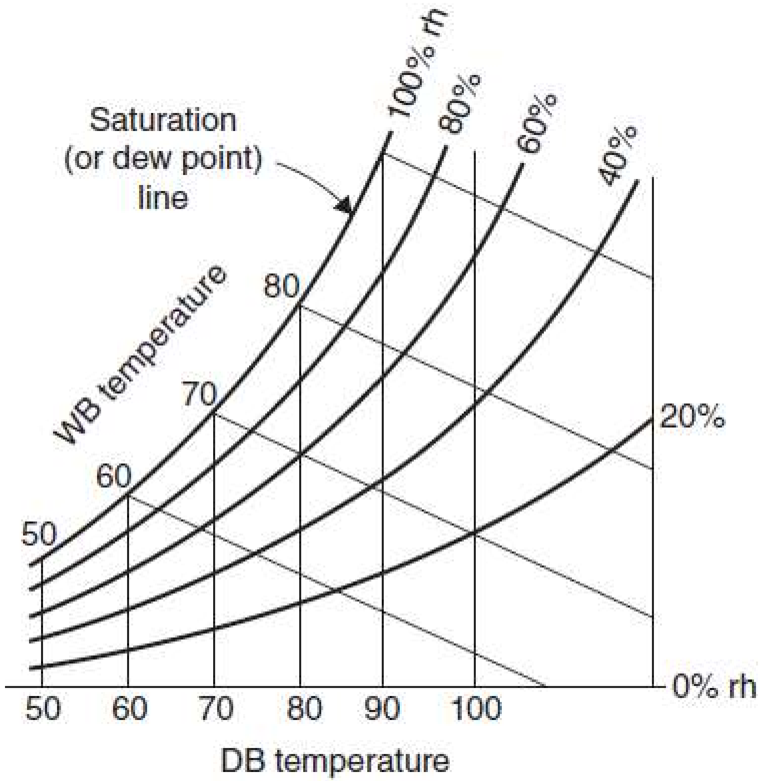


Fig. 4.4 Some basic components of the psychrometric chart: DB and WB temperatures and RH.

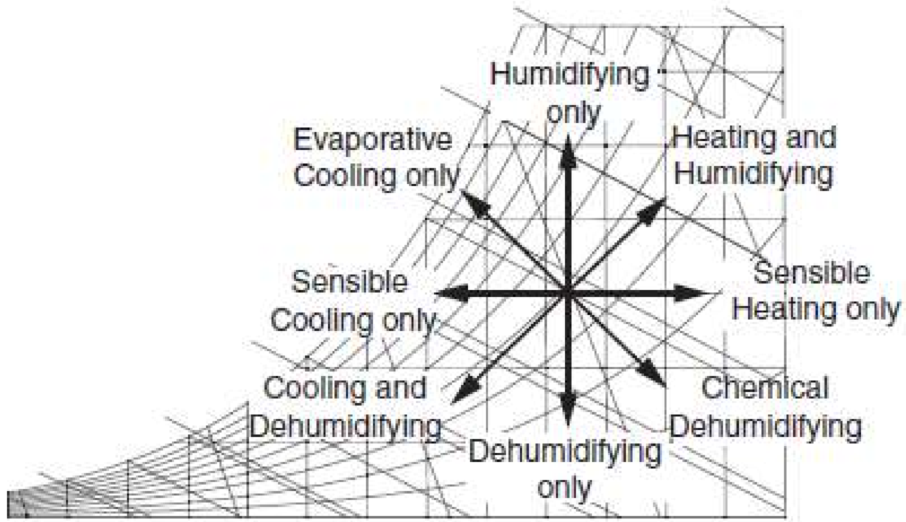


Fig. 4.5 Climatic-conditioning processes expressed on the psychrometric chart. (Adapted from "Architectural Design Based on Climate," by M. Milne and B. Givoni, in Watson (ed.), in Energy Conservation in Building Design. *Redrawn by Sharon Alitema.)*

Psychrometry

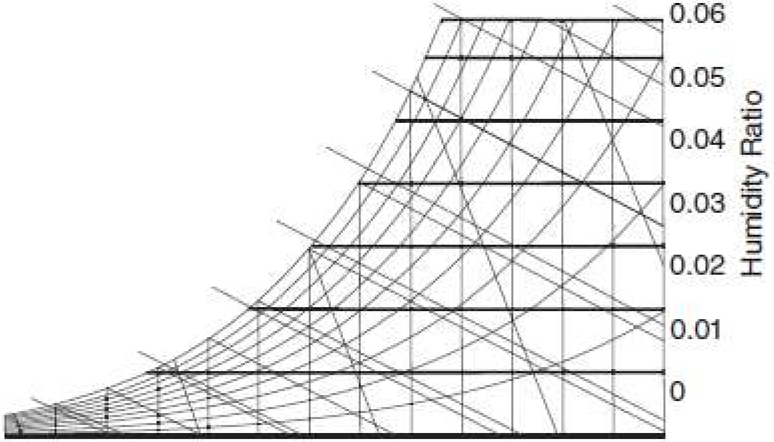


Fig. 4.6 Humidity ratio on the psychrometric chart: I-P units are lb moisture/lb of dry air; SI units are kg moisture/kg dry air. (Drawn by Sharon Alitema.)

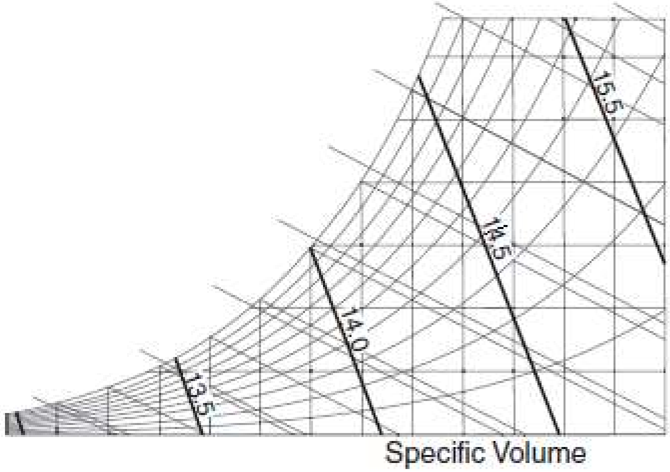


Fig. 4.7 Specific volume on the psychrometric chart: I-P units are ft^3/lb dry air; SI units are m^3/kg dry air. (Drawn by Sharon Alitema.)

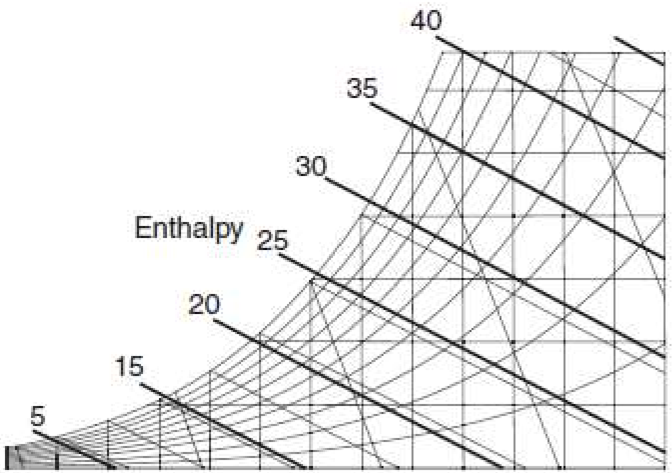


Fig. 4.8 Enthalpy on the psychrometric chart: I-P units are Btu/lb; SI units are kJ/kg. (Drawn by Sharon Alitema.)

Thermal comfort

- ASHRAE standard 55 (2013) defines as "the condition of mind which expresses satisfaction with the thermal environment"
- Factors:
  - Personal: clothing, metabolism, behavioral adaptations (drinking or eating warm or cold foods)
  - Measurable environmental: temperature, surface temperature, air motion, humidity
  - Psychological: color, texture, sound, light, movement, aroma
- Please note that the measurable environmental factors have been tested extensively in laboratories. But, other factors have been excluded (or underdeveloped, or not studied or not investigated) !!

Fig. 4.9 Indicators of coolness in a courtyard in Savannah, Georgia, include running water and shade from trees that move with the breeze. The senses of sight, hearing, touch, smell, and taste all may be involved in a perception of coolness. (© Alison Kwok; all rights reserved.)

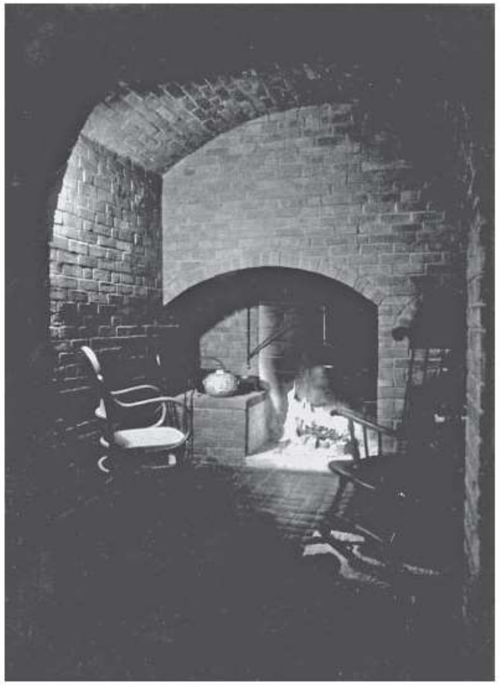


Fig. 4.10 The open fire seems the very spirit of warmth, despite the heat lost by large quantities of exhaust air up the chimney. The senses of sight, hearing, touch, and smell all may be involved in a perception of warmth, wrapped in this red-brick environment. (Courtesy of the architect and photographer, Edward Allen.)

Comfort standards

- The concept of comfort zone (Fig. 4.11)

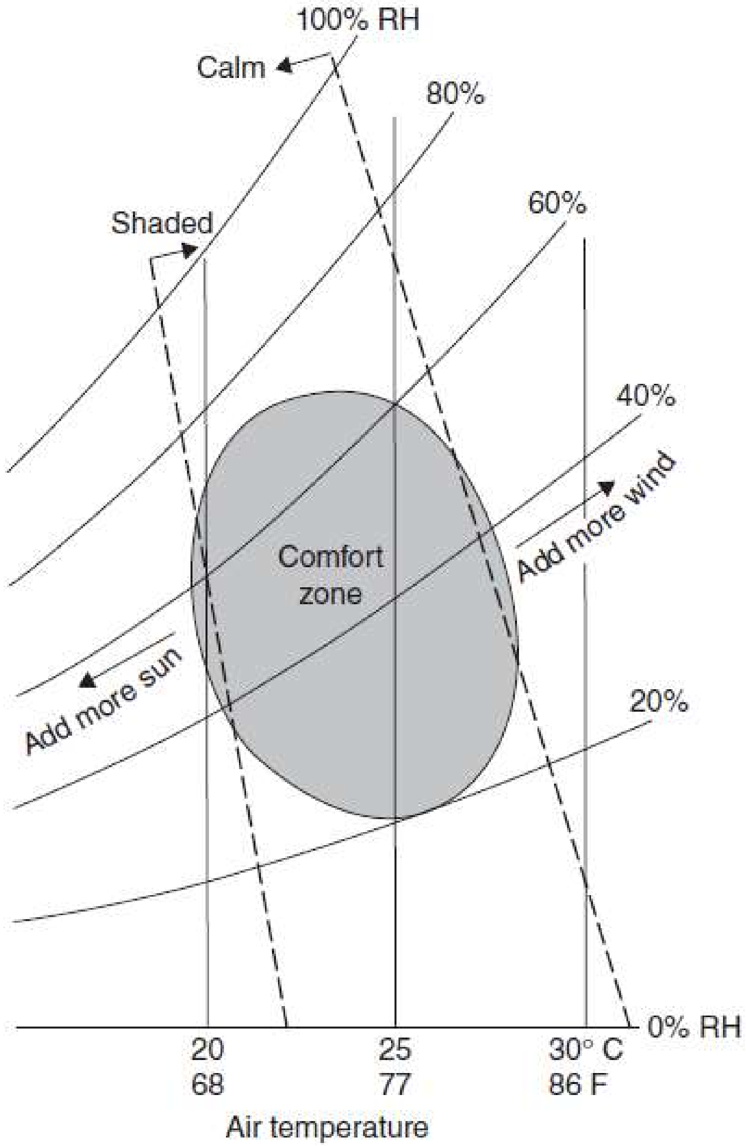


Fig. 4.11 *Comfort zone defined by relative humidity and air temperature.*

Metabolism

- Body heat production: measured in metabolic unit, MET
- 1 MET = the energy production per unit of body surface area by a seated person at rest (1MET = 50kcal/h m^2, 18.4BTU/h ft^2, 58.2W/m^2)
- Body surface area:

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

$$A_D = \text{DuBois surface area, m}^2$$

$$m = \text{mass,kg}$$

$$l = \text{height, m}$$

  - Ex.) 1.73m tall, 70 kg man → A_D=1.8m^2
- The total heat production per a normal adult: 1MET*1.8m^2=106W (360BTU/h) ← a seated person at rest
- Refer To Table G.5

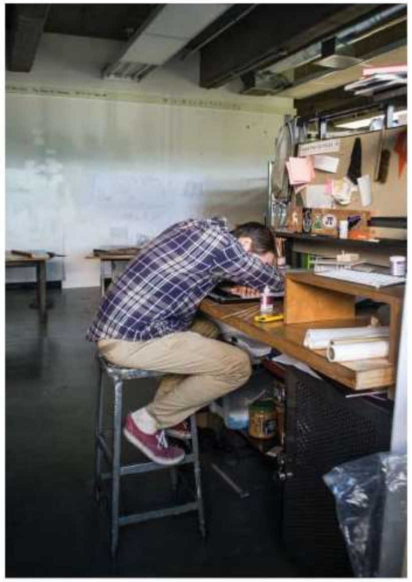
TABLE 4.1 Metabolic Rates for Typical Tasks

Activity	Metabolic Rate[a] met units[b]	Btu/h ft²	W/m²
Resting			
Sleeping	0.7	13	40
Reclining	0.8	15	45
Seated, quiet	1.0	18	60
Standing, relaxed	1.2	22	70
Walking (on the level)			
2 mph (0.9 m/s)	2.0	37	115
3 mph (1.2 m/s)	2.6	48	150
4 mph (1.8 m/s)	3.8	70	220
Office activities			
Reading, seated	1.0	18	60
Writing	1.0	18	60
Typing	1.1	20	65
Filing, seated	1.2	22	70
Filing, standing	1.4	26	80
Walking about	1.7	31	100
Lifting, packing	2.1	39	120
Driving/flying			
Car	1.0–2.0	18–37	60–115
Aircraft, routine	1.2	22	70
Aircraft, instrument landing	1.8	33	105
Aircraft, combat	2.4	44	140
Heavy vehicle	3.2	59	185
Miscellaneous occupational activities			
Cooking	1.6–2.0	29–37	95–115
Housecleaning	2.0–3.4	37–63	115–200
Seated, heavy limb movement	2.2	41	130
Handling 110-lb (50-kg) bags	4.0	74	235
Pick and shovel work	4.0–4.8	74–88	235–280
Machine work			
Sawing (table saw)	1.8	33	105
Light (electrical industry)	2.0–2.4	37–44	115–140
Heavy	4.0	74	235
Miscellaneous leisure activities			
Dancing, social	2.4–4.4	44–81	140–255
Calisthenics/exercise	3.0–4.0	55–74	175–235
Tennis, singles	3.6–4.0	66–74	210–270
Basketball	5.0–7.6	90–140	290–440
Wrestling, competitive	7.0–8.7	130–160	410–505

Source: Reprinted with permission; ©ASHRAE, www.ashrae.org. 2017 *ASHRAE Handbook—Fundamentals.*

[a]For average adult with a body surface area of 19.6 ft² (1.8 m²). For whole-body average heat production, see also Table G.5.

[b]One met = 18.4 Btu/h ft² = 58.2 W/m².



(*a*) 0.7 Met—Sleeping

(*b*) 1.4 Met—Standing, Modeling

(*c*) 2.1 Met—Leaning, Modeling

(*d*) 3.4 Met—Heavy Lifting

Fig. 4.1 *An architecture student demonstrates various levels of activity: (a) sleeping at the studio desk (0.7 met); (b) standing, working on a model (1.4 met); (c) standing/leaning, intently working on a physical model (2.1 met); and (d) heavy lifting of textbooks (3.4 met).*

G.5 HEAT GAINS FROM BUILDING OCCUPANTS

Table G.5 Rates of Heat Gain from Occupants of Conditioned Spaces

		Heat Gain							
		W				*Btu/h*			
Activity	**Location**	**Adult Male**	**Adjusted[b]**	**Sensible[a] Heat**	**Latent[a] Heat**	**Adult Male**	**Adjusted[b]**	**Sensible[a] Heat**	**Latent[a] Heat**
Seated at theater	Theater, matinee	115	95	65	30	390	330	225	105
Seated at theater, night	Theater, night	115	105	70	35	390	350	245	105
Seated, very light work	Offices, hotels, apartments	130	115	70	45	450	400	245	155
Moderately active office work	Offices, hotels, apartments	140	130	75	55	475	450	250	200
Standing, light work; walking	Department or retail store	160	130	75	55	550	450	250	200
Walking, standing	Drug store, bank	160	145	75	70	550	500	250	250
Sedentary work	Restaurant[c]	170	160	80	80	590	550	275	275
Light bench work	Factory	235	220	80	140	800	750	275	475
Moderate dancing	Dance hall	265	250	90	160	900	850	305	545
Walking 4.8 km/h (3 mph), light machine work	Factory	295	295	110	185	1000	1000	375	625
Bowling[d]	Bowling alley	440	425	170	255	1500	1450	580	870
Heavy work	Factory	440	425	170	255	1500	1450	580	870
Heavy machine work, lifting	Factory	470	470	185	285	1600	1600	635	965
Athletics	Gymnasium	585	525	210	315	2000	1800	710	1090

Source: Reprinted with permission; ©ASHRAE, www.ashrae.org. 2017 *ASHRAE® Handbook—Fundamentals*.

[a] All values are rounded to the nearest 5 W (and 5 Btu/h). Based on 75°F (24°C) room dry-bulb temperature. For 80°F (27°C) room dry-bulb temperature, the total heat remains the same but the sensible heat values should be decreased by approximately 20% and the latent heat values increased accordingly.

[b] Adjusted heat gain based on the normal percentage of men, women, and children for the application listed, assuming that the gain from an adult female is 85% (and from children 75%) of that from an adult male.

[c] Adjusted heat gain includes 60 Btu/h (18 W) for food per individual: 50% sensible, 50% latent.

[d] Assume only one person per alley actually bowling and all others as sitting, standing, or walking slowly.

Clothing

- The insulating value of clothing
  - measured in CLO
  - 1 CLO = equivalent to the typical American man's business suit in 1941 (0.155 m^2K/W)

TABLE 4.3 Typical Insulation Values for Clothing Ensembles

Ensemble Description[a]	clo[b]
Walking shorts, short-sleeve shirt	0.36
Trousers, short-sleeve shirt	0.57
Trousers, long-sleeve shirt	0.61
Same as above, plus suit jacket	0.96
Same as above, plus vest and T-shirt	1.14
Trousers, long-sleeve shirt, long-sleeve sweater, T-shirt	1.01
Same as above, plus suit jacket and long underwear bottoms	1.30
Sweatpants, sweatshirt	0.74
Long-sleeve pajama top, long pajama trousers, short 3/4-sleeve robe, slippers (no socks)	0.96
Knee-length skirt, short-sleeve shirt, pantyhose, sandals	0.54
Knee-length skirt, long-sleeve shirt, full slip, pantyhose	0.67
Knee-length skirt, long-sleeve shirt, half-slip, pantyhose, long-sleeve sweater	1.10
Same as above; replace sweater with suit jacket	1.04
Ankle-length skirt, long-sleeve shirt, suit jacket, pantyhose	1.10
Long-sleeve coveralls, T-shirt	0.72
Overalls, long-sleeve shirt, T-shirt	0.89
Insulated coveralls, long-sleeve thermal underwear, long underwear bottoms	1.37

Source: Reprinted with permission; ©ASHRAE, www.ashrae.org. 2017 *ASHRAE Handbook—Fundamentals*.

[a]All ensembles include shoes and briefs or panties. All ensembles except those with pantyhose include socks, unless otherwise noted.

[b]One clo = 0.88 ft^2 h °F/Btu = 0.155 m^2 K/W.

(*a*) 0.5 Clo
(*b*) 1.0 Clo
(*c*) 1.25 Clo
(*d*) 2.8 Clo

Fig. 4.3 *Approximate insulating value of clothing: (a) shorts and T-shirt (0.5 clo); (b) trousers, long-sleeve shirt, T-shirt (1.0 clo); (c) skirt, half-slip, leggings, long-sleeve shirt, long-sleeve sweater (1.25) clo; (d) insulated trousers, long-sleeve thermal underwear, down jacket, long underwear bottoms, wool scarf (2.8 clo).*

Variables

- Dry—Bulb (DB) temperature
  - cannot be a comfort indicator by itself
- Wet-Bulb (WB) temperature
- Relative Humidity (RH)
- MRT (Mean Radiant Temperature)
- Operative Temperature (OT)

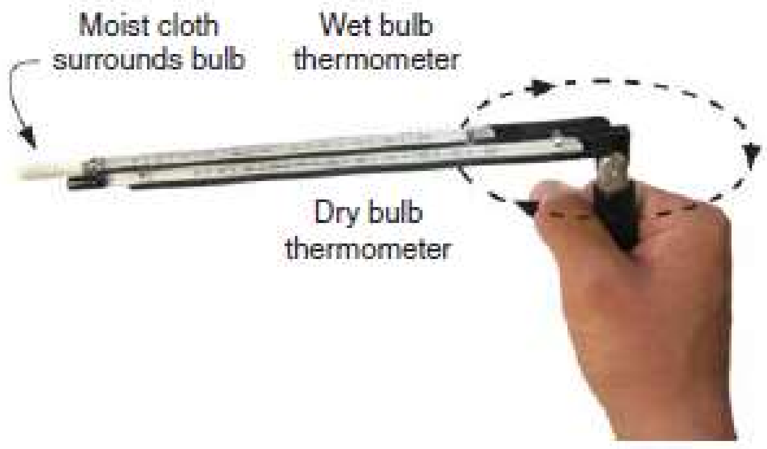
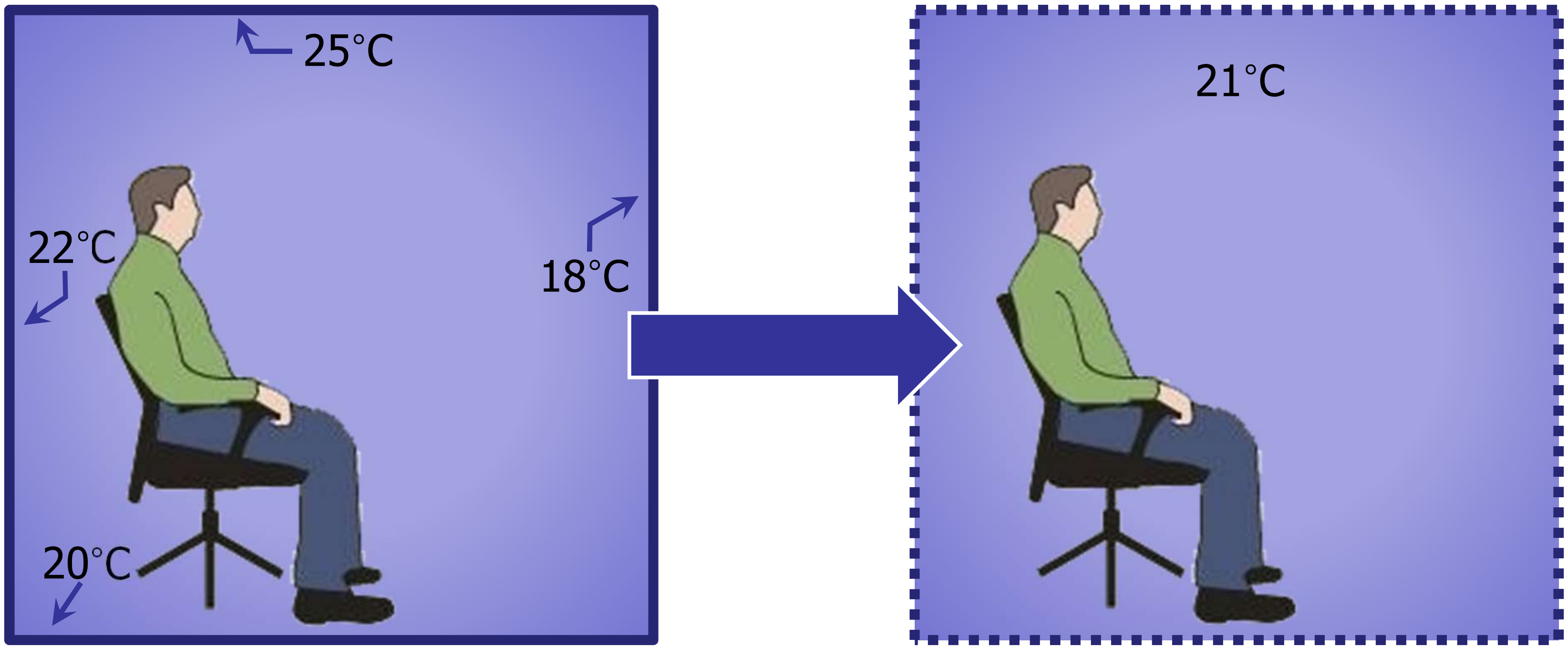


Fig. 4.13 *Sling psychrometer and its usage. Air motion encourages evaporation from the moist cloth, lowering the wet-bulb temperature below the surrounding air temperature, whereas the dry-bulb temperature stays constant at the surrounding air temperature. (At 100% RH, WB and DB temperatures will be equal.)*

MRT: Mean Radiant Temperature



$$\text{I-P or SI units } \bar{t}_r = \frac{\sum t\alpha}{360} = \frac{t_1\alpha_1 + t_2\alpha_2 + t_3\alpha_3 + \cdots t_n\alpha_n}{360} \quad (4.2)$$

where

$\bar{t}_r$ = mean radiant temperature, °F (°C)
α = surface exposure angle (relative to the occupant) in degrees
t = surface temperature, °F (°C)

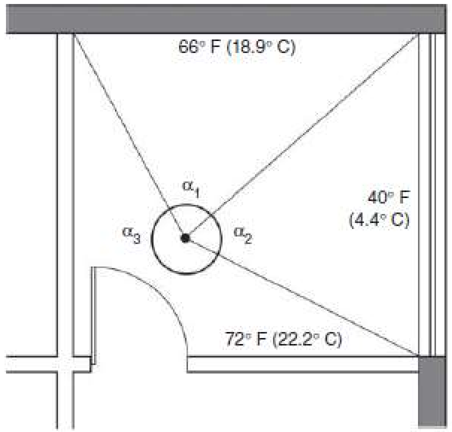
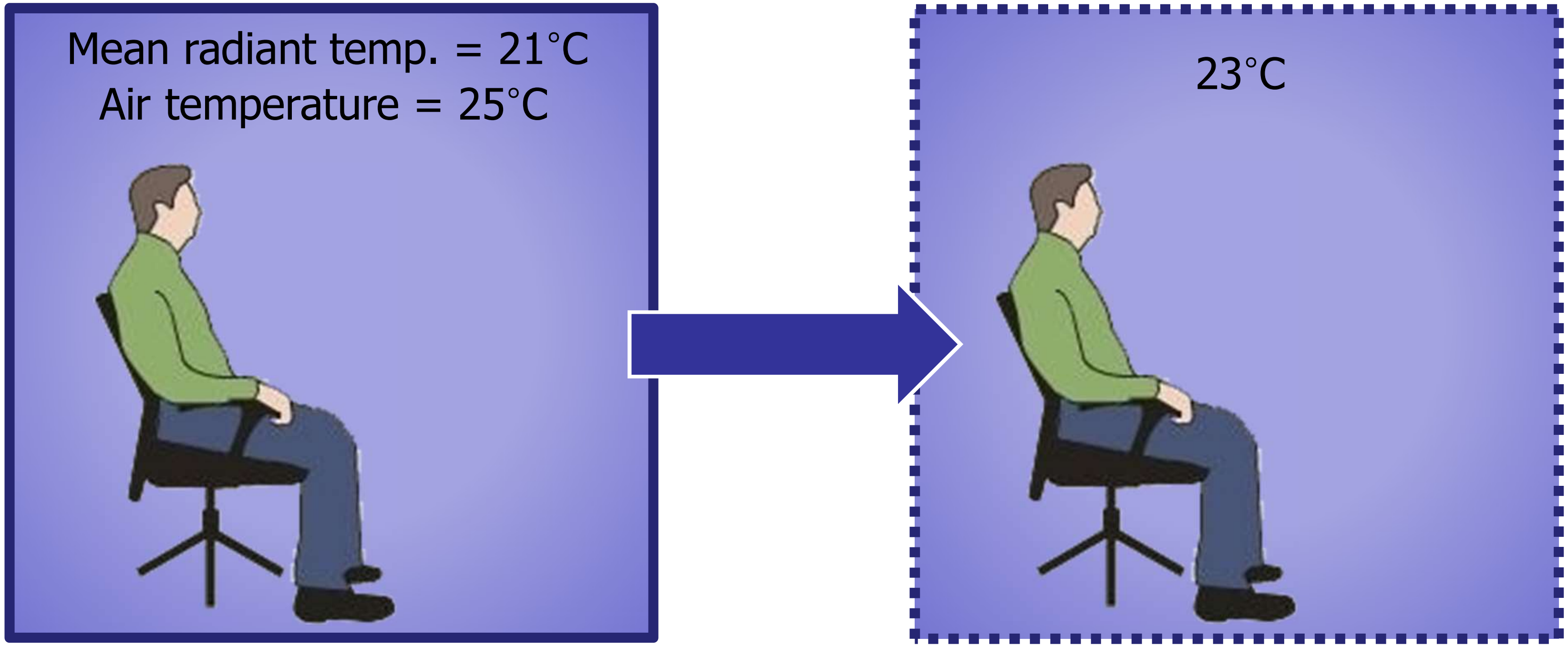


***Fig. 4.14** Graphic method of calculation for mean radiant temperature using the geometry of the room relative to a particular location. Using Equation 4.2, the surface temperature of the wall or window is multiplied by the exposure angle relative to the occupant's location. (Drawn by Tyler Mavichien; © Alison Kwok, all rights reserved.)*

Definition of MRT

- Mean Radiant Temperature is defined as the uniform temperature of an imaginary surrounding enclosure in which radiant transfer from the human body would equal the radiant heat transfer in the actual nonuniform enclosure (ASHRAE F. 2017).

OT: Operative Temperature



t_o = operative temperature (‘C)
t_a = air temperature (‘C)
t_r = mean radiant temperature (‘C)
h_c = convective heat transfer coefficient (W/m^{2}K)
h_r = radiative heat transfer coefficient (W/m^{2}K)

$$t_o = \frac{h_c t_a + h_r t_r}{h_c + h_r}$$

Operative temperature = $\frac{1}{2}$ (mean radiant temp. + air temp.)

If (V<=0.4m/s) & (MRT<=50’C) → t_o can be assumed to be equal to $(t_a + t_r)/2$.

ASHRAE Standard 55-2017

For sedentary persons in 0.5-1.0 CLO without noticeable air motion (V<=0.2m/s)

- 80% occupant acceptability
- Two zones: one for 0.5 CLO and the other for 1.0 CLO
- OT (Operative temperature)

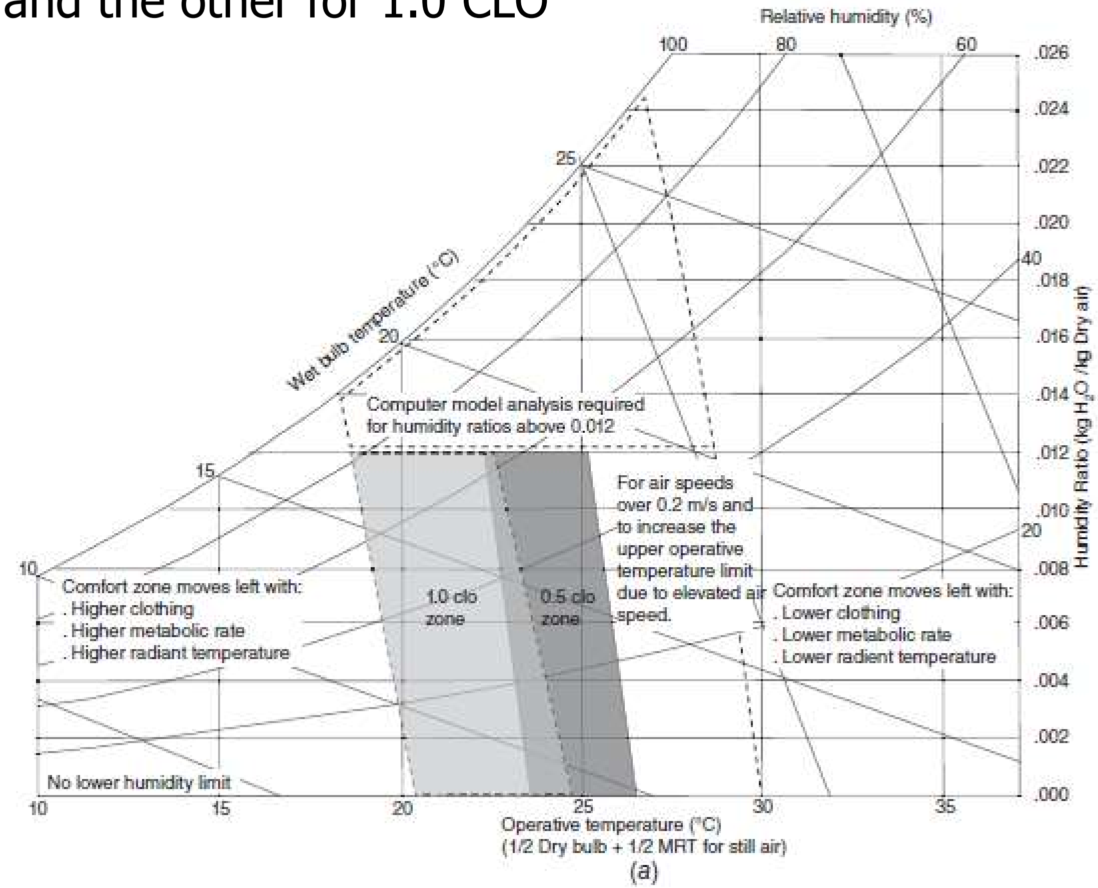


Fig. 4.12 (a, b) ANSI/ASHRAE Standard 55–2017 comfort zone. (c) Relationships between increasing air speeds and temperature relative to thermal comfort. (Reprinted with permission; ©ASHRAE, www.ashrae.org. ANSI/ASHRAE Standard 55–2017, Thermal Environmental Conditions for Human Occupancy.)

Quantification of thermal comfort

- Fanger (1970), Thermal Comfort
- The human thermal response, perceived as thermal comfort or discomfort, is shaped by six primary factors
- Two personal variables
  - metabolic rate (met), clothing insulation (clo)
- Four environmental variables
  - air temperature, mean radiant temperature, air speed, and relative humidity.

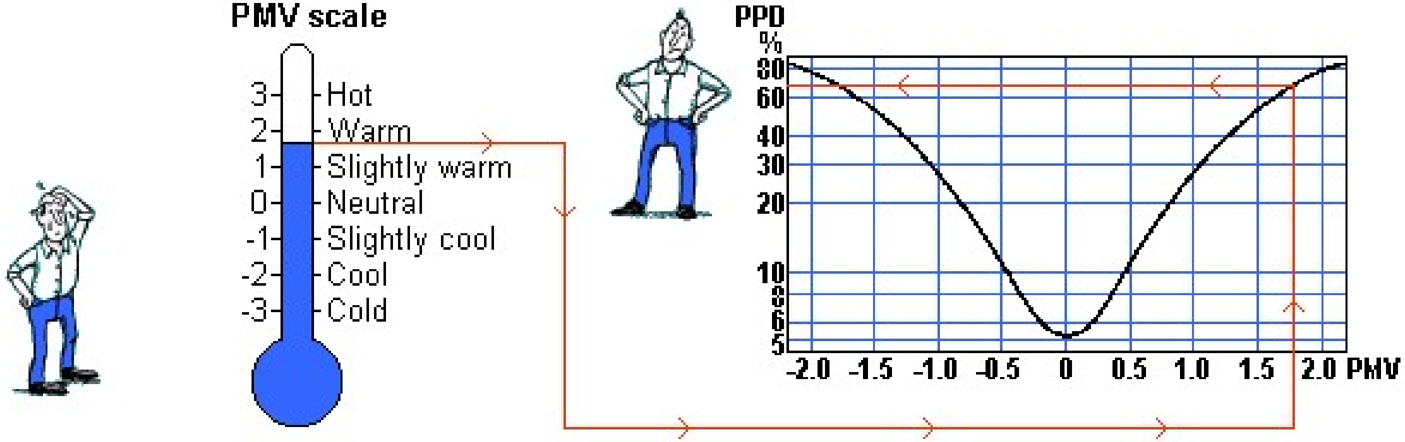
Calculation of PMV & PPD

- PMV (Predicted Mean Vote) scale
  - -3 (cold), -2(cool), -1(slightly cool), 0(neutral), 1(slightly warm), 2 (warm), 3 (hot)
- PPD (Predicted Percentage Dissatisfied, %)

$$t_{cl} = 35.7 - 0.0275(M - W) - R_{cl}\left\{\begin{array}{l}(M - W) - 3.05\left[5.73 - 0.007 * (M - W) - P_a\right] \\ -0.42\left[(M - W) - 58.15\right] - 0.0173M(5.87 - P_a) \\ -0.0014 * M * (34 - t_a)\end{array}\right\}$$

$$\begin{aligned} RHS &= 3.9610^{-8} f_{cl}\left[(t_{cl} + 273)^4 - (t_r + 273)^4\right] + f_{cl} h_c (t_{cl} - t_a) + 3.05\left[5.73 - 0.007(M - W) - P_a\right] \\ &\quad +0.42\left[(M - W) - 58.15\right] + 0.0173M(5.87 - P_a) + 0.0014M(34 - t_a) \\ L &= (M - W - RHS) \\ PMV &= 0.303\left[\exp(-0.036M) + 0.028\right]L \\ PPD &= 100 - 95\exp\left[-\left(0.03353PMV^4 + 0.2179PMV^2\right)\right] \end{aligned}$$

PMV & PPD



The theoretical minimum PPD is 5% !!!!!

Table 7 Typical Insulation and Permeability Values for Clothing Ensembles

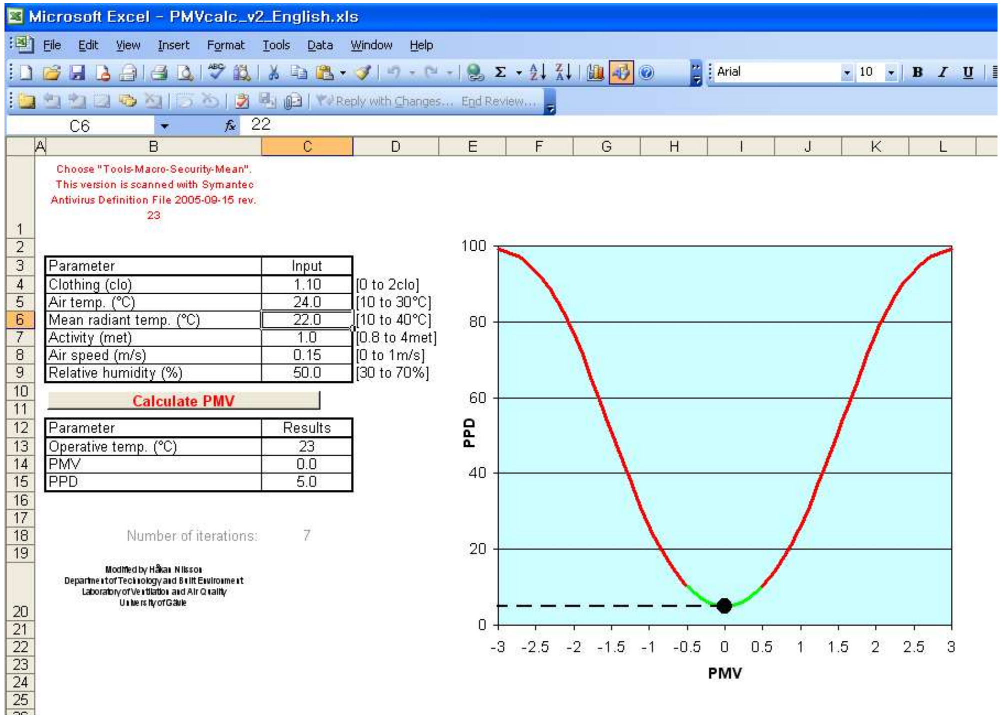
Ensemble Description[a]	I_{cl} (clo)	I_t[b] (clo)	f_{cl}	i_{cl}	i_m[b]
Walking shorts, short-sleeved shirt	0.36	1.02	1.10	0.34	0.42
Trousers, short-sleeved shirt	0.57	1.20	1.15	0.36	0.43
Trousers, long-sleeved shirt	0.61	1.21	1.20	0.41	0.45
Same as above, plus suit jacket	0.96	1.54	1.23		
Same as above, plus vest and T-shirt	1.14	1.69	1.32	0.32	0.37
Trousers, long-sleeved shirt, long-sleeved sweater, T-shirt	1.01	1.56	1.28		
Same as above, plus suit jacket and long underwear bottoms	1.30	1.83	1.33		
Sweat pants, sweat shirt	0.74	1.35	1.19	0.41	0.45
Long-sleeved pajama top, long pajama trousers, short 3/4 sleeved robe, slippers (no socks)	0.96	1.50	1.32	0.37	0.41
Knee-length skirt, short-sleeved shirt, panty hose, sandals	0.54	1.10	1.26		
Knee-length skirt, long-sleeved shirt, full slip, panty hose	0.67	1.22	1.29		
Knee-length skirt, long-sleeved shirt, half slip, panty hose, long-sleeved sweater	1.10	1.59	1.46		
Same as above, replace sweater with suit jacket	1.04	1.60	1.30	0.35	0.40
Ankle-length skirt, long-sleeved shirt, suit jacket, panty hose	1.10	1.59	1.46		
Long-sleeved coveralls, T-shirt	0.72	1.30	1.23		
Overalls, long-sleeved shirt, T-shirt	0.89	1.46	1.27	0.35	0.40
Insulated coveralls, long-sleeved thermal underwear, long underwear bottoms	1.37	1.94	1.26	0.35	0.39

Source: From McCullough and Jones (1984) and McCullough et al. (1989).

[a] All ensembles include shoes and briefs or panties. All ensembles except those with panty hose include socks unless otherwise noted.

[b] For $\bar{t}_r = t_a$ and air velocity less than 0.2 m/s (I_a = 0.72 clo and i_m = 0.48 when nude). 1 clo = 0.155 (m^2·K/)W.

From ASHRAE handbook fundamentals 2013



Available on http://innova.dk/PMV_Calculation.thermal_comfort11.0.html

Occupants in Naturally Ventilated (NV) buildings

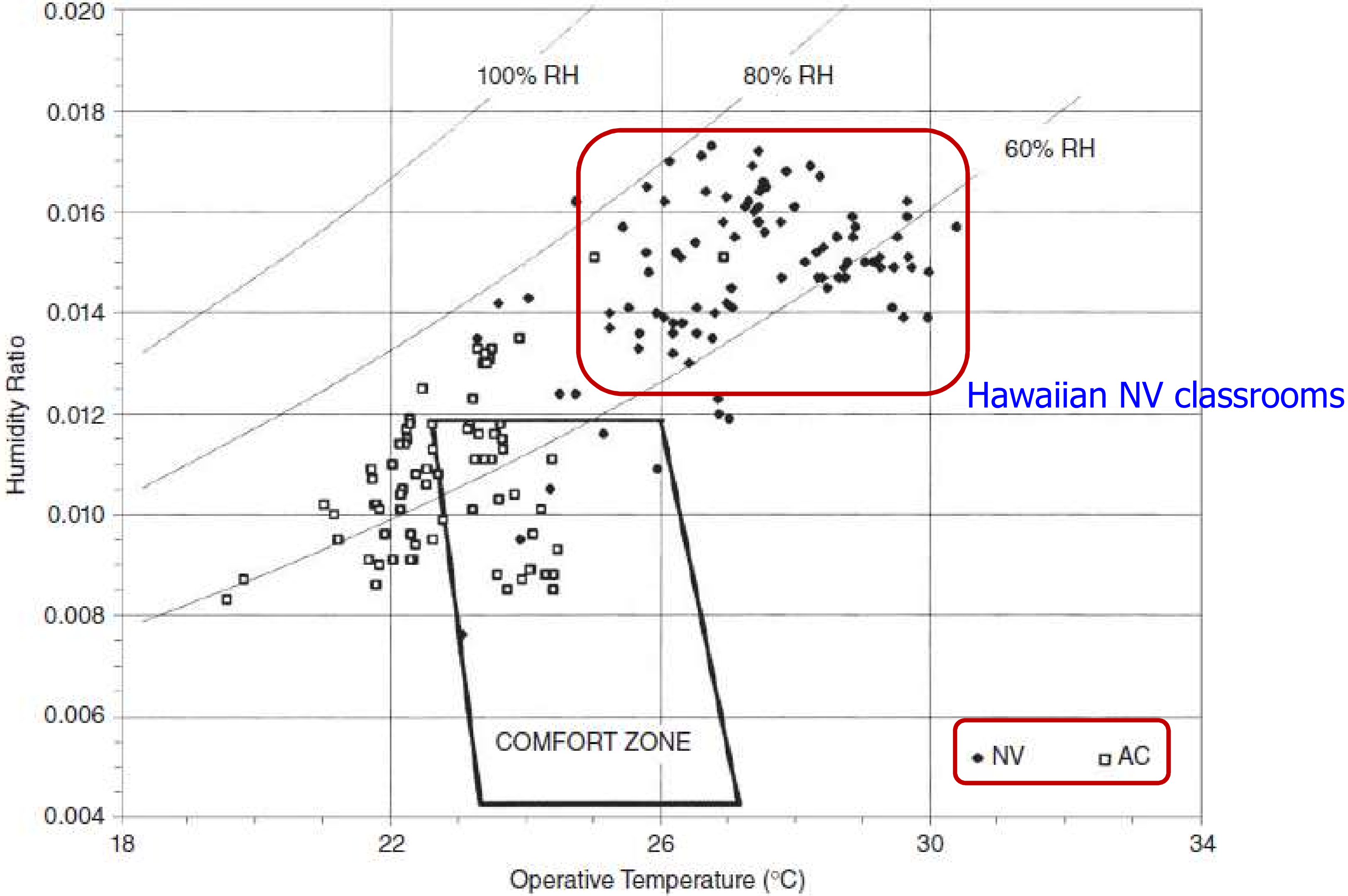


Fig. 4.15 Natural ventilation and comfort. Measured conditions compared to the ASHRAE comfort zone (warm season) for naturally ventilated and air-conditioned classrooms in Hawaii. The majority of the occupants voted these conditions acceptable. A higher temperature and humidity comfort zone for naturally ventilated buildings is supported by studies such as this. (Kwok, 1998. Reprinted with permission of ASHRAE, from the ASHRAE Transactions, 1998, Vol. 104, Number 1. Note that the comfort zone has been modified to conform to ASHRAE Standard 55–2017.)

Long-term acclimatization influences the sensation of thermal comfort.

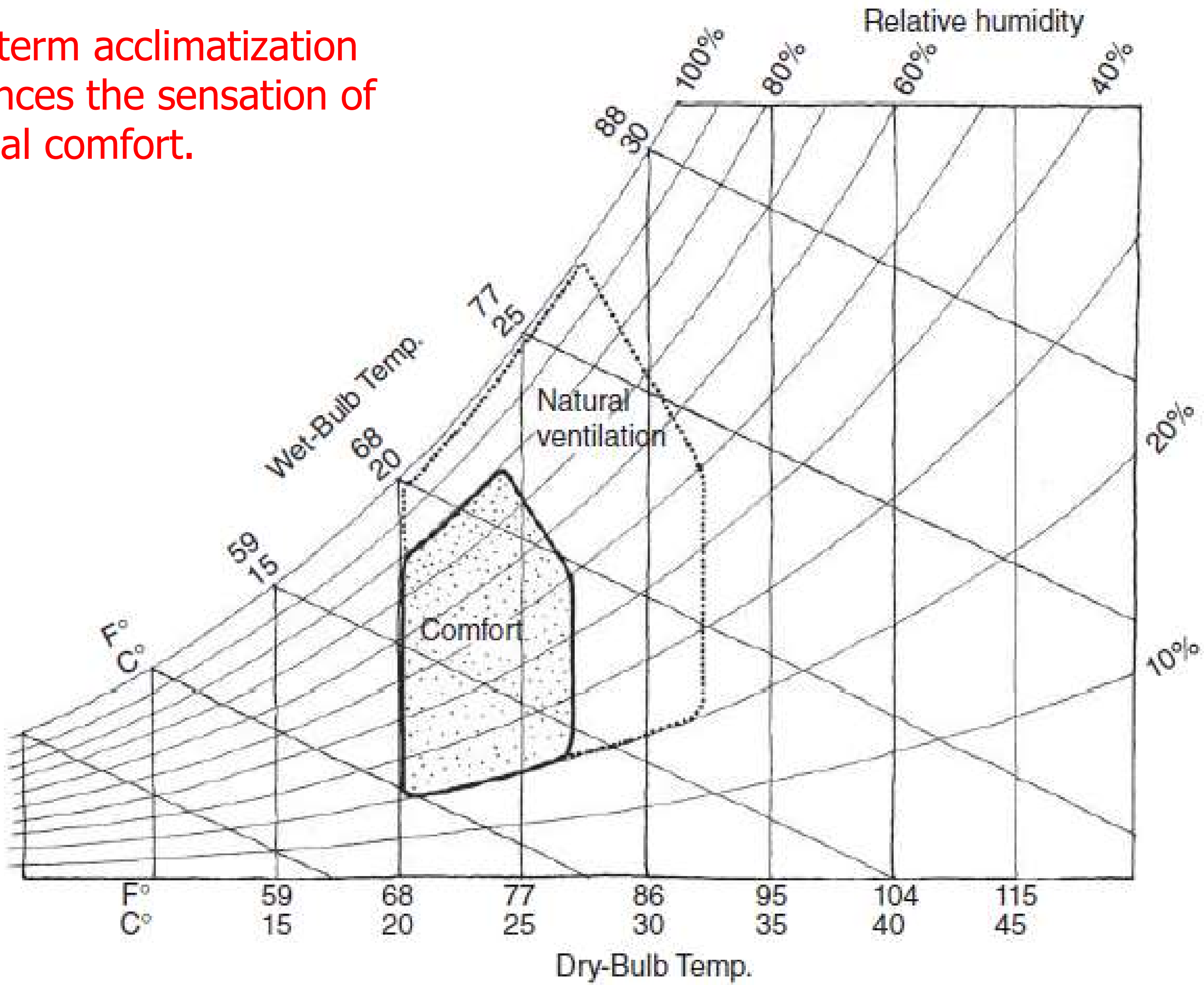


Fig. 4.16 *Suggested boundaries of outdoor air temperature and humidity within which indoor comfort can be provided by natural ventilation. Assumed air speed is 2 m/s (400 fpm). The higher limits for "hot-developing countries" assume acclimatization by those cultures. (Based upon Givoni, 1998.)*

Indoor air velocity

TABLE 4.6 Air Velocity and Comfort

Air Velocity	Possible Lower-Temperature Comfort Sensation (between 80°F and 90°F; Larger Numbers Correspond to High-Humidity Areas)	Probable Impact
Up to 50 fpm (0.25 m/s)	No change in comfort sensation	Unnoticed
50–100 fpm (0.25–0.51 m/s)	2–3F° lower (1.1–1.7C°)	Pleasant
100–200 fpm (0.51–1.02 m/s)	4–5F° lower (2.2–2.8C°)	Generally pleasant but causing a constant awareness of air movement
200–300 fpm (1.02–1.52 m/s)	5–7F° lower (2.8–3.9C°)	From slightly to annoyingly drafty
Above 300 fpm (1.52 m/s)	More than 5–7F° lower (2.8–3.9C°)	Requires corrective measures if work is to be efficient and health secured

Source: Adapted from Victor Olgyay, *Design with Climate: Bioclimatic Approach to Architectural Regionalism*, Copyright © 1963, Princeton University Press. Reprinted by permission.

Indoor air velocity

(*a*) 0.0 mph (0.0 m/s)

(*b*) 4.5 mph (2.0 m/s)

(*c*) 7.8 mph (3.5 m/s)

(*d*) 11.2 mph (5.0 m/s)

Fig. 4.18 *a-d Various air speed rates are shown using a fan and graduation tassel.*

Localized comfort: (1) draft

- Draft = excessive air motion
- Unwanted local cooling of the body
- The warmer the air, the greater the tolerance.
  - Many HVAC systems deliver SA temperature as low as 13'C with 0.25m/s → can cause 40% dissatisfaction
  - Ceiling fan with the same air speed, for comfort at higher temperature, 80'F(27'C) → less than 15% dissatisfaction

68F = 20'C
73.5F = 23.0'C
79F = 26.1'C

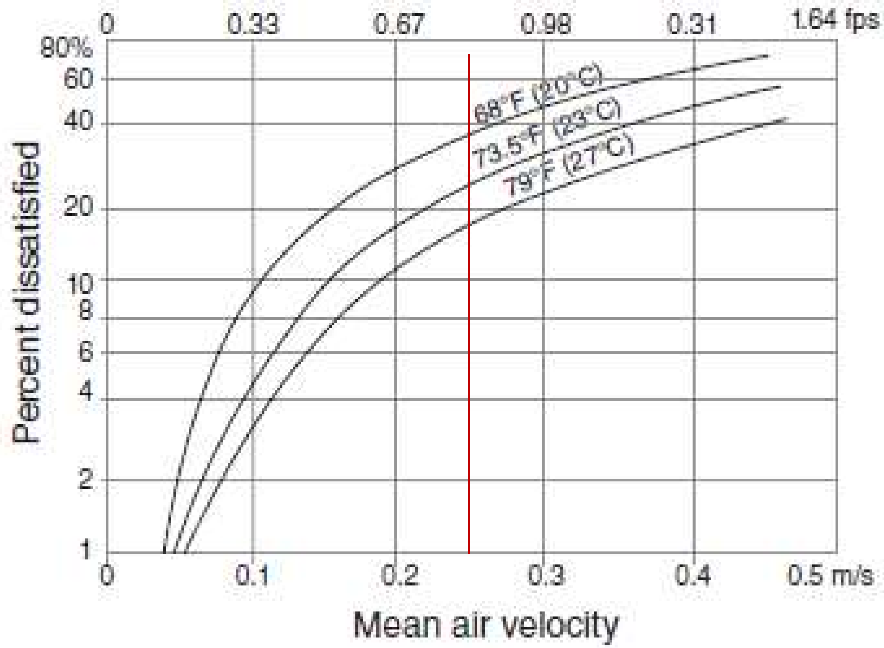


***Fig. 4.20** Percentage of people dissatisfied as a function of mean air velocity. Note the influence of air temperature: The lower the temperature, the higher the dissatisfaction. (Reprinted with permission; ©ASHRAE, www.ashrae.org. 2017* ASHRAE Handbook—Fundamentals.)

(2) Radiant asymmetry

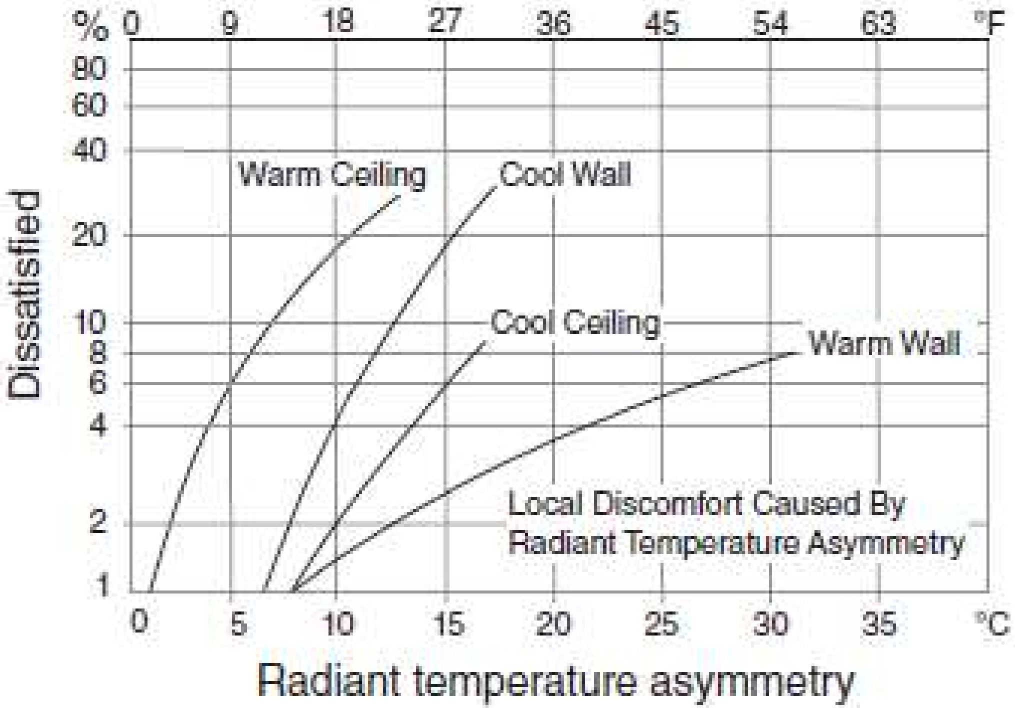


Fig. 4.21 *Percentage of people expressing discomfort due to radiant asymmetry. A warmer ceiling produces the highest discomfort; a warmer wall, the least discomfort. (Reprinted with permission; ©ASHRAE, www.ashrae.org. 2017 ASHRAE Handbook—Fundamentals.)*

X-axis: The difference between the temperatures of two opposite surfaces

(3) Vertical T difference

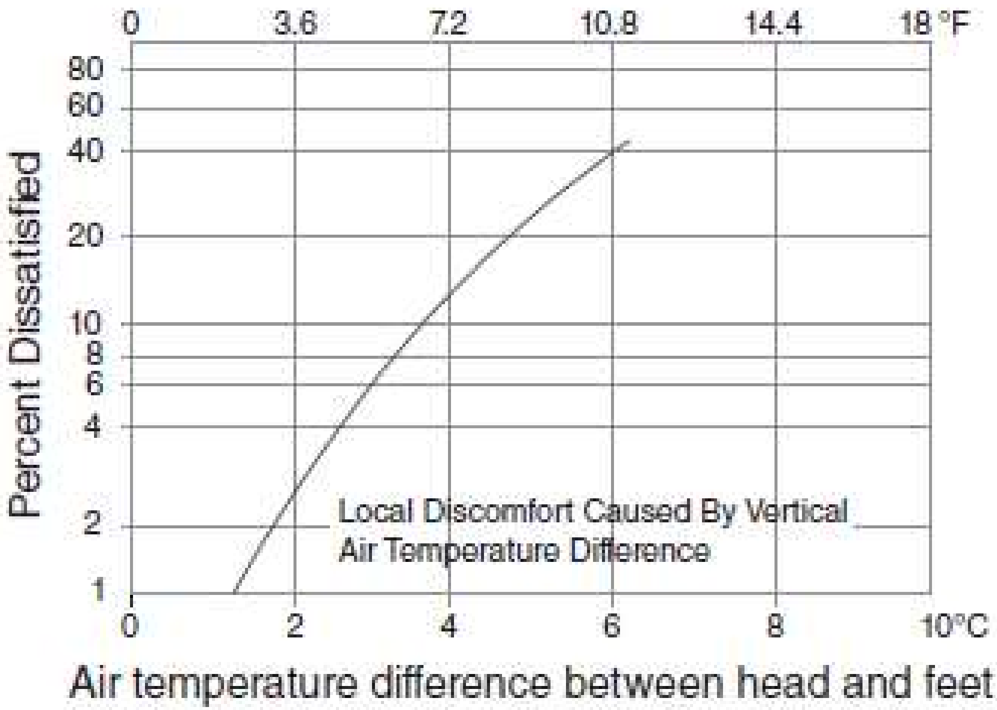


Fig. 4.22 *Percentage of people dissatisfied as a function of the vertical air temperature difference between the head (higher temperature) and ankles (lower temperature). A cold floor proved uncomfortable. (Reprinted with permission; ©ASHRAE, 2017* ASHRAE Handbook—Fundamentals.*)*