Aalto University
School of Engineering

Comfortable and Healthy Indoor Climate

EEN-E4001

Lecture 3: Thermal comfort

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Learning outcomes

- Understanding of factors affecting thermal comfort
- Understanding what is <u>the whole body thermal sensation</u>
- Understanding what is <u>local thermal discomfort</u>

THERMAL COMFORT

„state of mind which expresses satisfaction with the thermal environment“

(ASHRAE)

Thermal Comfort

- Thermal conditions within living and working environments play a critical role in influencing occupant comfort and wellbeing.
- Research has shown that along with air quality, thermal comfort is one of the critical variables influencing worker productivity.

➢ **Man is in thermal balance when the internal heat production is equal the heat loss**.

ANALYSIS OF THERMAL COMFORT

- Evaluation of thermal sensation in field with surveys

- Modelling heat exchange between the human body and the environment

ISO 7730 & ASHRAE 55/1994

Short discussion

How the heat transfer from body happens ?

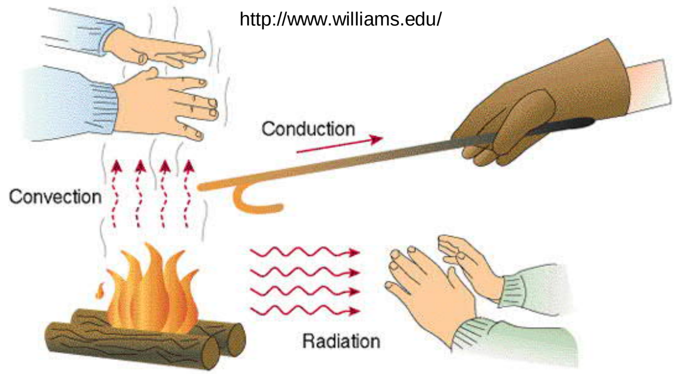
Heat Transfer and Thermal Comfort

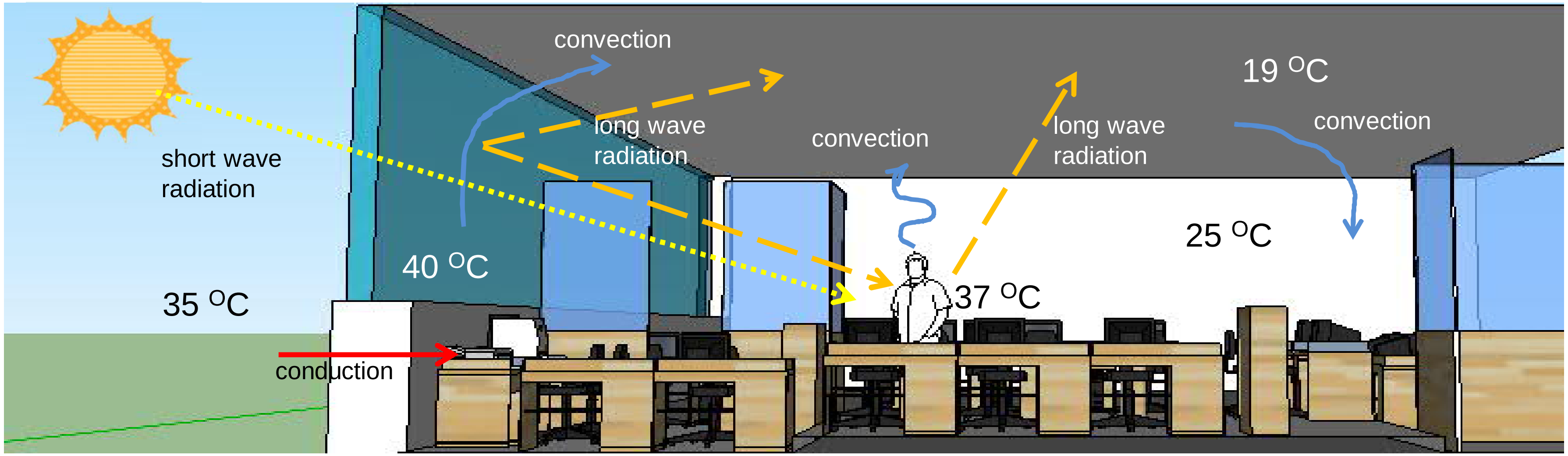
- Maintenance of thermal balance (heat production = heat loss) is an essential factor of human thermal sensation in all conditions.
- Thermal balance is affected by
  - Sensible heat transfer (dry)
  - Latent heat transfer (wet)

Basic Principles of Heat Transfer

Three physical mechanisms of heat transfer:

- **Convection**
- **Conduction**
- **Thermal Radiation**





Globe Temperature (GT)

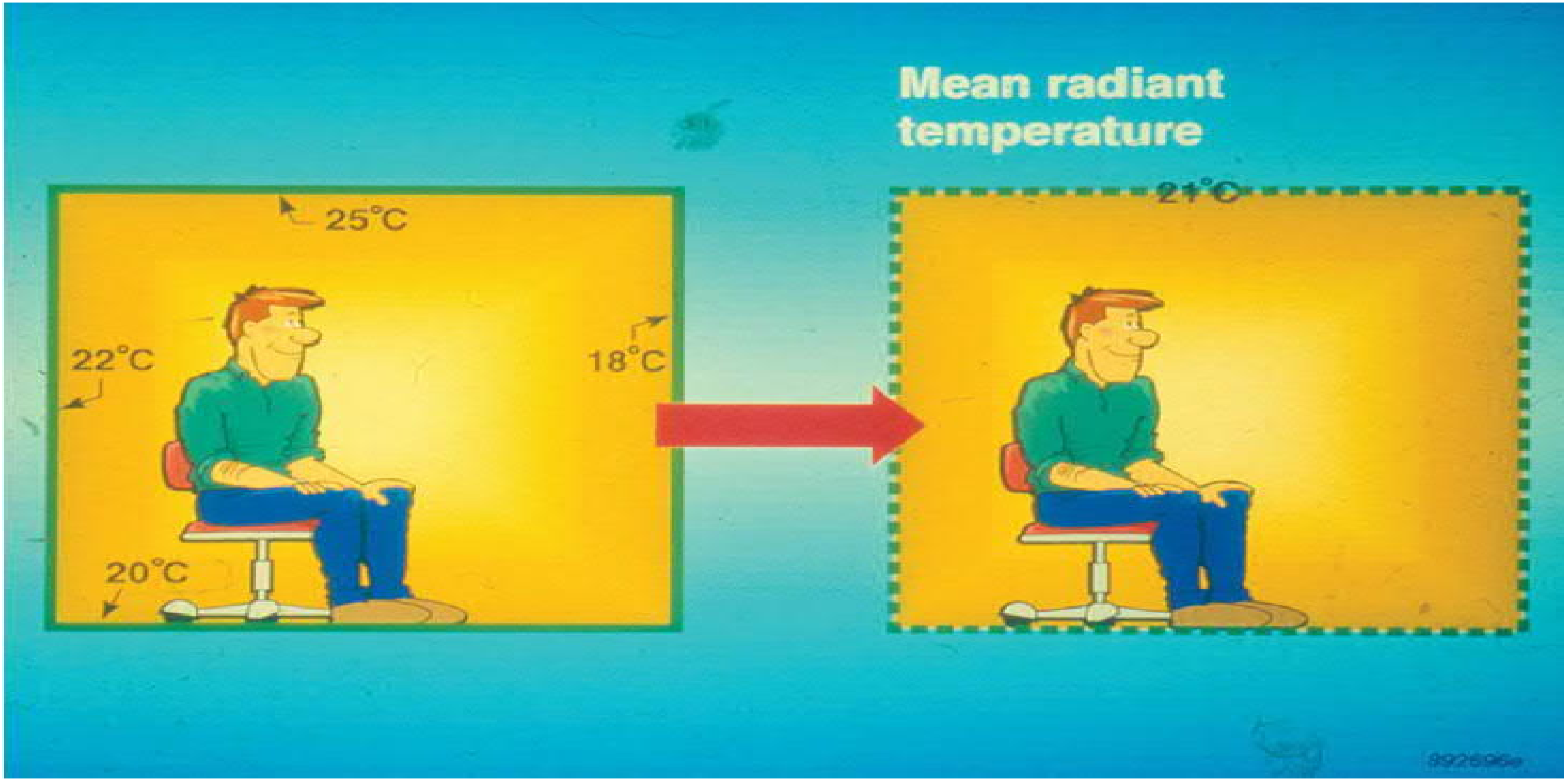
- **The mean radiant temperature (MRT) can be measured using a black-globe thermometer.**
- The globe can in theory have any diameter but as the formulae used in the calculation of the mean radiant temperature depend on the diameter of the globe, a diameter of 0.15 metres, specified for use with these formula, is generally recommended.
- The surface of the globe shall be darkened, by means of a layer of matte black paint.

Mean Radiant Temperature (MRT)

$$MRT = \left[(GT + 273)^4 + 2,5 \cdot 10^8 \cdot v_a^{0,6}(GT - T_a)\right]^{1/4} - 273$$

- where:
  - MRT is the mean radiant temperature (° C);
  - GT is the globe temperature (° C);
  - v_a is the air velocity at the level of the globe (m/s);
  - T_a is air temperature (° C).

Mean Radiant Temperature



Radiant Temperature

Mean radiant temperature (t_{mr}) is defined as a uniform surface temperature of an enclosure in which an occupant would exchange the same amount of radiant heat as in the actual non-uniform enclosure.

$$t_{mr} = t_1F_{p1} + t_2F_{p2} + \ldots + t_nF_{pn} / (F_{p1} + F_{p2} + \ldots + F_{pn})$$

where F_{pn} is an angle factor between a person and a surface n

or $$t_{mr} = t_1A_1 + t_2A_2 + \ldots + t_nA_n / (A_1 + A_2 + \ldots + A_n)$$

where A_n is an area of surface n

Angle Factors

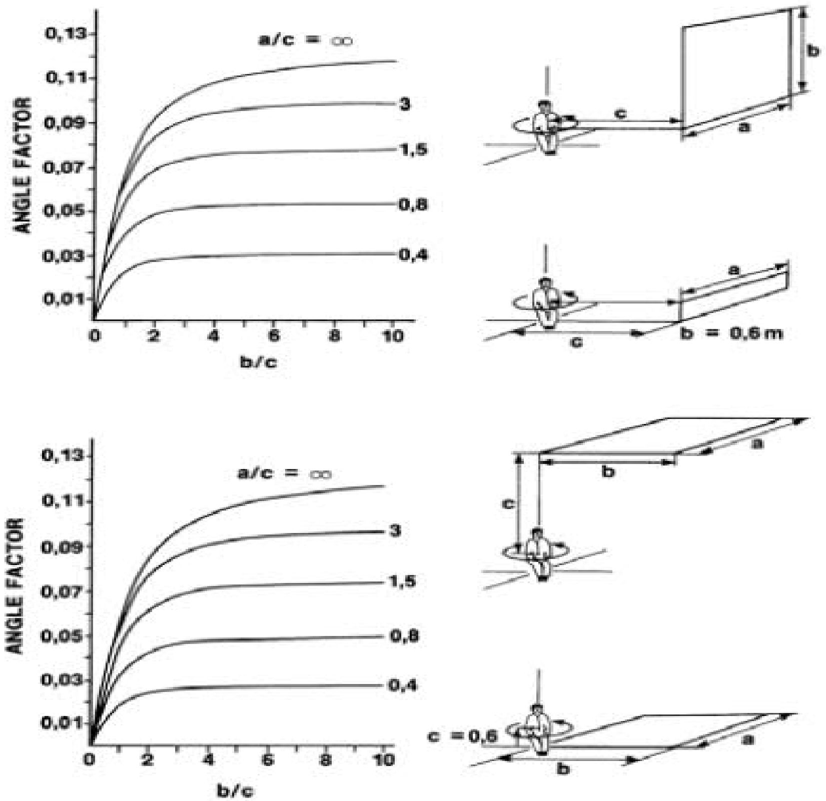


Figure 2.2 Mean value of angle factor between a seated person and a) horizontal rectangle b) vertical rectangle

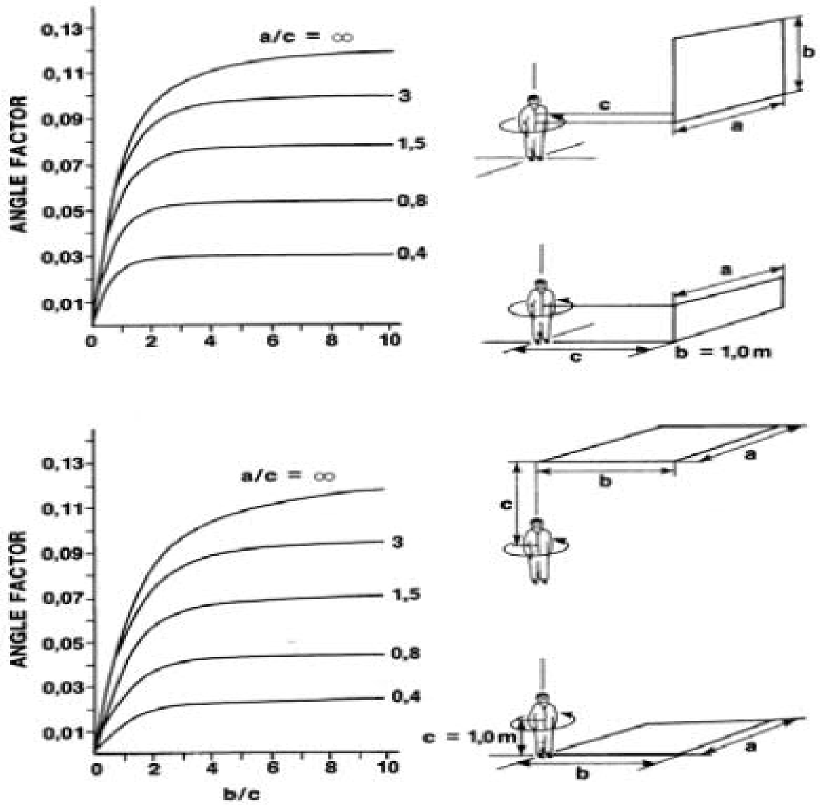
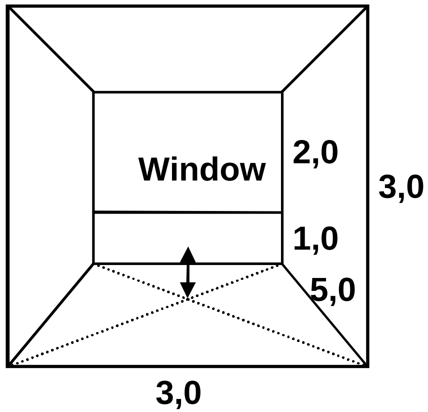


Figure 2.3 mean value of angle factor between a standing person and a) horizontal rectangle b) vertical rectangle

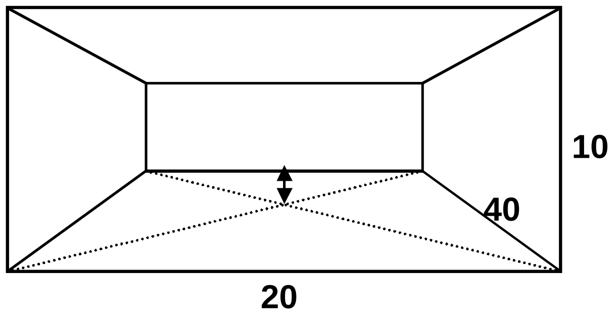
Angle Factors – Typical Values

	Angle factor $F_{p\text{-}N}$			
	office room		industrial room	
Surface	Seated	Standing	Seated	Standing
floor	0,32	0,24	0,48	0,48
ceiling	0,12	0,12	0,22	0,22
front wall (win)	0,03	0,04	0,03	0,03
window	0,06	0,06	-	-
back wall	0,09	0,10	0,03	0,03
right side wall	0,19	0,22	0,12	0,12
left side wall	0,19	0,22	0,12	0,12

Office room



Industrial room



Source: Olesen

Operative Temperature

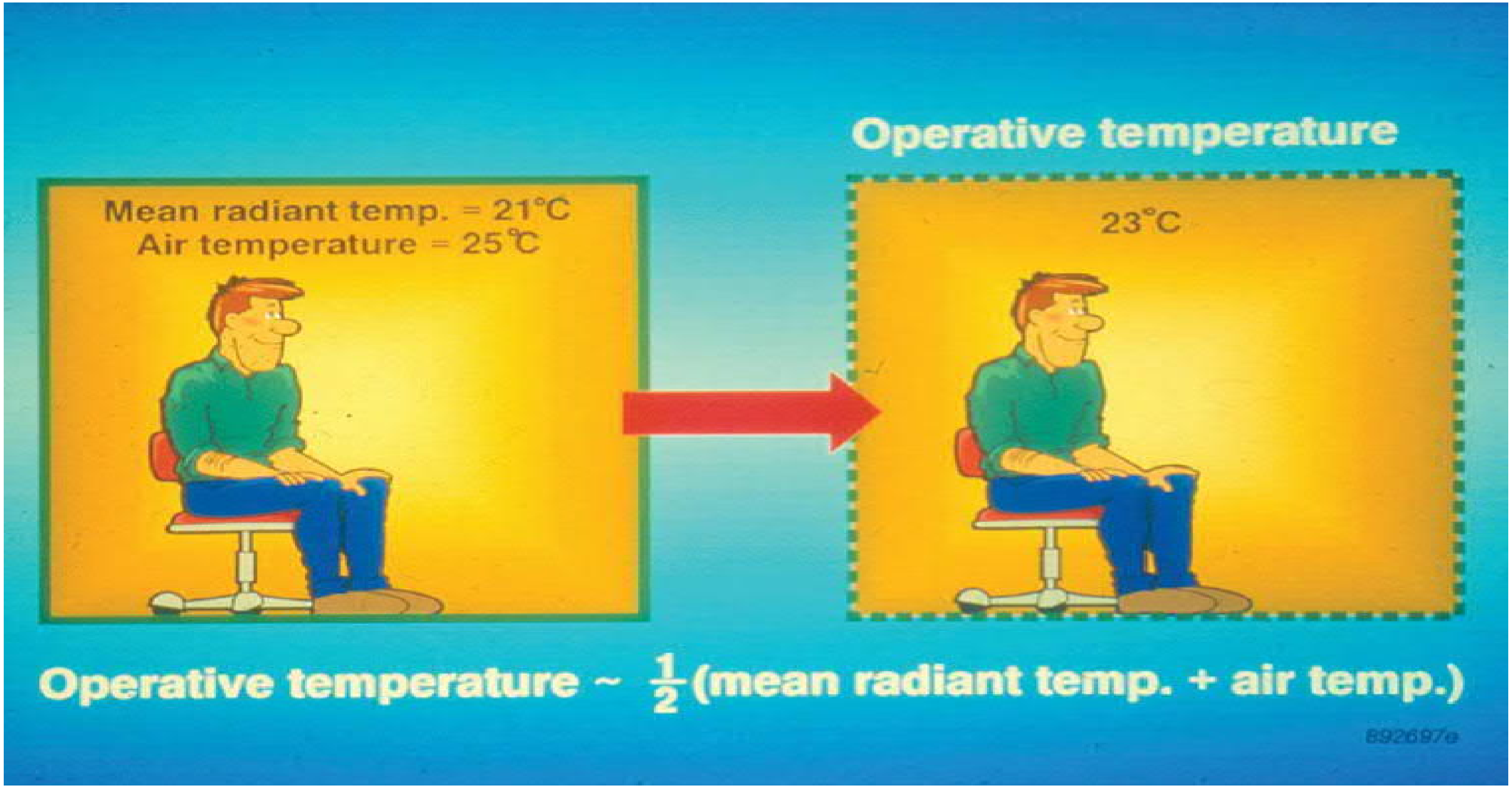
- Operative temperature can be defined as the average of the mean radiant (t_{mr}) and dry pulp air (t_a) temperatures

$$t_{op} = (t_{mr}+t_a)/2$$

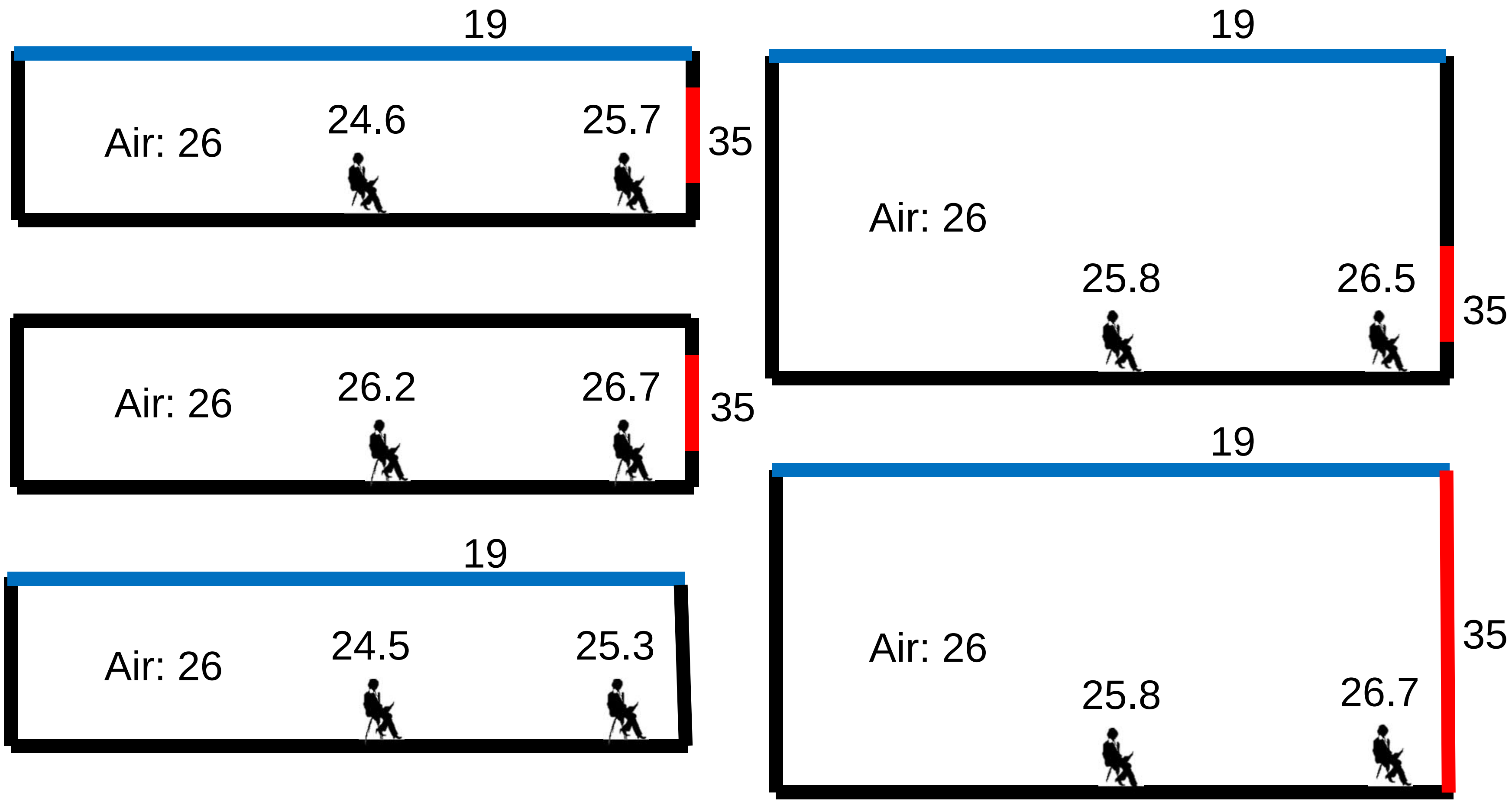
- Heat release of human body is 50 % of radiation and 50 % of convection.

- Operative temperature (t_{op}) is defined as a uniform temperature of an enclosure in which an occupant would exchange the same amount of heat by radiation plus convection as in the actual non-uniform environment.

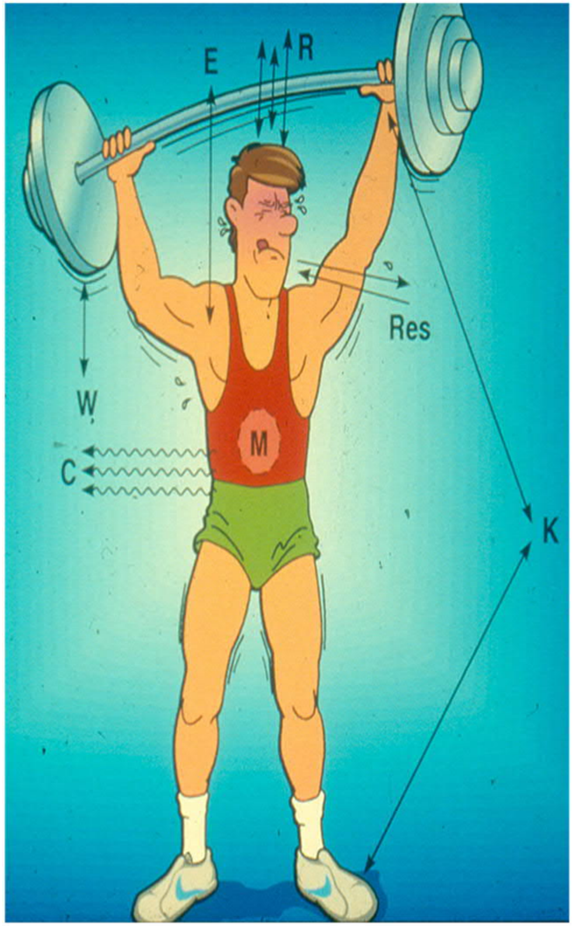
Operative Temperature



Operative Temperature:Examples (^{O}C)



Human body energy balance



$$S = M \pm W \pm R \pm C \pm K - E - RES$$

- S =the rate of heat storage,
- M =the rate of metabolic heat production,
- W = the rate of mechanical work accomplished
- R = the rate of heat exchange by radiation,
- C = the rate of heat exchange by convection, K =the rate of heat exchange by conduction,
- E =the rate of heat exchange by evaporation
- RES =the rate of heat exchange by respiration.

Short discussion

What you can do to improve your thermal sensation ?

The Whole Body Thermal Sensation
Factors Influencing Thermal Comfort

- Human
  - Metabolic Rate
  - Clothing Insulation

- Space
  - Air Temperature (Dry-Bulb)
  - Relative Humidity
  - Air Velocity
  - Radiation (Mean Radiant Temperature)

Thermal comfort

I - Clothing Insulation ($m^2.K/W$)

1 clo=0,155$m^2.K/W$

0,6-1,2

clo <0,5

>3,5

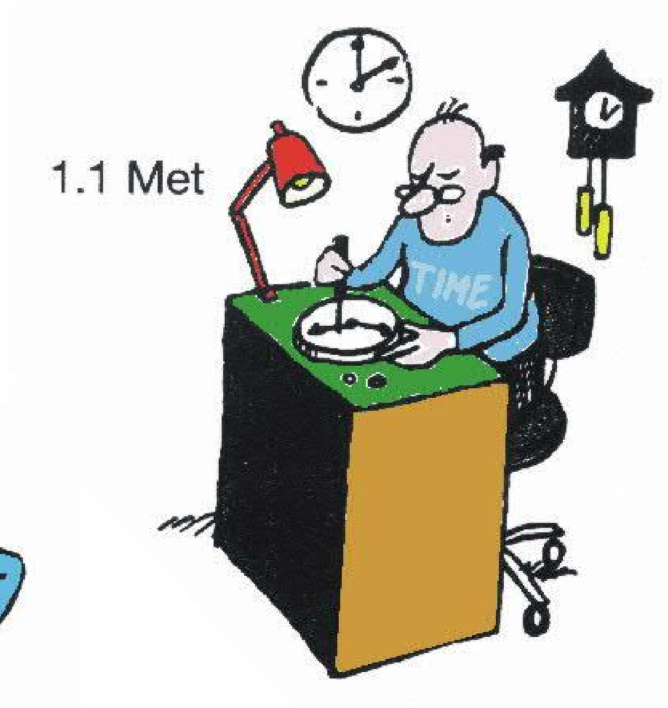
21

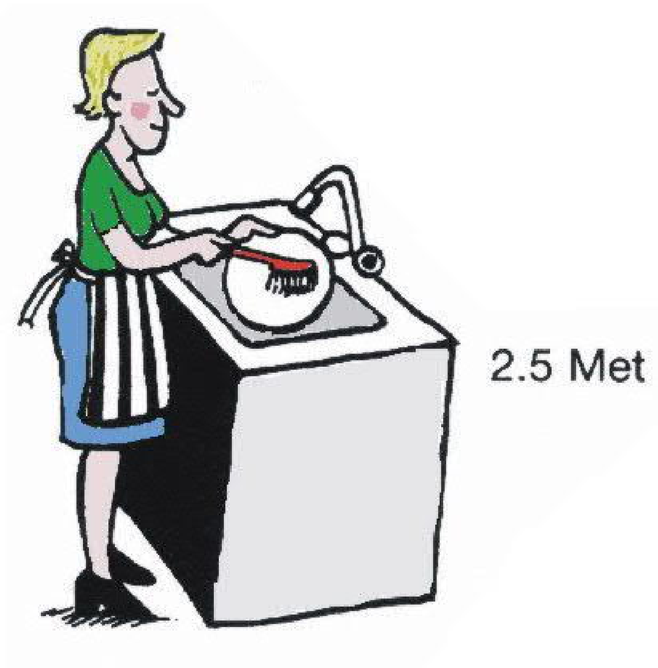
Work clothing	clo	m^2KW^{-1}.	Daily wear clothing	clo	m^2KW^{-1}.
Underpants, boiler suit, socks, shoes	0.70	0.110	Panties, T-shirt, shorts, light socks, sandals	0.30	0.050
Underpants, shirt, boiler suit, socks, shoes	0.80	0.125	Underpants, shirt with short sleeves, light trousers, light socks, shoes	0.50	0.080
Underpants, shirt, trousers, smock, socks, shoes	0.90	0.140	Panties, petticoat, stockings, dress, shoes	0.70	0.105
Underwear with short sleeves and legs, shirt, trousers, jacket, socks, shoes	1.00	0.155	Underwear, shirt, trousers, socks, shoes	0.70	0.110
Underwear with long legs and sleeves, thermo-jacket, socks, shoes	1.20	0.185	Panties, shirt, trousers, jacket, socks, shoes	1.00	0.155
Underwear with short sleeves and legs, shirt, trousers, jacket, heavy quilted outer jacket and overalls, socks, shoes, cap, gloves	1.40	0.220	Panties, stockings, blouse, long skirt, jacket, shoes	1.10	0.170
Underwear with short sleeves and legs, shirt, trousers, jacket, heavy quilted outer jacket and overalls, socks, shoes	2.00	0.310	Underwear with long sleeves and legs, shirt, trousers, V-neck sweater, jacket, socks, shoes	1.30	0.200
Underwear with long sleeves and legs, thermo-jacket and trousers, Parka with heavy quitting, overalls with heave quilting, socks, shoes, cap, gloves	2.55	0.395	Underwear with short sleeves and legs, shirt, trousers, vest, jacket, coat, socks,	1.5	0.230

Thermal comfort

M - Metabolic Rate (m^2.K/W)

1Met = 58,15 W/m^2

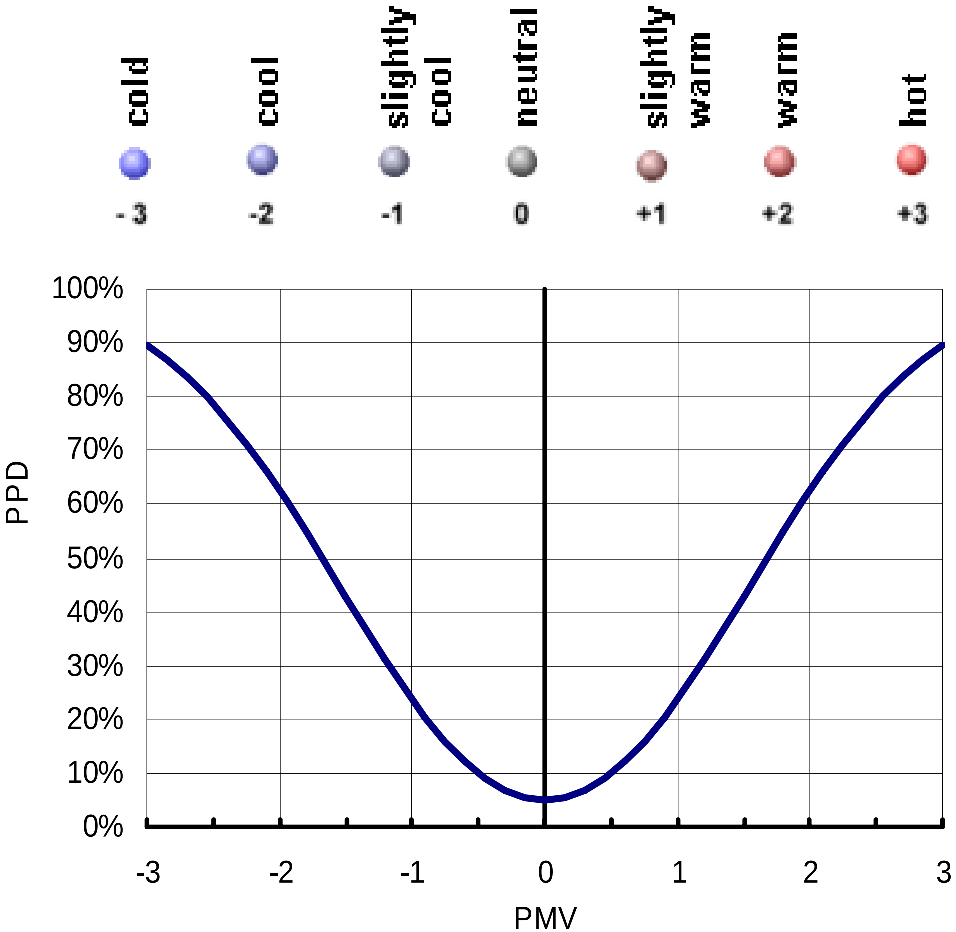




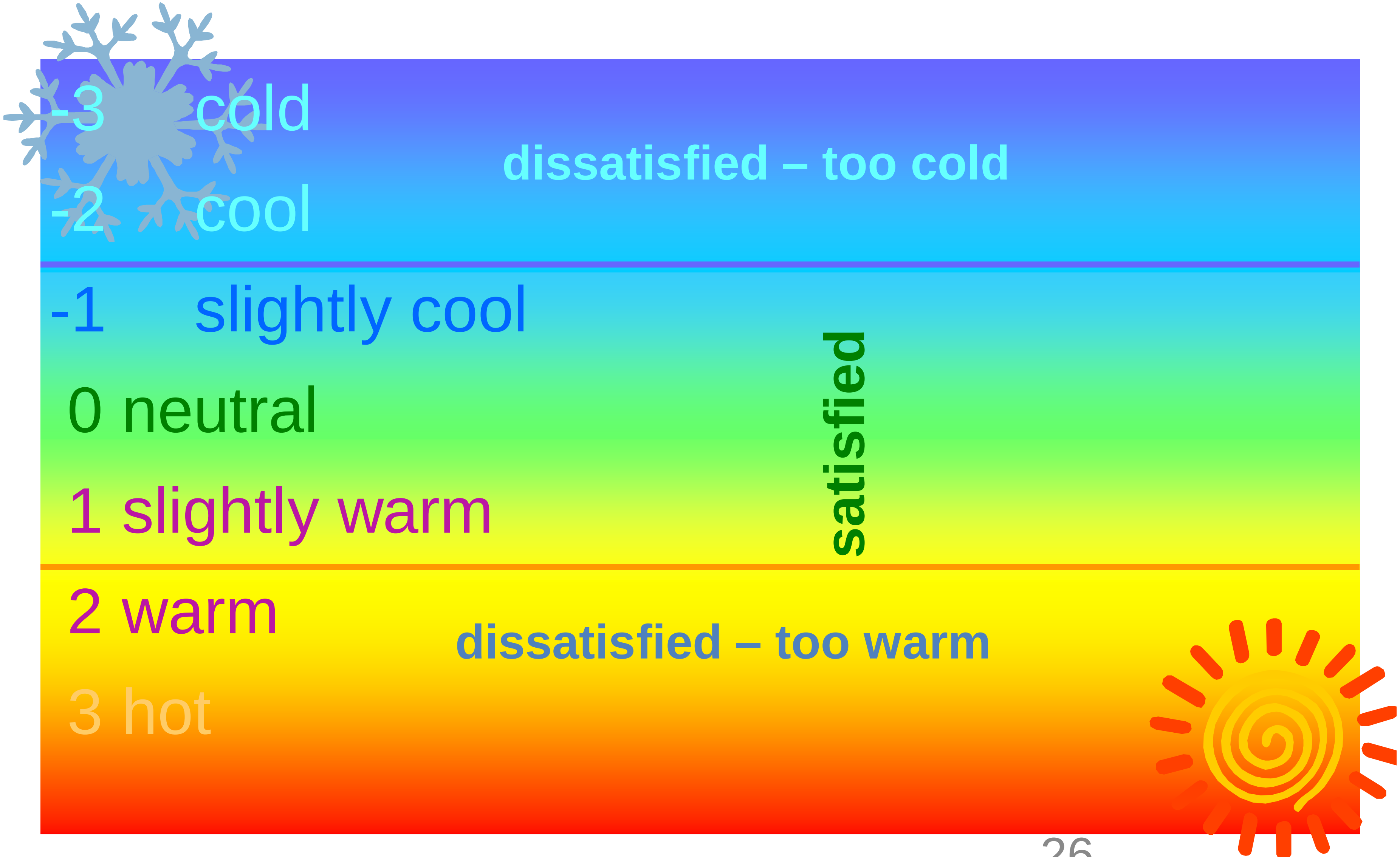
Activity	Metabolic Rate	
	W/m²	met
Reclining	46	0.8
Seated, relaxed	58	1.0
Sedentary activity (office, dwelling, school, laboratory)	70	1.2
Standing, light activity (shopping laboratory , light industry)	93	1.6
Standing, medium activity (Shop assistant, domestic work, machine work)	116	2.0
Walking on level ground		
2 km/h	110	1.9
3 km/h	140	2.4
4 km/h	165	2.8
5 km/h	200	3.4

Thermal comfort evaluation

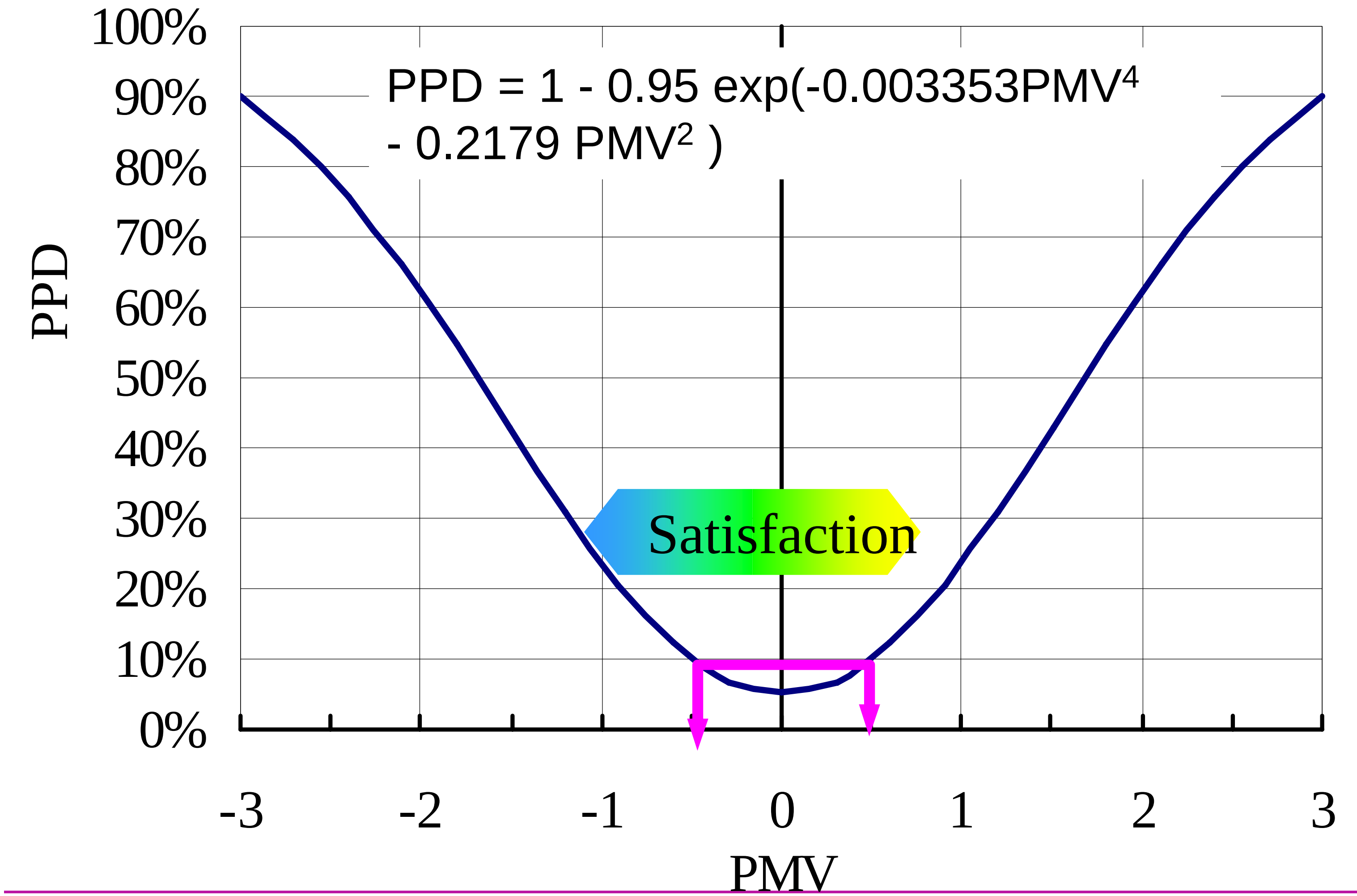
- PMV index
  (Predicted mean vote)
- PPD index
  (Predicted percentage of dissatisfied)



Comfort measure: Predicted Mean Vote



PMV and PPD


PPD = 1 - 0.95 exp(-0.003353PMV4
- 0.2179 PMV2)
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
PPD
Satisfaction
-3
-2
-1
0
1
2
3
PMV

Fanger Equation

$$PMV = \left[0.303\exp(-0.036m) + 0.028\right] \bullet \begin{bmatrix} m - w - 0.00305\left(5733 - 6.99(m-w) - p\right) \\ -0.42(m - w - 58.15) - 0.000017m(5867 - p) \\ -0.0014m(307 - T_a) - F \end{bmatrix}$$

$$F = 3.96 \cdot 10^{-8} f\left(T_{cl}^4 - T_{mrt}^4\right) + f\,h\left(T_{cl} - T_a\right)$$

$$h = \max\left\{2.38\left(T_{cl} - T_a\right)^{1/4}; 12.06\sqrt{v}\right\}$$

$$T_{cl} = 308.9 - 0.028(m - w) - R\,F$$

Thermal comfort

1st condition : Body heat balance

Standard recommendations
EN ISO 7730 and ASHRAE 55-2004 :

$-0.5 < PMV < +0.5$ ⇒ $PPD < 10\ \%$

Range of validity of the model of Fanger

- Valid only in steady-state conditions
- Metabolism from 46 to 230 W/m² (0.8 to 4 met);
- Clothing from 0 to 2 clo ;
- Air temperature from10 to 30 ° C;
- MRT from 10 to 40 ° C;
- Air velocity up to 1 m/s;
- Partial pressure of water vapor from 0 to 2700 Pa.

Thermal comfort

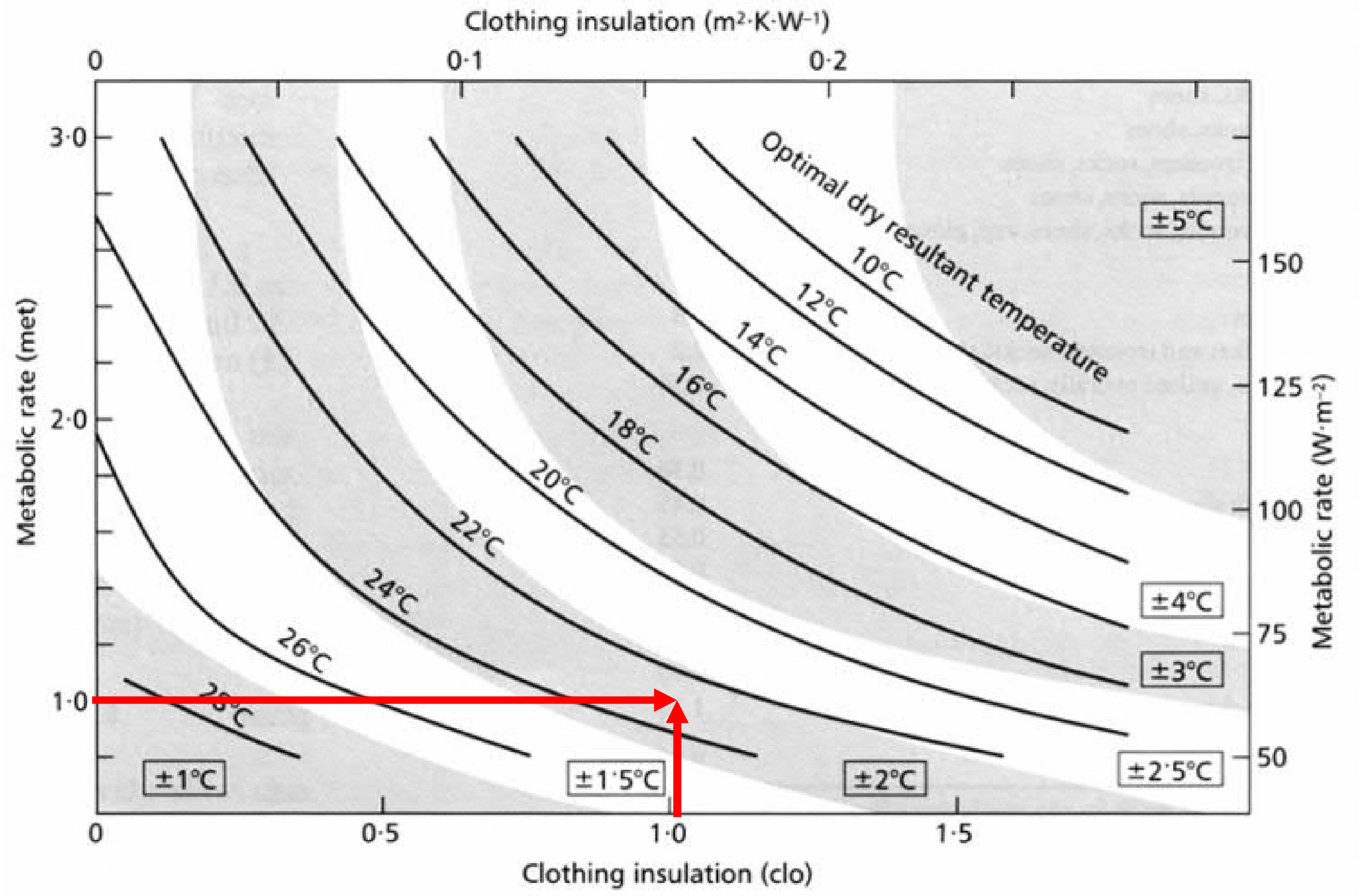
- EN ISO 7730 – parmeters especially for HVAC systems design
- Main parameters of IEQ in Appendix A of EN 12831
- 3 cathegories of thermal comfort according to PPD and PMV

Categories of thermal environment (EN ISO 7730)

Category of indoor thermal environment	Thermal state of the body as a whole	
	PPD	PMV
A	< 6%	– 0,2 < PMV < + 0,2
B	< 10%	– 0,5 < PMV < + 0,5
C	< 15%	– 0,7 < PMV < + 0,7

PMV - predicted mean vote, PPD - predicted percentage of dissatisfied

Optimum Air Temperature Depending on Clothing and Metabolic Rate (ASHRAE 55)



Indoor resultant (operative) temperature

Type of building, Space	Clothing, winter (clo)	Activity (met)	Category of indoor environment	Operative temperature, winter (°C)
Office	1,0	1,2	A	21,0 - 23,0
			B	20,0 - 24,0
			C	19,0 - 25,0
Open space office	1,0	1,2	A	21,0 - 23,0
			B	20,0 - 24,0
			C	19,0 - 25,0
Cafe, restaurant	1,0	1,2	A	21,0 - 23,0
			B	20,0 - 24,0
			C	19,0 - 25,0
Shopping center	1,0	1,6	A	17,5 - 20,5
			B	16,0 - 22,0
			C	15,0 - 23,0
Housing	1,0	1,2	A	21,0 - 23,0
			B	20,0 - 24,0
			C	19,0 - 25,0

Temperature criteria for the design

Example criteria for operative temperature and mean air velocity for typical spaces[a]

Type of building/space	Clothing cooling season (summer; Clo)	Clothing heating season (winter; Clo)	Activity (met)	Category	Operative temperature cooling season (summer; °C)	Operative temperature heating season (winter; °C)	Mean air velocity cooling season (summer; m s^{-1})	Mean air velocity heating season (winter; m s^{-1})
Office	0.5	1.0	1.2	A	24.5 ± 0.5	22.0 ± 1.0	0.18	0.15
				B	24.5 ± 1.5	22.0 ± 2.0	0.22	0.18
				C	24.5 ± 2.5	22.0 ± 3.0	0.25	0.21
Cafeteria/restaurant	0.5	1.0	1.4	A	23.5 ± 1.0	20.0 ± 1.0	0.16	0.13
				B	23.5 ± 2.0	20.0 ± 2.5	0.20	0.16
				C	23.5 ± 2.5	20.0 ± 3.5	0.24	0.19
Department/store	0.5	1.0	1.6	A	23.0 ± 1.0	19.0 ± 1.5	0.16	0.13
				B	23.0 ± 2.0	19.0 ± 3.0	0.20	0.15
				C	23.0 ± 3.0	19.0 ± 4.0	0.23	0.18

[a] Relative humidity is assumed to be 60% for 'summer' and 40% for 'winter'.

Thermal comfort

According to EN ISO 7730 there are two conditions for thermal comfort

1. The heat balance of the individual is balanced without overexertion of its self-regulatory mechanisms

2. There are no local discomforts due to:

   - air velocity/draught
   - radiant assymmetry
   - the vertical temperature gradient
   - floor temperature

Draught Rating, DR

Draught sensation can be estimated using Draught Rating (DR)

$$DR = (34 - t_a)(\bar{v} - 0{,}05)^{0{,}62}(0{,}37 * \bar{v} * Tu + 3{,}14)$$

DR = share of people, who are dissatisfied due to draught, %

t_a = local air temperature, ^oC

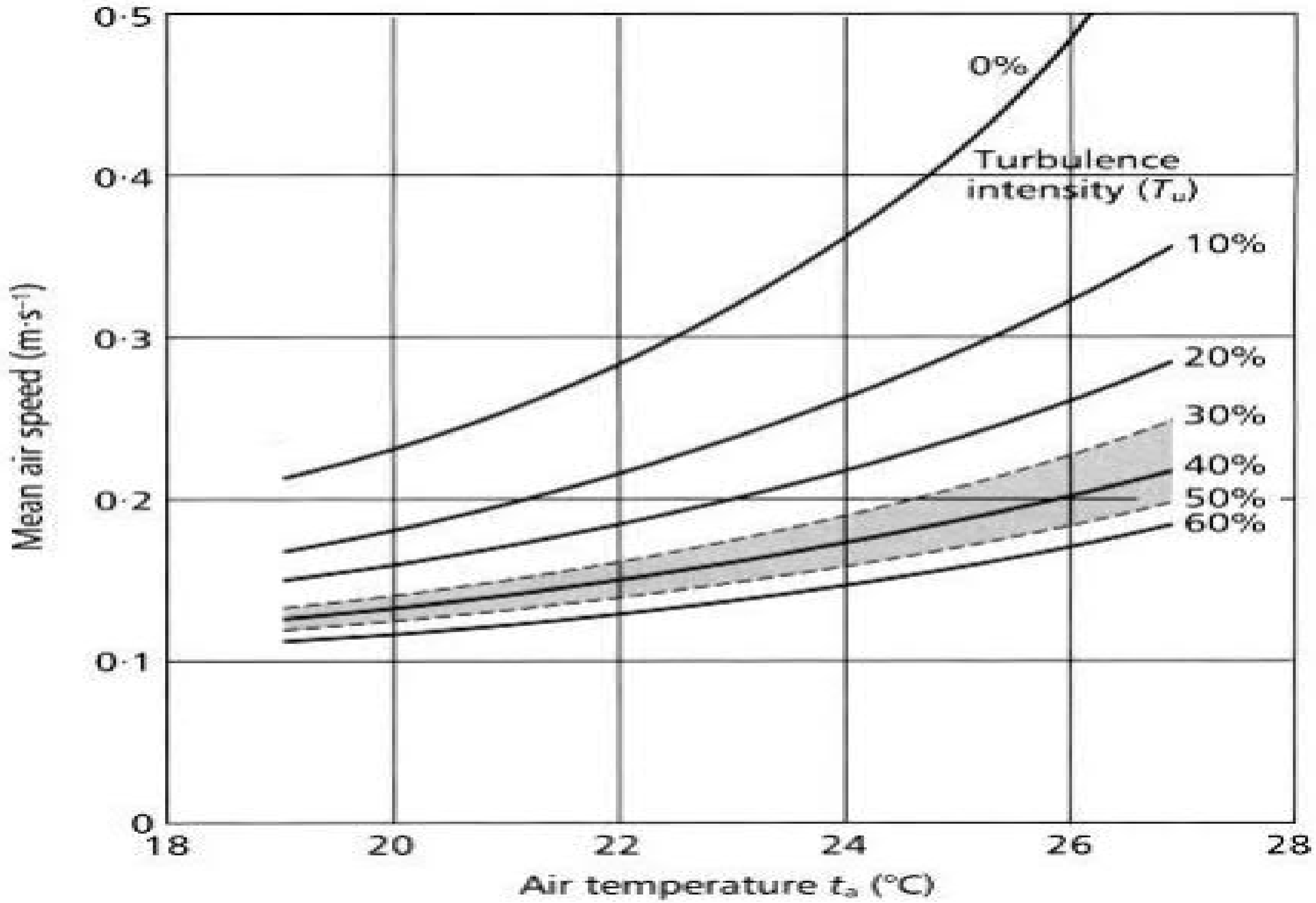
$\bar{v}$ = average air velocity, m/s

T_u = local turbulence intensity, %

$$Tu = 100 * \frac{v_{sd}}{v}$$

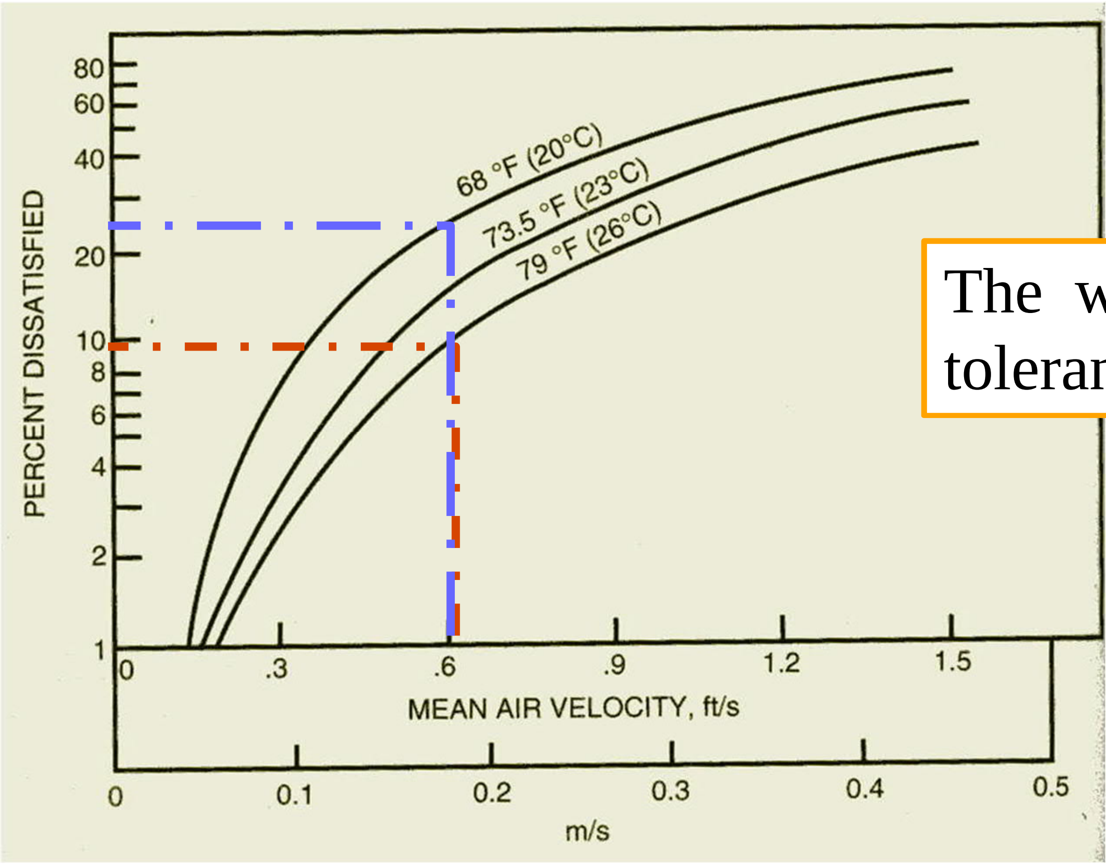
v_{sd} standard deviation of flow velocity, m/s

Draught Rating DR = 15%



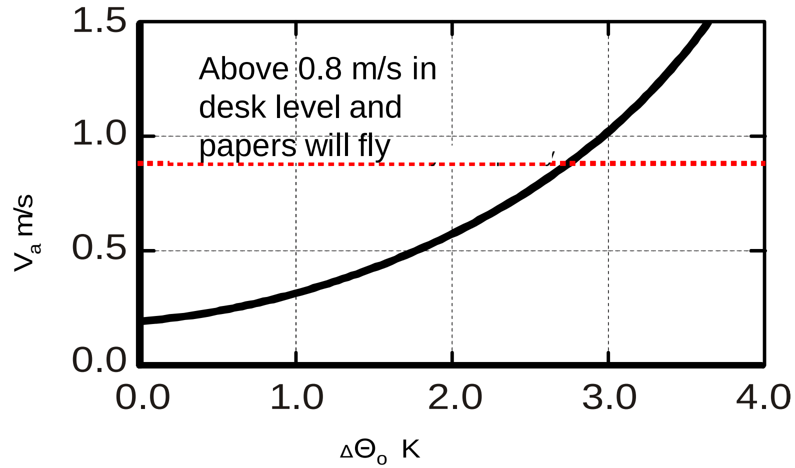
Local thermal discomfort

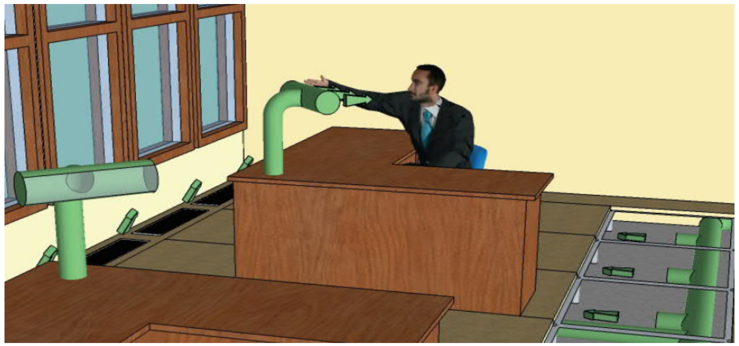
Air velocity



The warmer air is, the larger tolerance is .

Increased Room Air Velocity



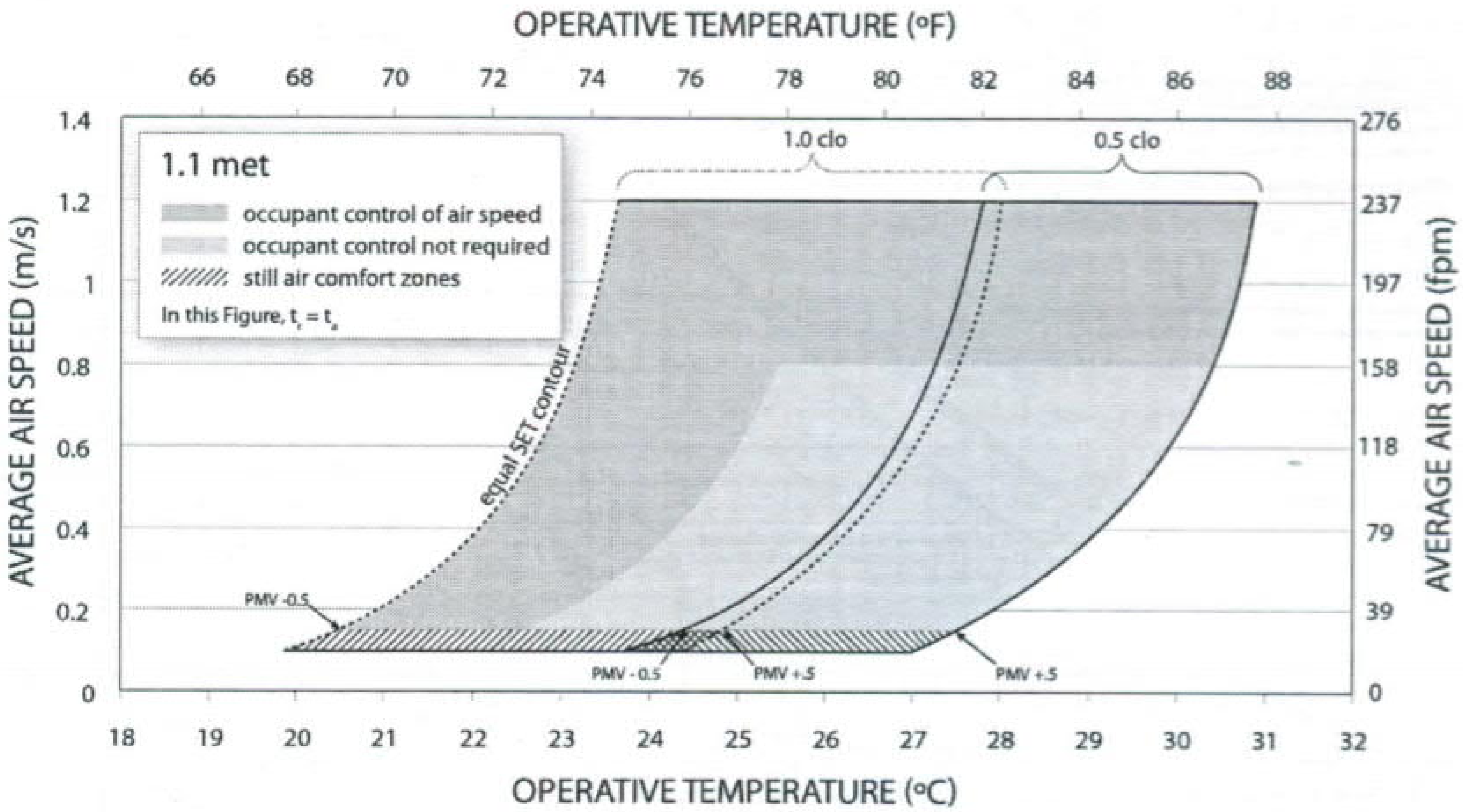


Personalized ventilation

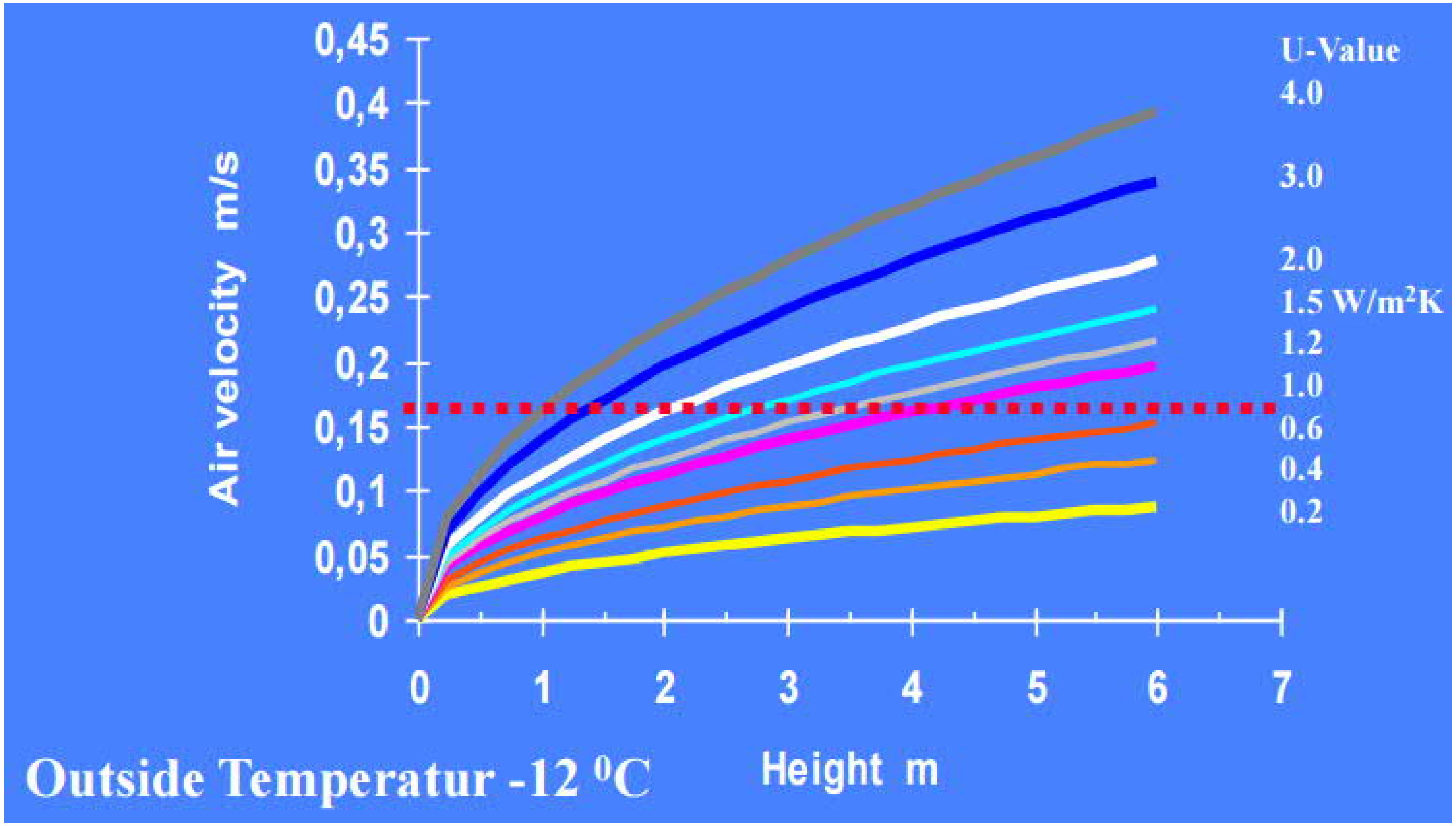
Air speed required to offset increased temperature (EN ISO 7730).

- The air speed increases by the amount necessary to maintain the same total heat transfer from the skin.
- Acceptance of the increased air speed will require occupant control of device creating the local air speed.

Acceptable Range of Operative Temperature



Down Draught of Cold Window Surface



Cold surface temperature creates strong convection flow and increases the risk of draught

Standard Effective Temperature (SET)

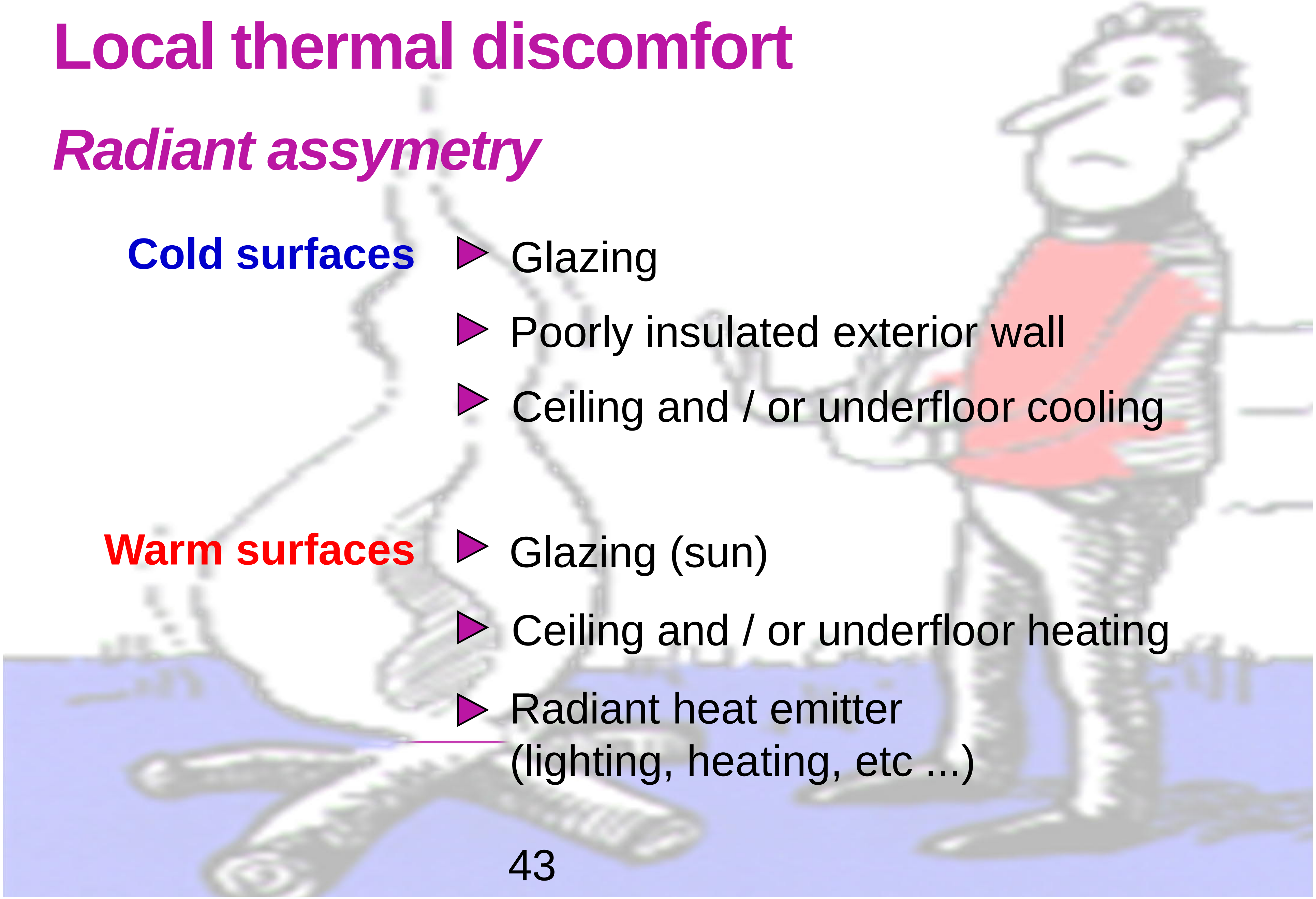
- It is a comprehensive comfort index based on heat-balance equations that incorporates the personal factors clothing and metabolic rate as well as skin temperature and skin wetness.
- ASHRAE 55-2010 defines SET as the temperature of an imaginary environment at
  - 50% relative humidity;
  - <0.1 m/s average air speed;
  - mean radiant temperature equal to average air temperature;

  total heat loss from the skin of an imaginary occupant with
  - an activity level of 1.0 met; a clothing level of 0.6 clo;

  is the same as that from a person in the actual environment, with actual clothing and activity level.

Local thermal discomfort

Radiant assymetry



Cold surfaces

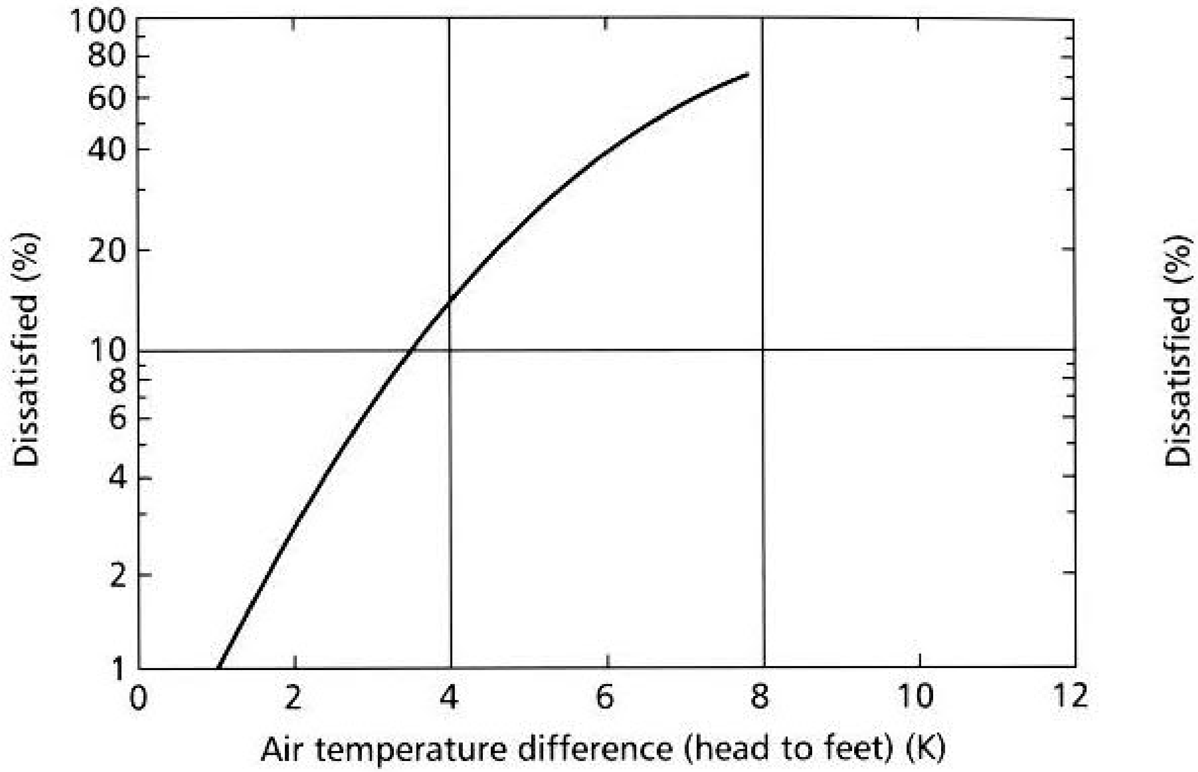
- Glazing
- Poorly insulated exterior wall
- Ceiling and / or underfloor cooling

Warm surfaces

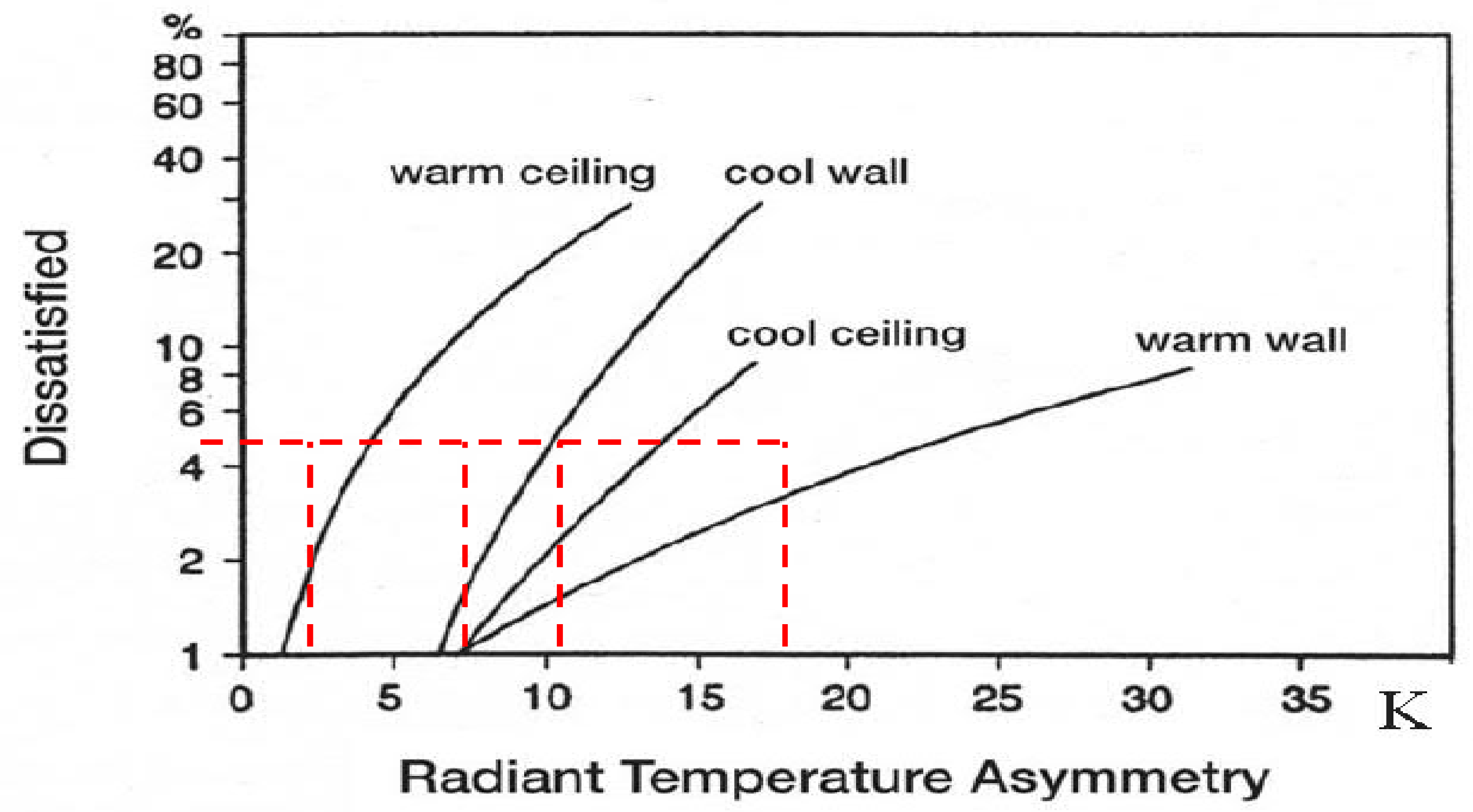
- Glazing (sun)
- Ceiling and / or underfloor heating
- Radiant heat emitter
(lighting, heating, etc ...)

Vertical Temperature Asymmetry

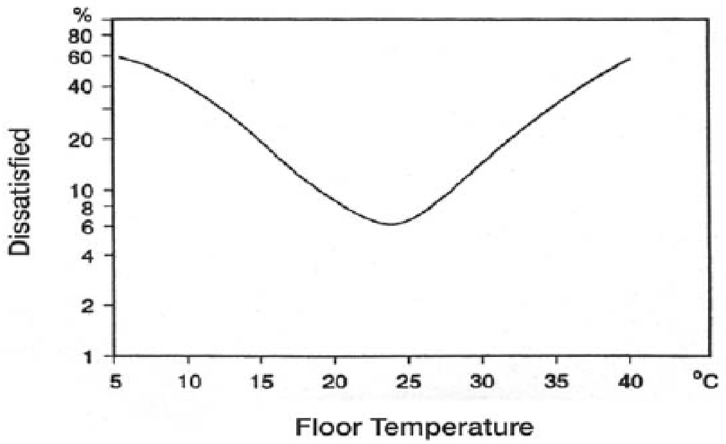
General recommendation is that temperatures between head and feet should not differ by >3°C



Radiant Temperature Assymmetry



Floor Temperature



- SEATED/STANDING PERSONS:
  (66.2F) 19 °C < t_s < 29 °C (84.2F)
- BY HIGHER ACTIVITY LEVELS A LOWER FLOOR TEMPERATURE IS ACCEPTABLE

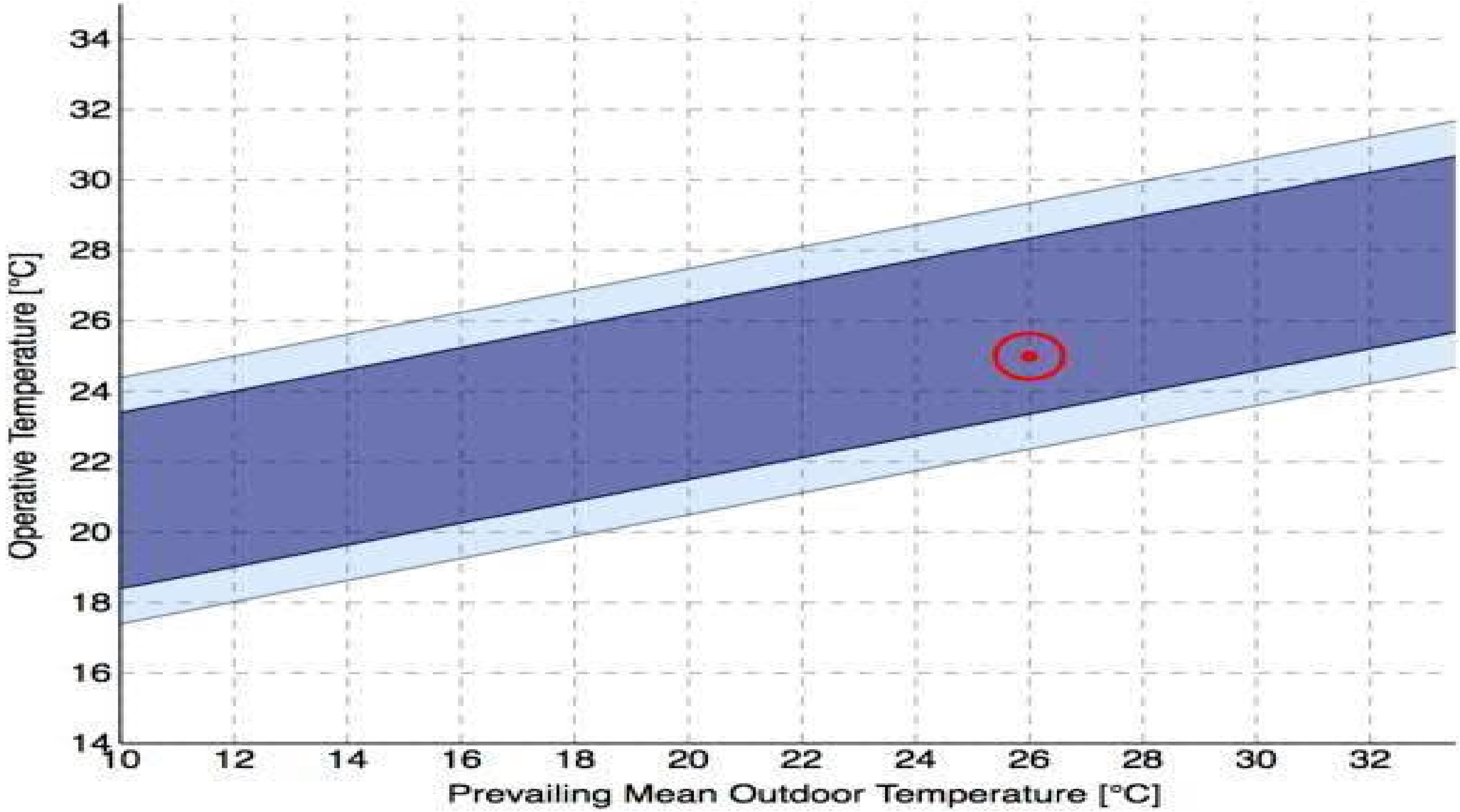
Thermal comfort in buildings without mechanical cooling

- The adaptive model is based on the idea that outdoor climate influences indoor comfort because humans can adapt to different temperatures during different times of the year.
- There are basically three categories of thermal adaptation to explain the difference between field observations and PMV predictions:
  - **Behavioural** (clothing, activity, personalized control);
  - **Physiological** (acclimatization, genetic adaptation);
  - **Psychological** (expectation, opportunity to adapt).
- The adaptive hypothesis predicts that contextual factors, such as having access to environmental controls, and past thermal history influence building occupants' thermal expectations and preferences.

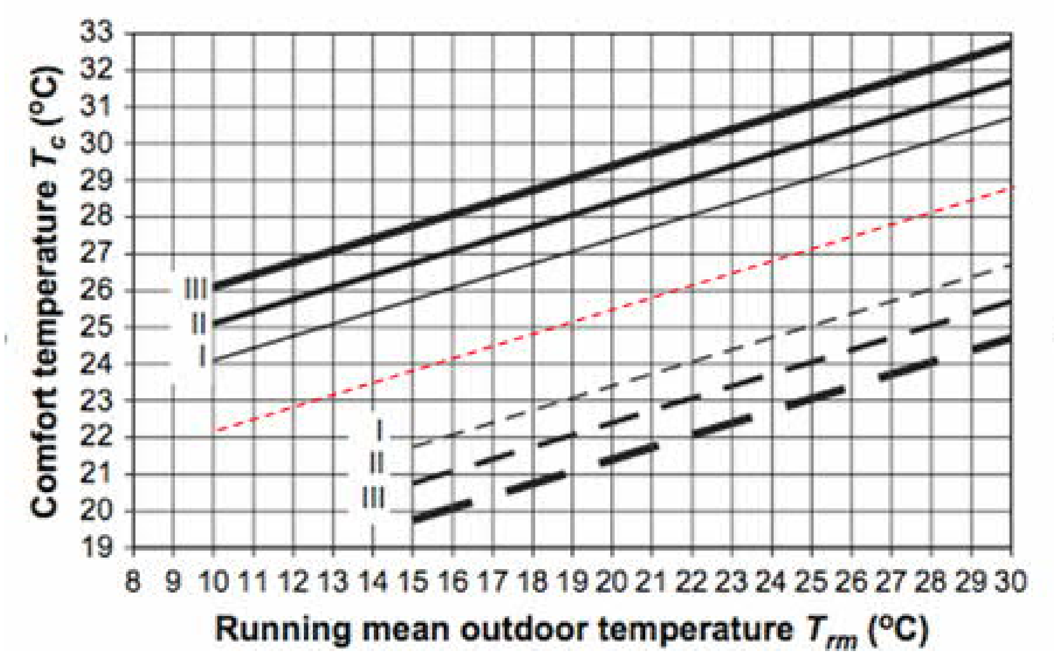
Adaptive Thermal Comfort Model

- Adaptive models of thermal comfort are implemented in standards such as ASHRAE 55, European EN 15251 and ISO 7730 standard.
- According ASHRAE in order to apply the adaptive model,
  - there should be no mechanical cooling system for the space,
  - occupants should be engaged in sedentary activities with metabolic rates of 1-1.3 met, and
  - a prevailing mean temperature greater than 10 °C (50 °F) and less than 33.5 °C (92.3 °F).
- EN15251 can be applied to mixed-mode buildings provided the system is not running.
- The adaptive chart relates indoor comfort temperature to prevailing outdoor temperature and defines zones of 80% and 90% satisfaction.

Adaptive Thermal Comfort Model (ASHRAE 55)



Adaptive Thermal Comfort Model (EN 15251)



Category Explanation:
I High level of expectation only used for spaces occupied by very sensitive and fragile persons
II Normal expectation for new buildings and renovations
III A moderate expectation (used for existing buildings)
IV Values outside the criteria for the above categories (only acceptable for a limited periods)

$$\mathbf{T_{comf} = 0.33\ T_{rm} + 18.8}$$

The allowable maximum difference between this comfort temperature and the actual indoor **operative** temperature (T_{diff}) is given in terms of the categories

- Category I: ±2K
- Category I: ±3K
- Category I: ±4K

Thermal Comfort Indicators

Index	Dry-bulb Air Temperature	Radiant Temperature	Air Velocity	Turbulence Intencity	Relative Humidity	MET (Activity)	Clothing	Outdoor Air Temperature
Air Temperature	X							
Operative Temperature	X	X						
Draught Rating (local)	X		X	X				
PMV & PPD – Index (whole body)	X	X	X		X	X	X	
Standard Effective Temperature	X	X	X		X	X	X	
Adaptive Thermal Comfort Model	X	X						X

Thank you

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