BUILDINGS HVAC SYSTEM

THERMAL COMFORT

Programma

- Comfort Conditions
  - Metabolic rate
  - Comfort conditions
  - Thermal comfort
  - Discomfort index
  - Local discomfort indexes
  - Categories of thermal environments

Steady-State Thermal Equilibrium

- In Thermal equilibrium the human body thermal balance is:

$$M - W - E_{sk} - \mathrm{E_{res}} - (R + C) = 0$$

  - M Metabolic rate
  - W work
  - E_{SK} evaporative heat loss from skin
  - E_{res} evaporative heat loss for respiration
  - R, C convective and radiative sensible heat loss

Transient Energy Balance

- In Thermal equilibrium the human body thermal balance is:

$$S_{cr} + S_{sk} = M - W - E_{sk} - \mathrm{E_{res}} - (R + C) = 0$$

  - M Metabolic rate
  - W work
  - E_{SK} evaporative heat loss from skin
  - E_{res} evaporative heat loss for respiration
  - R, C convective and radiative sensible heat loss
  - S_{cr} = heat storage in body core
  - S_{sk} = heat storage in skin surface

Metabolic rate

- The metabolic rate M is the rate of energy release per unit area of skin surface as a result of the oxidative processes in the living cells.
- Metabolic rate can features a base part, at rest and a part dependent on pysical activity.
- The unit of metabolic rate is called the met. 1 met = 58,24 W/m^2
- the value is dependent on the surface of human body, this can be computed using the Du Bois formula

$$A_b = 0{,}202 \times W_b^{0{,}425} \times H_b^{0{,}725} \qquad W_b[kg]; H_b[\mathrm{m}]$$

- with H_b=1.72 m, W_b=70 kg , A_b=1.82 m^2

Metabolic rate

Activity	Metabolic Rate Met Units	W/m²
Resting		
Sleeping	0.7	40
Reclining	0.8	45
Seated, quiet	1.0	60
Standing, relaxed	1.2	70
Walking (on level surface)		
0.9 m/s, 3.2 km/h, 2.0 mph	2.0	115
1.2 m/s, 4.3 km/h, 2.7 mph	2.6	150
1.8 m/s, 6.8 km/h, 4.2 mph	3.8	220
Office Activities		
Reading, seated	1.0	55
Writing	1.0	60
Typing	1.1	65
Filing, seated	1.2	70
Filing, standing	1.4	80
Walking about	1.7	100
Lifting/packing	2.1	120

Mechanical Work

- The mechanical work is expressed as a fraction of metabolic rate
- The work is computed introducing an efficiency μ

$$\mathrm{W} = \mu \cdot M$$

- The values are low
  - 0.05 for office work
  - Walking on a slope rises to between 0.2 and 0.4

Convective sensible heat exchange

- Convective heat loss or, occasionally, sensible heat gain is expressed as

$$\Phi_C = f_{cl} \cdot h_c \cdot A_b \cdot (t_{cl} - t_a)$$

  - f_{cl} ratio of the clothed surface area to the naked surface area $f_{cl} = A_{cl}/A_b$
  - t_{cl} cloth temperature
  - t_a air temperature
  - A_b naked surface area
- the convective heat-transfer coefficient h_c for a person standing in moving air, when the air velocity is with $0.15 \leq v \leq 1.5$ m/s can be computed as

$$h_c = 14.8 \cdot v^{0.69} \quad \mathrm{W/(m^2\ K)}$$

Radiation sensible heat echange

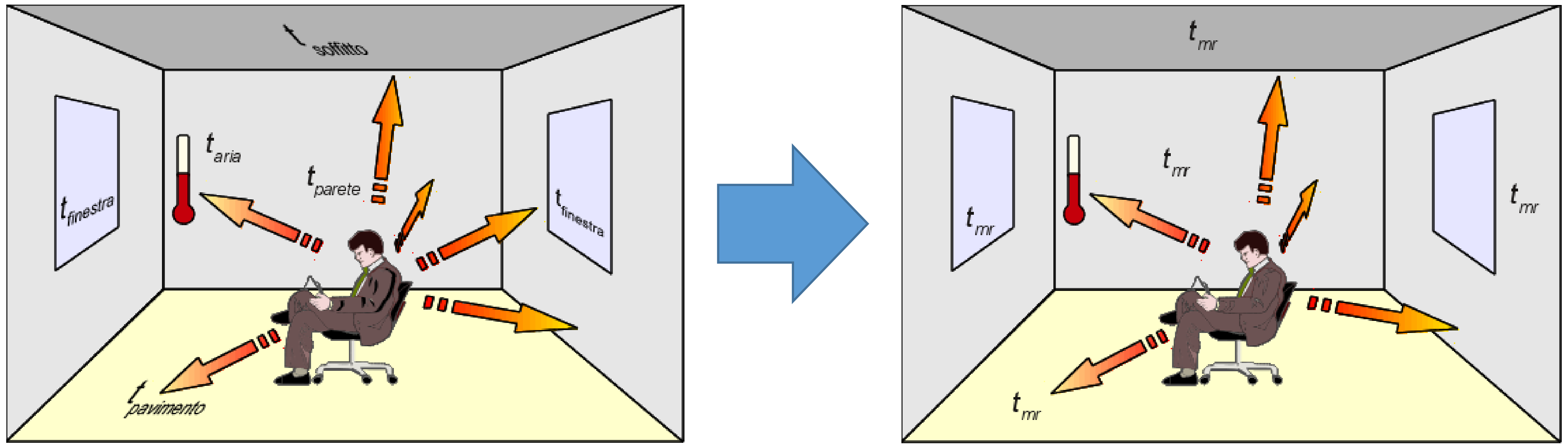
- Heat exchange

$$\Phi_R = f_{cl} \cdot A_{\mathrm{b}} \cdot \varepsilon_{\mathrm{cl}} \cdot \sigma \cdot (T_{cl}^4 - T_2^4)$$

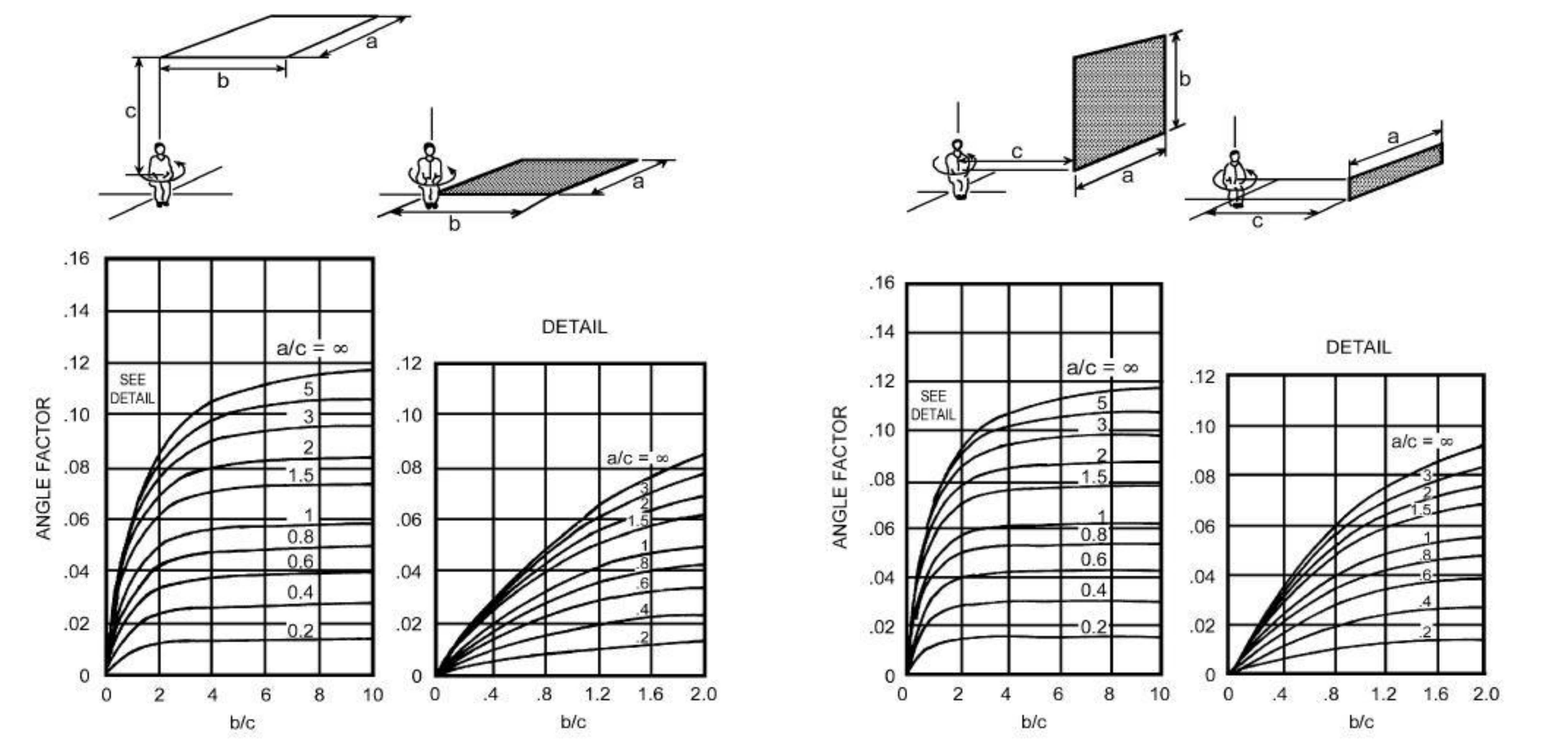
- As temperature T_2 is used the mean radiant temperature T_r
- T_{mr} is defined as the temperature of a uniform black enclosure in which an occupant would have the same amount of radiative heat exchange as in an actual indoor environment.
- Writing the heat exchange with black surfaces

$$(t_{MR} + 273.15)^4 = \sum_i (t_i + 273.15)^4 \cdot F_{p-i}$$

  - F_{p-i} shape factor
  - $\sum F_{p-1} = 1$



Forms factor for a seated person



A. HORIZONTAL RECTANGLE (ON CEILING OR ON FLOOR)   B. VERTICAL RECTANGLE (ABOVE OR BELOW CENTER OF PERSON)

Radiation heat transfer linearization

- Radiation heat exchange is not linear
- The term can be linearized
- Temperature differences are low, and the temperatures are expressed in kelvin

$$T_{cl}^4 - T_{mr}^4 = \boxed{\left(T_{cl}^2 + T_{mr}^2\right) \cdot \left(T_{cl}^2 - T_{mr}^2\right)} = \left(T_{cl}^2 + T_{mr}^2\right) \cdot \boxed{\left(T_{cl} + T_{mr}\right) \cdot \left(T_{cl} - T_{mr}\right)}$$

$$\bar{T} = \frac{T_{cl} + T_{mr}}{2}$$

$$\bar{T}^2 \cong \frac{T_{cl}^2 + T_{mr}^2}{2}$$

$$T_{cl}^4 - T_{mr}^4 \cong 4 \cdot \bar{T}^3 \cdot \left(T_{cl} - T_{mr}\right) = \boxed{4 \cdot \bar{T}^3 \cdot \left(t_{cl} - t_{mr}\right)}$$

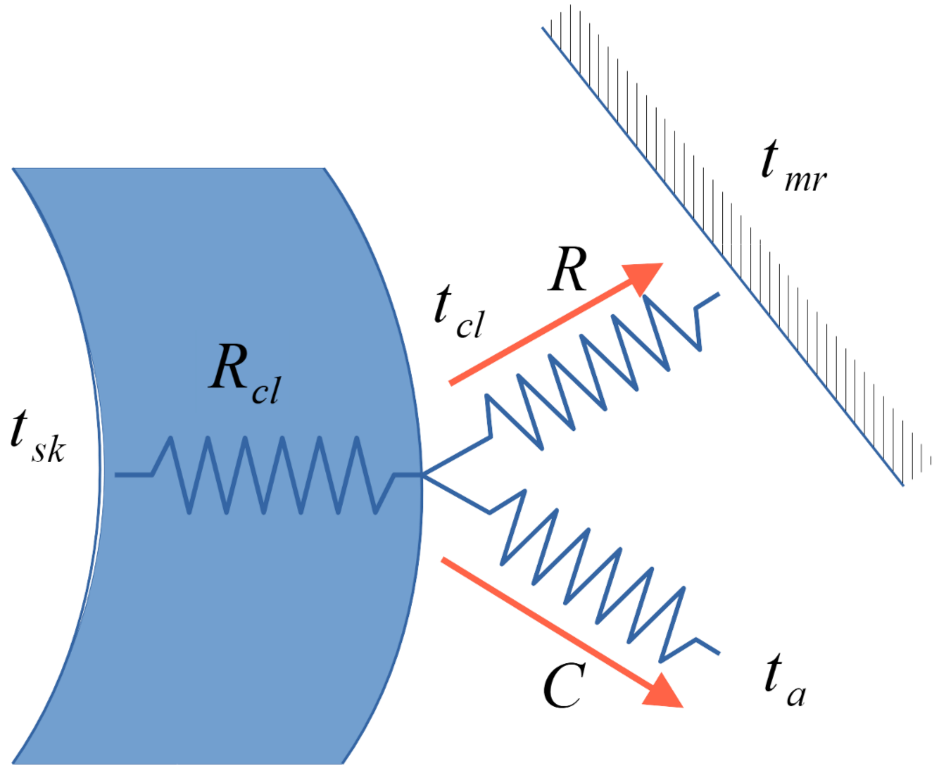
$$\Phi_R = A_\mathrm{b} \cdot \mathrm{f}_{cl} \cdot \boxed{\varepsilon \cdot \sigma \cdot \frac{\bar{T}^3}{4}} \cdot \left(t_{cl} - t_{mr}\right) = A_b \cdot f_{cl} \cdot \boxed{h_r} \cdot \left(t_{cl} - t_{mr}\right)$$

Operative temperature

- The specific heat transfer rate can be computed as

$$\Phi_C/A_b = C = f_{cl} \cdot h_C \cdot (t_{cl} - t_a)$$
$$\Phi_R/A_b = R = f_{cl} \cdot h_R \cdot (t_{cl} - t_{mr})$$

- t_a and t_{mr} can be joined, operative temperature t_o



$$\mathrm{C} + \mathrm{R} = f_{cl} \cdot h \cdot (t_{cl} - t_o)$$

$$h = h_C + h_R$$

$$t_o = \frac{h_C \cdot t_a + h_R \cdot t_{mr}}{h_C + h_R}$$

- With $v < 0.15$ m/s $h_c = 4 \frac{\mathrm{W}}{\mathrm{m^2\,K}}$, $h_r = 4.7 \frac{\mathrm{W}}{\mathrm{m^2\,K}}$

Heat flow rate and operative temperature

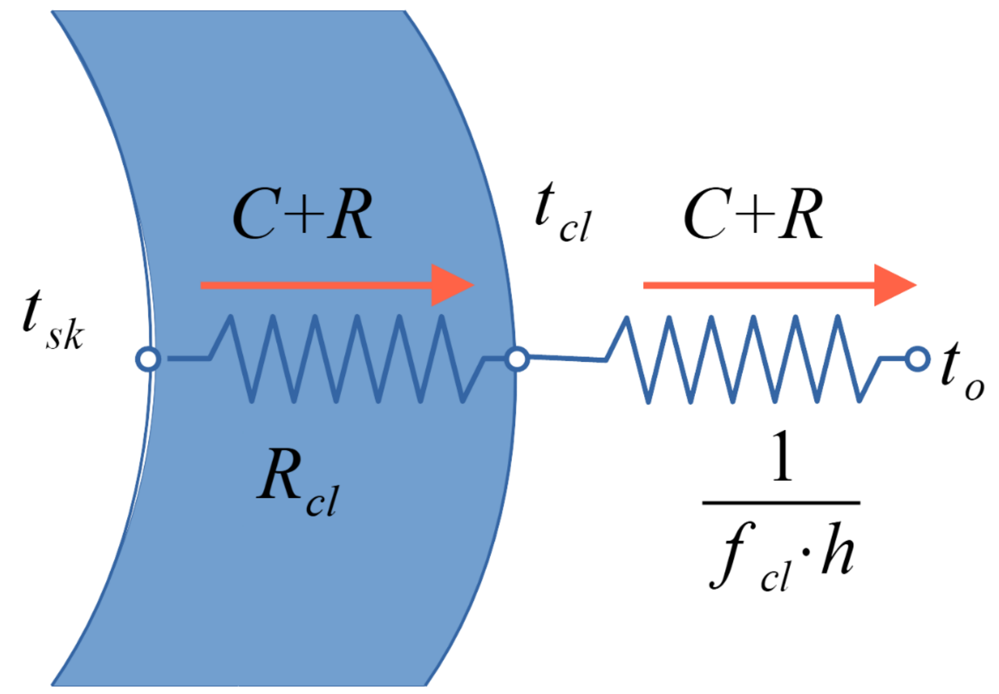
- t_{cl} can be removed by solving the equivalent heat tranfer net

$$C + R = \frac{t_{sk} - t_{cl}}{R_{cl}} = \frac{t_{cl} - t_o}{\frac{1}{f_{cl} \cdot h}}$$

$$C + R = \frac{t_{sk} - t_o}{R_{cl} + \frac{1}{f_{cl} \cdot h}}$$

$$C + R = \mathrm{F_{cl}} \cdot f_{cl} \cdot h\ (t_{sk} - t_o)$$

$$F_{cl} = \frac{t_{cl} - t_o}{t_{sk} - t_o}$$



- F_{cl} clothing efficiency

Clothing

- Clothing adds both thermal resistance and resistance to the passage of vapor, thermal resistance is expressed in clo; 1 clo = 0,155 (m^2 K)/W , clothing thermal resistance is therefore expressed in I_{clo}
- The resistance of clothing to the passage of vapor can be expressed as $R^v{}_{cl}$ =0,90 R_{cl}/i_{cl} (s m^2)/kg_a where i_{cl} is the fraction of resistance to vapor passage and thermal resistance

clorh	Reistence (clo)
Summer (man)	0,5
Summer (woman)	0,3
winter (man)	1,0
winter (woman)	0,7
winter heavy	1,5

Typical clothing arrangements

Abbigliamento da lavoro	I_d		Abbigliamento giornaliero	I_d	
	clo	$m^2 \cdot K/W$		clo	$m^2 \cdot K/W$
Mutande, tuta, calzini, scarpe	0,70	0,110	Slip, maglietta, pantaloncini, calzini leggeri, sandali	0,30	0,050
Mutande, camicia, pantaloni, calzini, scarpe	0,75	0,115	Slip, sottoveste, calze, abito leggero con maniche, sandali	0,45	0,070
Mutande, camicia, tuta, calzini, scarpe	0,80	0,125	Mutande, camicia con maniche corte, pantaloni leggeri, calzini leggeri, scarpe	0,50	0,080
Mutande, camicia, pantaloni, giacca, calzini, scarpe	0,85	0,135	Slip, calze, camicia a maniche corte, gonna, sandali	0,55	0,085
Mutande, camicia, pantaloni, grembiule, calzini, scarpe	0,90	0,140	Mutande, camicia, pantaloni leggeri, calzini, scarpe	0,60	0,095
Biancheria intima a maniche e gambe corte, camicia, pantaloni, giacca, calzini, scarpe	1,00	0,155	Slip, sottoveste, calze, abito, scarpe	0,70	0,105
Biancheria intima a gambe e maniche corte, camicia, pantaloni, tuta, calzini, scarpe	1,10	0,170	Biancheria intima, camicia, pantaloni, calzini, scarpe	0,70	0,110
Biancheria intima a gambe e maniche lunghe, giacca termica, calzini, scarpe	1,20	0,185	Biancheria intima, completo da corsa (maglia e pantaloni), calzini lunghi, scarpe da corsa	0,75	0,115
Biancheria intima a maniche e gambe corte, camicia, pantaloni, giacca, giacca termica, calzini, scarpe	1,25	0,190	Slip, sottoveste, camicia, gonna, calzettoni spessi al ginocchio , scarpe	0,80	0,120
Biancheria intima a maniche e gambe corte, tuta, giacca termica e pantaloni, calzini, scarpe	1,40	0,220	Slip, camicia, gonna, maglione a girocollo, calzettoni spessi al ginocchio, scarpe	0,90	0,140
Biancheria intima a maniche e gambe corte, camicia, pantaloni, giacca, giacca termica e pantaloni, calzini, scarpe	1,55	0,225	Mutande, camiciola a maniche corte, camicia, pantaloni, maglione con scollo a V, calzini, scarpe	0,95	0,145

Abbigliamento tipico

Biancheria intima a maniche e gambe corte, camicia, pantaloni, giacca, giacca con imbottitura pesante e tuta, calzini, scarpe	1,85	0,285	Slip, camicia, pantaloni, giacca, calzini, scarpe	1,00	0,155
Biancheria intima a maniche e gambe corte, camicia, pantaloni, giacca, giacca con imbottitura pesante e tuta, calzini, scarpe, berretto, guanti	2,00	0,310	Slip, calze, camicia, gonna, gilet, giacca	1,00	0,155
Biancheria intima a maniche e gambe lunghe, giacca termica e pantaloni, giacca termica per esterno e pantaloni, calzini, scarpe	2,20	0,340	Slip, calze, blusa, gonna lunga, giacca, scarpe	1,10	0,170
Biancheria intima a maniche e gambe lunghe, giacca termica e pantaloni, parka con imbottitura pesante, tuta con imbottitura pesante, calzini, scarpe, berretto, guanti	2,55	0,395	Biancheria intima, camiciola con maniche corte, camicia, pantaloni, giacca, calzini, scarpe	1,10	0,170
			Biancheria intima, camiciola a maniche corte, camicia, pantaloni, gilet, giacca, calzini, scarpe	1,15	0,180
			Biancheria intima a maniche e gambe lunghe, camicia, pantaloni, maglione con scollo a V, giacca, calzini, scarpe	1,30	0,200
			Biancheria intima a maniche e gambe corte, camicia, pantaloni, gilet, giacca, cappotto, calzini, scarpe	1,50	0,230

Evaporative heat loss

- The latent heat flow is generated by two components:
  - Heat flow for respiration
  - Heat flow for transpiration from the skin
- The heat flow released by evaporation depends on the temperature of the skin, air humidity, air speed, percentage of wet skin, type of clothing
- Heat flow released by respiration, depends on the type of activity and the humidity and temperature of the air

Evaporative heat loss

- Evaporative heat loss from skin

$$E_{rsw} \approx \dot{m}_{rsw} \cdot h_{fg}$$

$\dot{m}_{rsw}$ mass flow rate of sweat

h_{fg} latent heat of vaporization

- Maximum evaporative heat loss

$$w_{rsw} = \frac{E_{rsv}}{E_{max}}$$

- E_{max} maximum evaporative heat loss due to regulatory sweating

$$E_{max} = h_{e,c} \cdot (p_{sk,s} - p_a)$$

- p_a water vapor pressure of air

- Heat and mass coefficients

$$i_m \cdot LR = \frac{h_{e,c}}{h_s}$$

i_m moisture permeability index

LR relazione di Lewis

$$LR = 16.5\ \text{°C/kPa}$$

- Without regulatory sweating
- $E_{df,min} = 0.06 \cdot E_{max}$

Evaporative heat loss

- With regulatory sweating, the diffusive term (part not covered by sweat)

$$E_{dif} = (1 - w_{rsw}) \cdot 0.06 \cdot E_{max}$$

- Total evaporative heat loss from skin

$$E_{sk} = E_{rsw} + E_{dif} =$$
$$w_{rsw} \cdot E_{max} + (1 - w_{rsw}) \cdot 0.06 \cdot E_{max}$$
$$E_{sk} = w_{sk} \cdot E_{max}$$

w_{sk} total skin wetness

- Respiration Losses
  - With respiration there is a sensible and latent heat exchange
  - Depends on the metabolic rate
  - Summer condition:

$$E_{res} = C_{res} + L_{res} \cong 0.09 \cdot M$$

  - Slightly higher in winter

$$E_{res} \cong 0.1 \cdot M$$

Thermal comfort

- Steady state for comfort

$$M = W + C + R + E_{sk} + E_{res}$$

$$M(1-0.05-0.1) = F_{cl} \cdot f_{cl} \cdot h(T_{sk} - T_o) + w_{sk} \cdot i_m \cdot LR \cdot h_s \cdot (p_{sk,s} - p_a)$$

- For a situation of comfort, the balance equation of the human body must be satisfied, this translates into an equation of the form

$$f(\boxed{I_{cl}, M, t_a, v_a, \mathrm{UR}, t_{mr},} t_{sk}, E) = 0$$

- Skin temperature and evaporative heat rate are expressed using other parameters. There are six free parameters

Thermal comfort

- is defined as the state of mind in which one acknowledges satisfaction with regard to the thermal environment. In terms of sensations, thermal comfort is described as a thermal sensation of being neither too warm nor too cold,
- global thermal comfort, relating to the person as a whole
- local comfort, the behavior of a specific part is studied
- both must be satisfied.

Comfort index

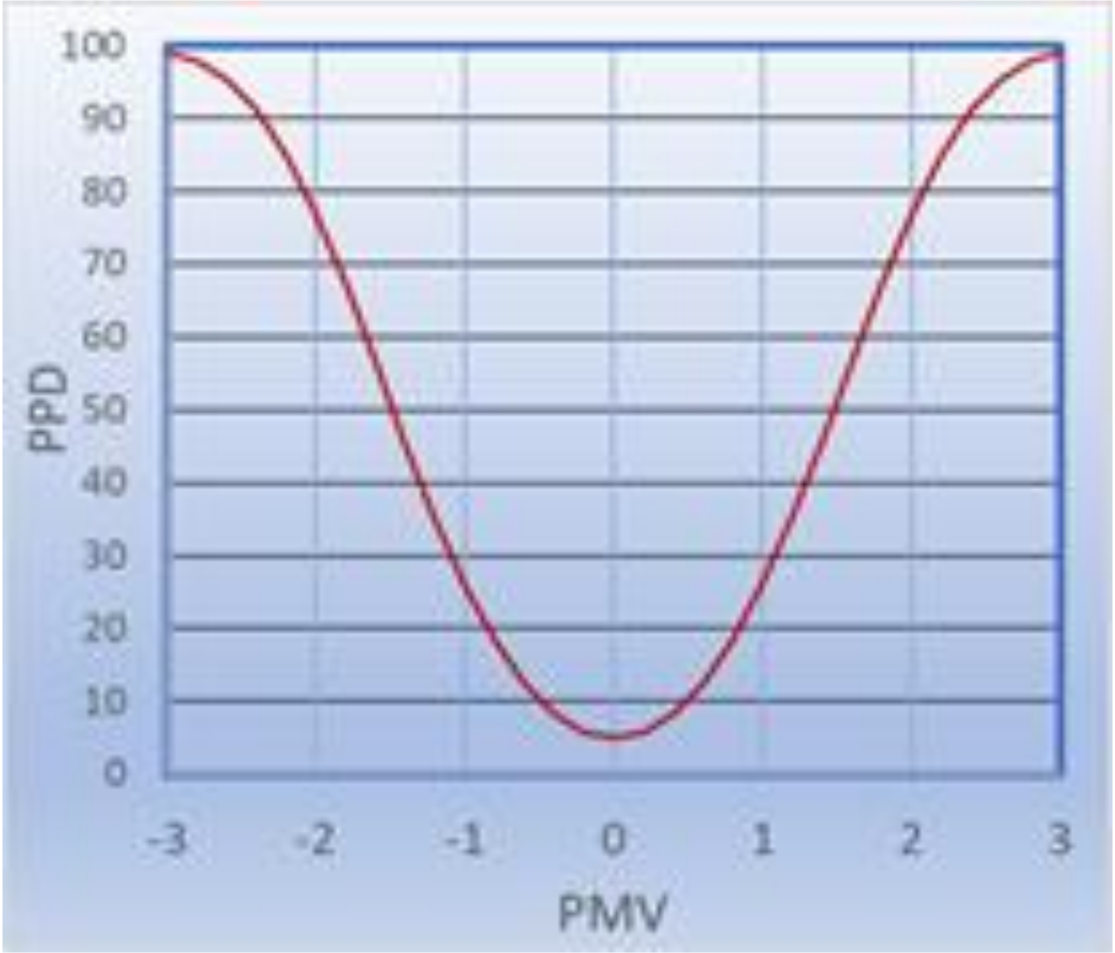
- ISO standard UNI-EN-ISO 7730 considers the PMV (predicted Mean Vote)
- PMV is a sensation index on a rating scale that depends on the subject's environmental and characteristic parameters such as clothing and activity.

VOTO	SENSAZIONE
+3	hot
+2	warm
+1	Slightly warm
0	neutral
-1	Slightly cool
-2	cool
-3	cold

comfort index

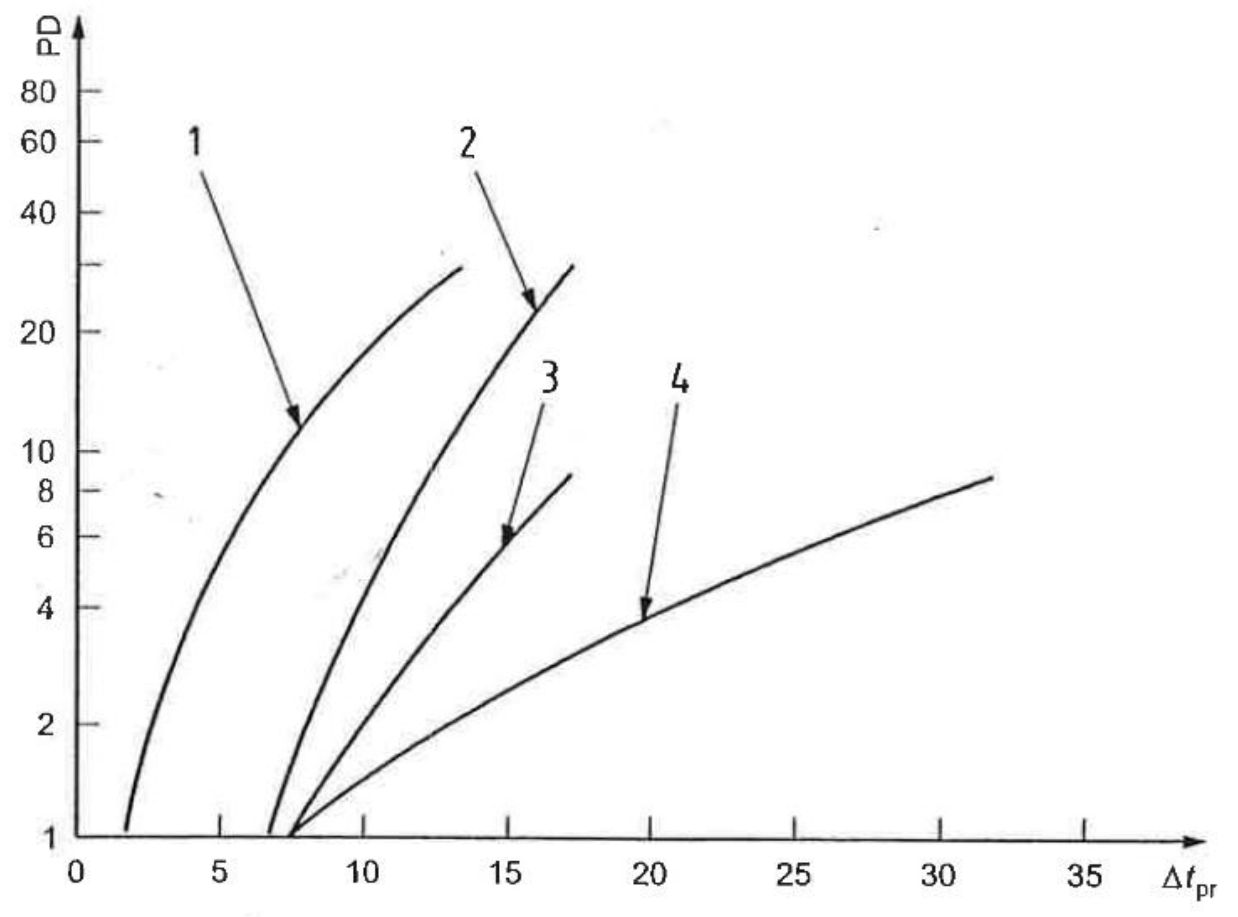
- The PMV statistically represents the vote that an individual would give to a thermal environment, it is also necessary to consider the dispersion of votes, therefore another index has been introduced:
- PPD (Predicted Percentage of Dissatisfied)PPD represents the percentage of people in the environment considered who would express a vote equal to or higher than 2, PPD has been correlated to PMV

$$PPD = 100 - 95 \cdot e^{-0.03353 \cdot PMV^4 - 0.2179 \cdot PMV^2}$$



Local discomfort

- In addition to global comfort, local comfort must also be verified, that is, situations in which uncomfortable conditions occur in some parts of the environment
- such situations may occur for example due to air currents or thermal gradients.



Key

PD percentage dissatisfied, %

Δt_{pr} radiant temperature asymmetry, °C

1 Warm ceiling.

2 Cool wall.

3 Cool ceiling.

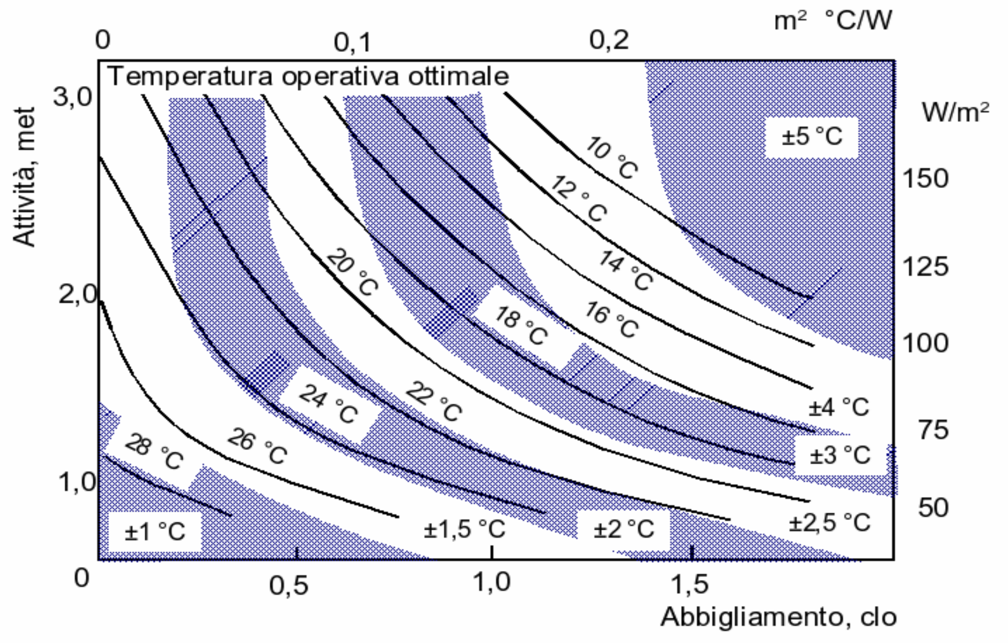
4 Warm wall.

UNI 7730 – Categories of thermal environment

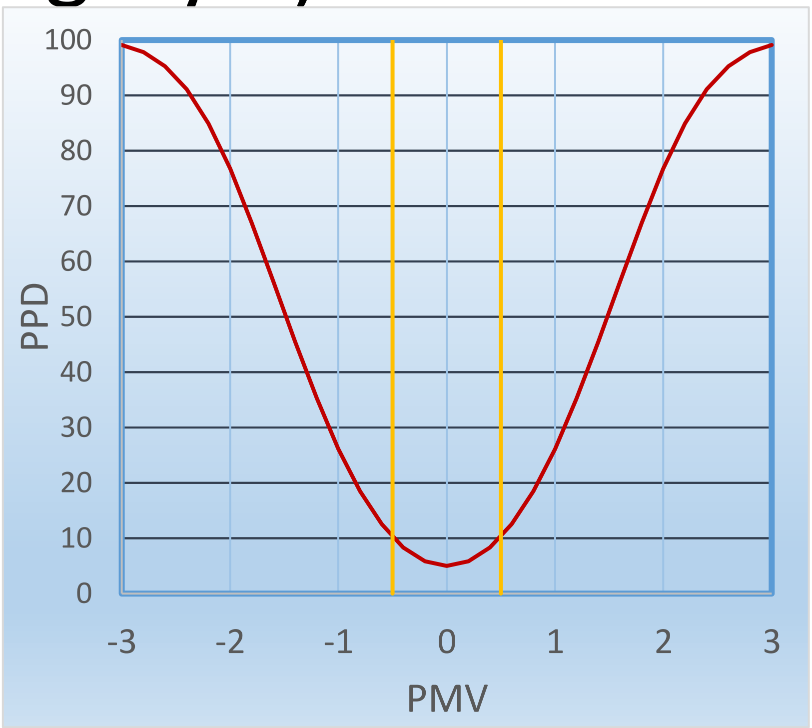
Category	Thermal state of the body as a whole		Local discomfort			
	PPD %	PMV	DR %	PD %		
				Vertical temperatue difference	Warm or cold floor	Radiant asymmetry
A	< 6	-0,2 < PMV < +0,2	< 10	< 3	< 10	< 5
B	< 10	-0,5 < PMV < +0,5	< 20	< 5	< 10	< 5
C	< 15	-0,7 < PMV < +0,7	< 30	< 10	< 15	< 10

Optimal operative temperatures

- The acceptability of an environment can be defined as that series of values of environmental parameters characterized by a PPD lower than or equal to a certain threshold.
- A commonly accepted limit value is a PPD lower than or equal to 10%, which corresponds to a PMV between -0.50 and +0.50 (category B)

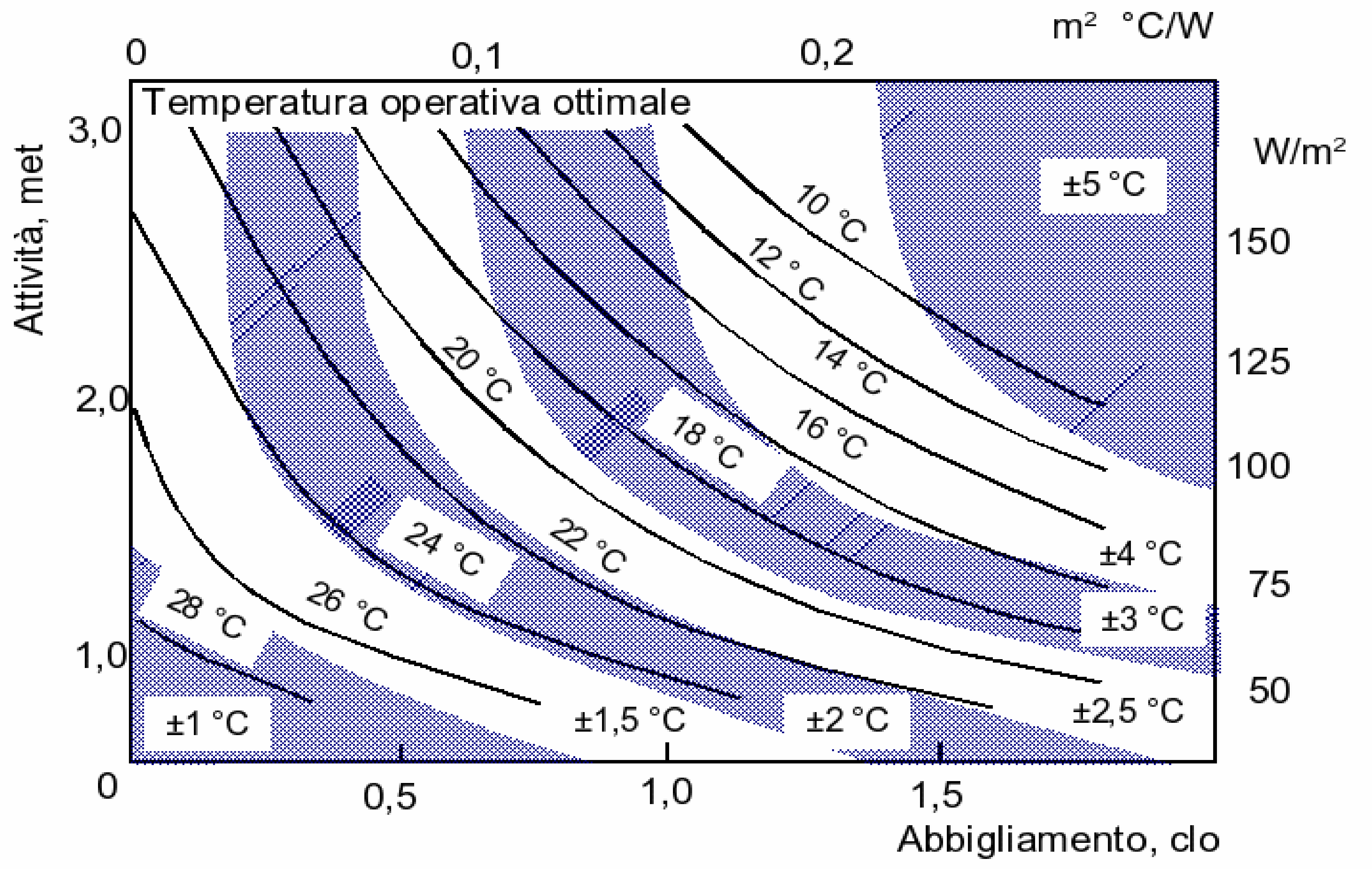


Le aree ombreggiate indicano l'intervallo di benessere Δt rispetto alla temperatura ottimale in cui 0,5 < PMV<0,5. Le velocità relative di aria è valutata pari a zero per M < 1 met e con la relazione v_{ar} = 0,3 (M-1) per M > 1 met. L'umidità relativa è pari al 50 %

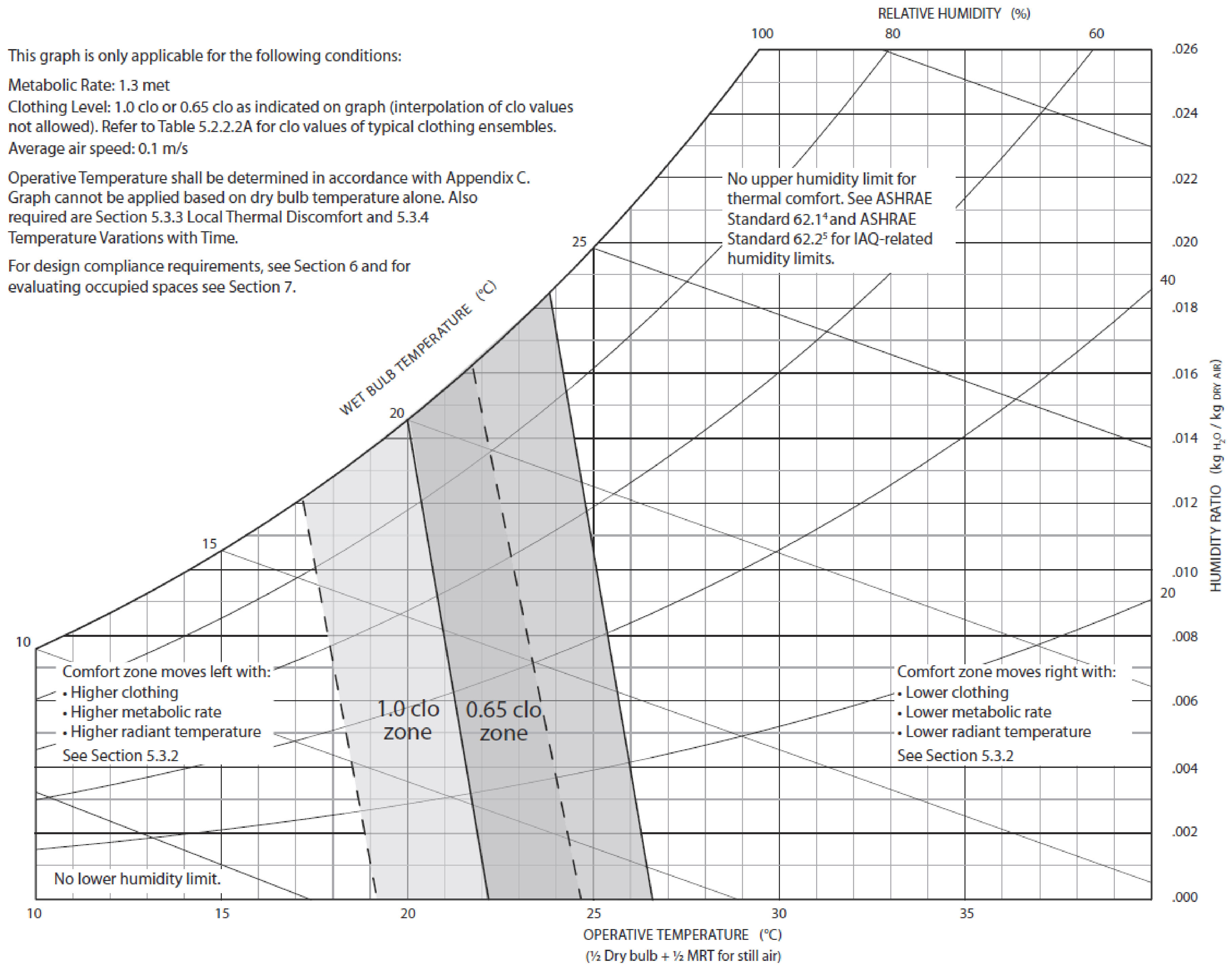


Optimal operative temperature

Category B: PPD < 10 %



ASHRAE 55 comfort area



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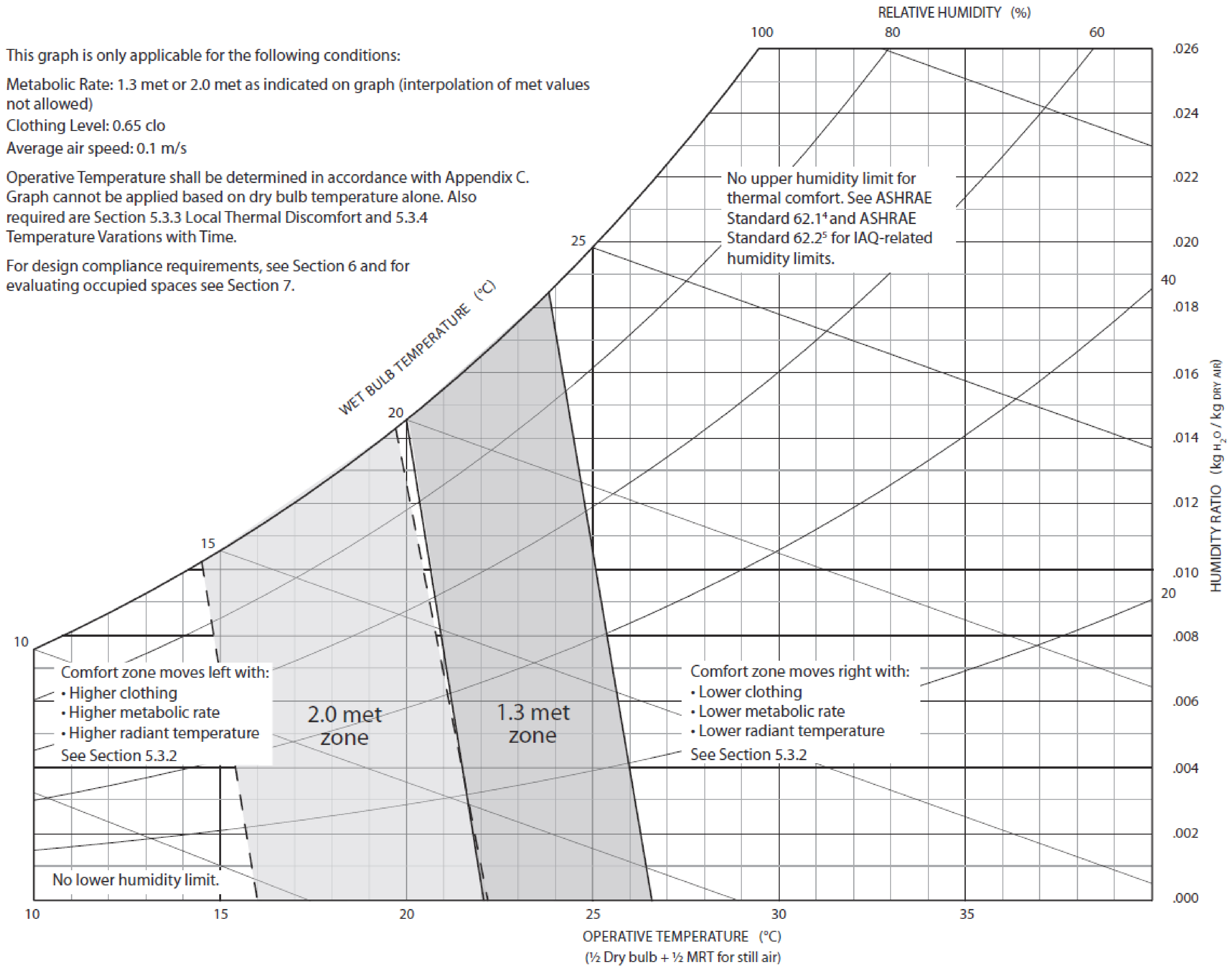
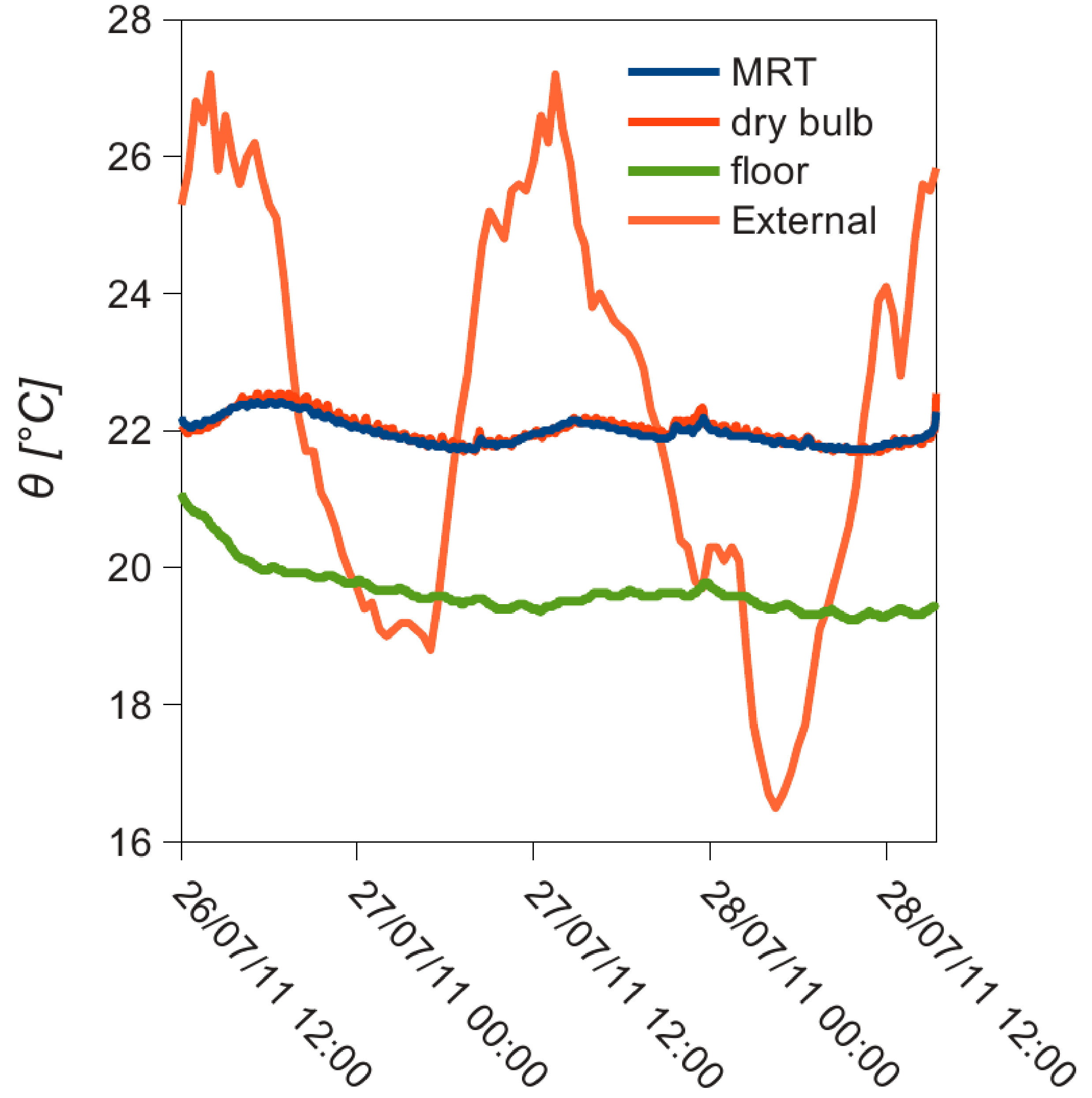


Thermal comfort measurement

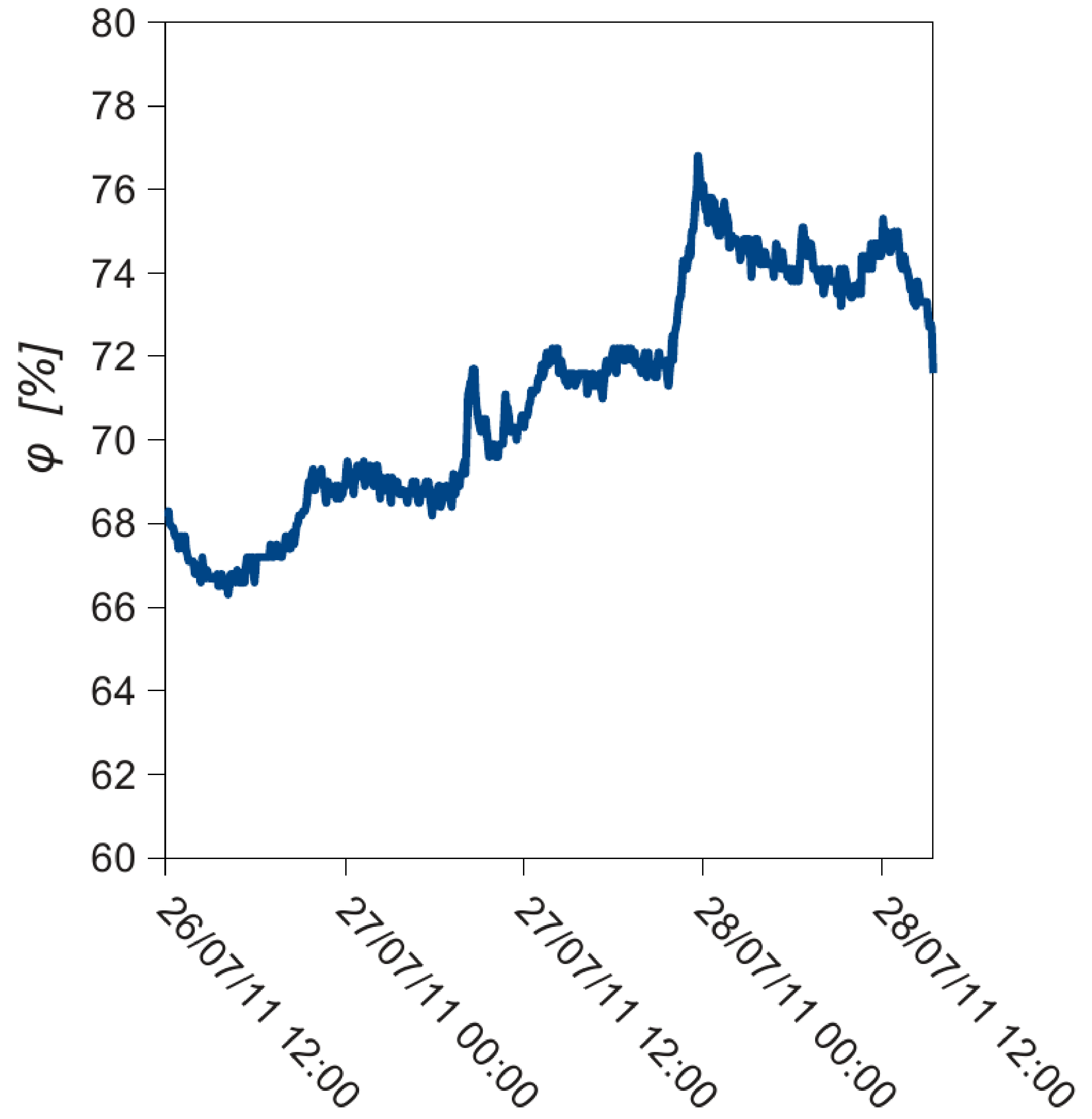
- Environmental and measurements are carried out with a BABUC M system

Babuc System

Summer

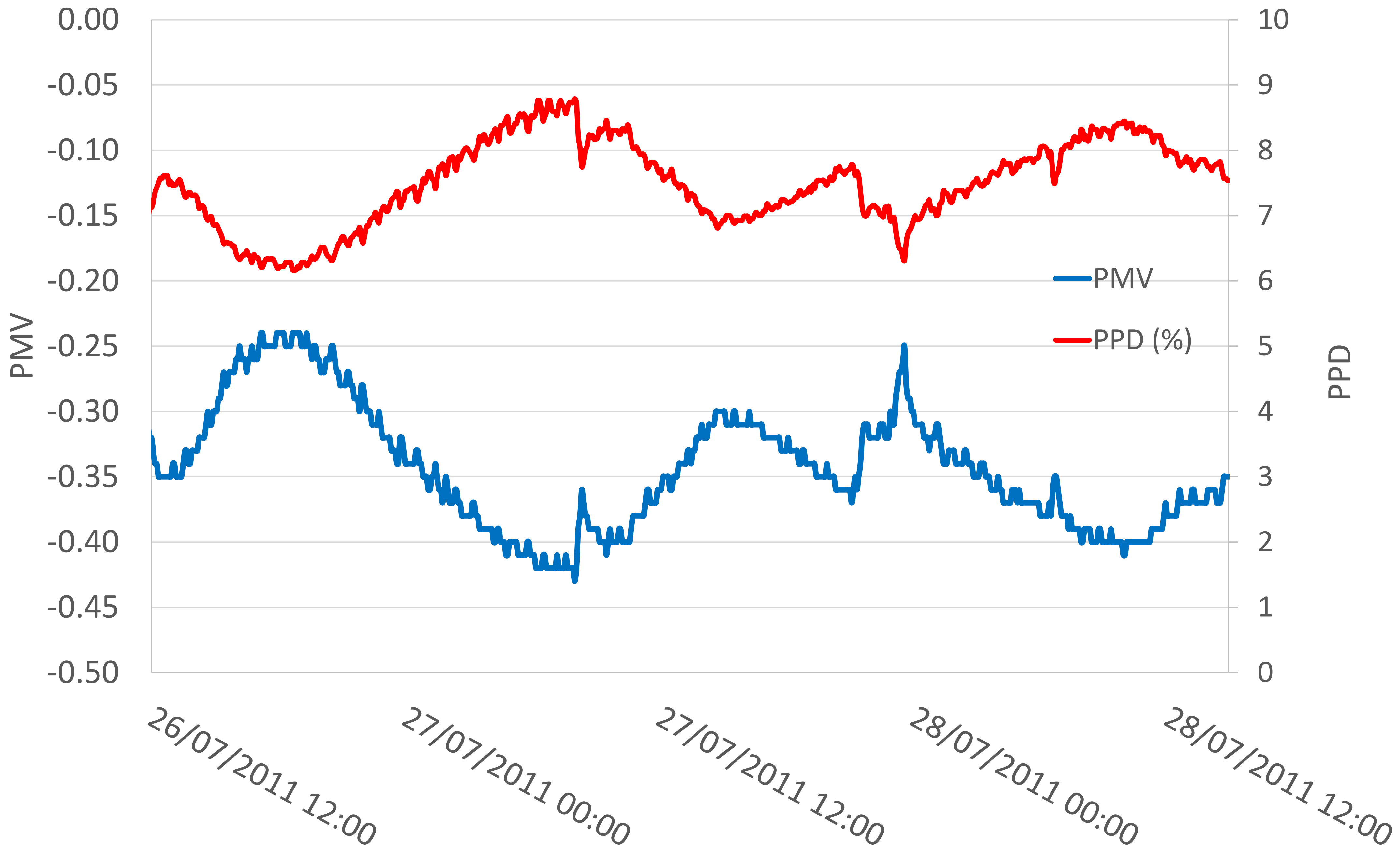


Temperatura



Umidità relativa

PMV and PPD clo 0,6



PMV and PPD clo 0,5